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SIMULATORS FOR MAINTENANCE TRAINING:
SOME ISSUES, PROBLEMS AND AREAS FOR FUTURE RESEARCH

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This report reviews past and present applications of simulation to maintenance training. Emphasis is on describing issues, problems and areas for future research as identified by recent authors. A variety of issues and problems are discussed under five headings Application of Simulation Technology to Technical Training, Determination of Simulation Requirements, Design and Specification of Simulation Requirements, User Acceptance of Maintenance Simulators, and the Cost Effectiveness of Maintenance Simulators. Requirements for future research are discussed under the following topics: Evaluating the Cost Effectiveness of Simulators; Comparing Simulators One With Another; Determining Training Requirements; Determining Simulation Requirements; Developing Exemplary Simulators; Developing Exemplary Mixes of Maintenance Training Media Obtaining User Acceptance; Developing Improved Regulations for Maintenance Simulators.

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SUMMARY

The Problem

Since the early 1950s the U. S. Air Force has sponsored the development of maintenance simulators, especially those which could be used to teach the troubleshooting of electronic equipment. Despite numerous studies which demonstrated their cost effectiveness, the use of simulators for maintenance training still is not widespread and there is considerable resistance to such usage. As the result of recent advances in simulation technology, and the need to conserve training dollars, the Air Force is making a concerted effort to develop more information about maintenance simulators and to demonstrate their applicability. This report reviewed past and present applications of simulation to maintenance training, concentrating on the major issues and problems involved. Also, the report identified some of the areas where further research data is required.

Methodology

The review concentrated on recent literature--since 1966--and made extensive use of secondary sources when reviewing the earlier literature. With a few exceptions, the articles reviewed pertained to maintenance training and the use of simulators and low-cost training devices such as mock-ups. Descriptions on research methodology and findings were kept to a minimum; the emphasis was on identifying issues, problems and areas for further research which had been discussed by authors of recent reports.

Review Topics

Following a historical overview of the research on maintenance simulators and related training devices, the report concentrated on reviewing issues, problems and research findings and requirements in five areas. Under "Application of Simulation Technology to Technical Training" research findings relating to the cost-effectiveness of electronic troubleshooting trainers and low-cost, low fidelity aids and mock-ups were reviewed. A section dealing with the "Determination of Simulation Requirements" surveyed current procedures and problems relating to the identification of tasks to be simulated, the selection of simulation requirements, and the relationship between simulation requirements, learning stages, and transfer of training. Practices and problems concerning the "Design and Specification of Simulation Requirements" were discussed in terms of the functional/physical fidelity issue, the physical and instructional features which might be incorporated into a simulator, and the procedures for selecting

simulator requirements and developing functional specifications. Techniques and research findings relating to the problem of obtaining instructor and student acceptance were reviewed under "User Acceptance of Maintenance Simulators." Finally, the "Cost-Effectiveness of Maintenance Simulators" was discussed in terms of the conditions which must prevail if the potential of maintenance simulators is to be realized.

Conclusions

The reviewers noted that current issues and problems related to maintenance simulators are similar to those of 20 years ago, and that many questions about the use of and effectiveness of maintenance simulators still remain. This situation exists even though simulation technology has made considerable strides in recent years, due in large part to advances in computer technology. To promote further the use of maintenance simulators the authors felt that research and developmental studies in the following areas were required:

a. Large scale field studies to demonstrate whether or not training based on maintenance simulators actually does transfer to the field.

b. Development of exemplary maintenance programs for classes of major equipments. These programs would combine the best features of different training approaches--new technical publications, CAI, maintenance simulators--and would attempt to provide the user community with the experience and data needed to commit themselves to an investment in the new methods.

c. Development of exemplary maintenance simulators for major classes of equipment. This effort would be designed to provide the data and experience needed to justify making a decision early in the weapons system acquisition cycle to use maintenance simulators instead of actual equipment trainers.

d. Continued investigation of procedures to identify training requirements which can be supported by simulators. This effort should concentrate on ways to identify these requirements during the new weapons system acquisition cycle.

e. Continued investigation of various procedures which can be used to develop the functional specifications for maintenance simulators, to include both the tasks which should be simulated and the instructional features which should be incorporated into the trainer.

f. Continued exploration of techniques for obtaining user acceptance, especially the acceptance of instructors and the key administrative personnel who must make the decision to purchase simulators of varying degrees of fidelity as opposed to actual equipment.

g. Comparative evaluation of the major types of simulators--flat-panel, three-dimensional, and computer-based--to determine what if any advantage one has over the others.

h. Development of improved regulations for specifying the points in the new weapons acquisition cycle at which decisions about simulators should be made, to include who the decision-makers and the resource groups should be, and what improved guidance should be provided to these persons.

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SIMULATORS FOR MAINTENANCE TRAINING: SOME ISSUES, PROBLEMS AND AREAS FOR FUTURE RESEARCH

INTRODUCTION

Review Objectives

Since World War II the military services, and especially the Air Force, have sponsored considerable research on the development and application of simulators for maintenance training. In recent years important new developments have occurred in this area. This report will review past and present applications of simulation to maintenance training and the major issues involved with this application. The report also will suggest areas for future research.

Countless research studies, field tests and application reports have demonstrated that for a variety of training situations simulators are more cost effective than Actual Equipment Trainers (AET). These findings are fully accepted with respect to pilot training (49); it is now unthinkable to develop a new aircraft without also developing flight simulators for pilot training. In fact, many airlines believe that in the 1980s it will be possible to conduct total pilot training in the flight simulator (30). This attitude towards the use of simulators does not yet apply to the training of maintenance personnel. Despite evidence to the contrary, there still is a reluctance to employ maintenance simulators; a tradition of usage has still to be established. Some of the reasons for this will be examined in this report.

Training technologists believe that maintenance training simulators should be employed because in many instances they are less costly and more effective than Actual Equipment Trainers or the use of operational equipment for training. Research and application studies also have shown that low-cost training equipments and training aids can be cost-effective substitutes for actual equipment trainers or expensive simulators. A simulator is another piece of equipment, and one should not be surprised by the findings that it too can be replaced, on occasion, by less expensive training devices. Selected research evidence in support of this "replacement" will be cited.

Review Limitations

While preparing this report, the authors did not attempt to exhaustively search through all possible sources of literature on maintenance training and maintenance simulators. Rather, they concentrated on reviewing the recent literature, and depended on secondary sources whenever possible. Extensive use was made of the excellent annotated bibliography prepared by Valverde (68). That document summarizes much of the research literature on maintenance training up through 1966.

Two other heavily used sources were the Kinkade and Wheaton chapter on Training Device Design (33) and G. G. Miller's report (43), titled "Some Considerations in the Design and Utilization of Simulators for Technical Training." Miller, Kinkade and Wheaton, and others have summarized the research evidence related to maintenance simulators, and this evidence strongly supports the contention that simulators for maintenance training should be used much more extensively. Therefore, instead of reciting much of the research evidence, this report reviews issues, problems, and research requirements related to the application of and acceptance of the research evidence.

Definitions

Throughout this report references will be made to training devices, training aids, simulators, and so on. Definitions for these terms have been reviewed by Kinkade and Wheaton (33). Although somewhat loosely formulated, the classification of training devices as shown in Figure 1 does have considerable practical value. The term "training device" is used to encompass all training devices and aids--"any arrangement of equipment components, apparatus, or materials which provide conditions that help trainees learn a task." In turn, training devices are divided into two classes, training aids, and training equipment. Training aids are defined as "devices used by an instructor to help him present subject matter." Training equipment is defined as "devices which provide for some form of an active practice by the trainee."

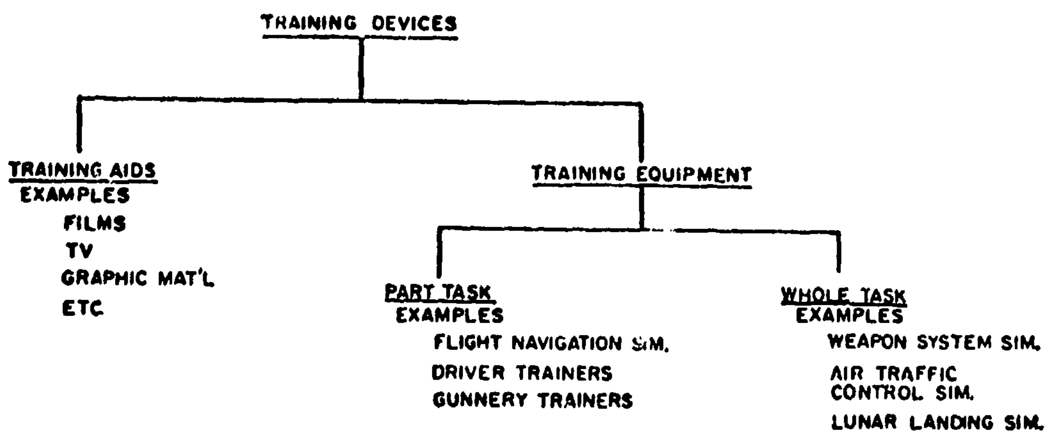

Figure 1. Classes of Training Devices (Adapted from Kinkade and Wheaton, 1972)

It is convenient to subdivide training equipment into "part-task" and "whole-task" trainers. A part-task trainer gives the student an opportunity to practice selected portions of a total job sequence; the training situation does not require total work-context inputs or total work-context outputs, just those related to a particular task. Part-task trainers are not intended to carry a student all the way to operational proficiency on the task being trained (46). In contrast, a "whole-task" trainer by definition must simulate all or at least a major segment of work-context inputs and must allow for the making of all responses appropriate to these stimulus inputs. Whole-task or total task training can occur only in the operational situation or in a complete simulator.

Training equipments sometimes are referred to as "trainers" and at other times as "simulators." Often times there is no clear distinction between a trainer and a simulator. In general, the term "trainer" is applied to training devices which either make no attempt to realistically represent the physical appearance of equipment, or, which employ all or portions of the equipment itself for training, e.g., actual equipment trainers. On the other hand, a "simulator" attempts to faithfully represent the stimulus and response options provided by all or portions of a piece of equipment; it attempts to provide functional fidelity. The simulator also may attempt to accurately represent the appearance and "feel" of equipment. This type of fidelity is called either equipment or physical fidelity. Obviously, simulators can have varying degrees of fidelity; they can have high physical fidelity and somewhat lower functional fidelity. More often they have high functional fidelity and somewhat lower physical or equipment fidelity. What difference this makes with respect to training will be a topic for later discussion. The reviewers noted a lack of published literature concerning the cost-effectiveness of recently designed maintenance training simulators, and they expressed a hope that those involved with maintenance simulator studies will publish their findings so that the presumed advantages of simulators can be adequately documented.

SIMULATION TECHNOLOGY AS APPLIED TO TECHNICAL TRAINING

Why Simulate?

Maintenance personnel are trained to work on real equipment. Why then not use real equipment for maintenance training? In the first instance, real equipment is designed to serve an operational need not related to training. Therefore, real equipment does not contain the desired features of a training device. Secondly, real equipment is almost always more costly than a representative training device. Finally, operational requirements take precedence over training requirements. Therefore, training centers often have difficulty getting equipment and spare parts because these are sent to the field.

Miller (42) has reviewed the reasons why the Air Force is interested in simulators. In addition to reducing costs, the Air Force feels that simulators are more reliable than actual equipment trainers, allow for conduct of training in a safer environment, provide a much greater capability for malfunction insertion, and are much less noisy. These also are the reasons why the Air Force and the airlines are placing increased emphasis on the use of flight simulators (28).

Six advantages to simulators have been offered by Baker and Warnick (5). They point out that simulators:

a. provide augmented feedback (extra knowledge of results information);

b. increase the number of and frequency of crises, conflicts, breakdowns and emergencies which can be covered during training;

c. reduce the operation time for certain events, thus increasing the amount of practice time;

d. allow for concentrated practice on part-tasks, and for varying the sequence of part-task training;

e. provide guidance and stimulus support during early or initial stages of learning; and

f. allow the instructor to vary the difficulty level of the task to be learned, and allow for the presentation of easy to difficult problems.

A Historical Overview of Maintenance Simulators

Most maintenance simulators, especially those for electronic/electrical systems and subsystems, have been designed to teach the conceptual aspects of organizational or between-stage troubleshooting, and the interpretation of faulty equipment operation, displays and test point readings. To a lesser extent they have been used to teach within-stage or intermediate level troubleshooting. They have been designed this way because of the general belief that maintenance training should entail "instruction in decision processes to a greater degree than operations training. This instruction must include formulation of decision rules, identification of decision alternatives, and actual decision making (37)."

Maintenance simulators also can be used to teach the names and locations of front panel displays and controls, the purpose of front panel controls, and the rudiments of how to energize and operate the equipment. Occasionally, simulators are employed to teach preventive maintenance, the performance of system self-checks, and the interpretation of normal vs. malfunction operations. In addition to simulators, activated mock-ups may be used to teach adjustments, alignments, and preventive maintenance routines.

Valverde (68) has reviewed the long list of trainers and simulators supported by the Air Force. Most of these early trainers were two-dimensional; a subsystem, the electrical system of a weapons system for example, was represented by graphical or plug-in "black boxes", each representing a stage of the equipment. Test points were provided on a block diagram display and meters might be used to show symptom information. Front panel controls often were represented by pictures or drawings, or by switches. Following the presentation of symptom information, a student was required to select the logical way to locate the malfunctioning black box. In early trainers, test point information often was displayed by go/no-go lights. In spite of their crudeness, these devices were effective in that they could be used to teach students the logical or conceptual aspects of troubleshooting. This skill is taught with considerable difficulty using real equipment, because of the danger in and the diffic[illegible]n inserting malfunctioning parts into the equipment.

Along with two-dimensional troub[illegible]g logic trainers, the Air Force also sponsored the development of a few three-dimensional trainers, the RMP-100A Radar Maintenance Trainer being one such example. In the early 1960s, Shriver, Fink, and Trexler (61) developed a trainer which converted a two-dimensional troubleshooting logic trainer into a full-scale, three-dimensional simulation of one cabinet of the NIKE HIPAR system. Test points for troubleshooting were located on simulated plywood chassis contained within the cabinet. The good and bad waveform outputs from these test points were displayed in two ways on successive iterations of trainer. First they appeared full scale on a single simulated oscilloscope. In the second model they appeared 1/5 scale at random locations on an egg crate-like display matrix. From the students' standpoint it made no difference how the waveforms were displayed even though the second display method was very low in physical fidelity (60).

Most of the foregoing trainers were manually operated in that each test point was associated with a switch on an instructor console. To set up for a particular malfunction the instructor had to throw a combination of switches.

In the 1950s and 1960s a few troubleshooting trainers were developed for non-electronic/non-electrical systems. The tank turret mock-up (17) was one such example. Also, during that period, many operational mock-ups were constructed to demonstrate system operation and to provide operator training. A few elaborate computer-driven animated display boards also were developed. These devices were sometimes used to show the effects of a malfunction on system operation, but the student could not interact with them for the purpose of obtaining "hands-on" experience at fault isolation.

As digital computers became more powerful, and especially smaller in size, the feasibility of employing them to control small troubleshooting logic trainers became evident. Actually, this development began in the late 1950s, and began to catch on in the mid-1960s with the development of the SMART trainer. It was the forerunner to the EC-II/EC-3 trainers currently manufactured by Educational Computer Corporation. The EC-II/EC-3 trainers consist of a large display panel containing diagrams and pictures of all the major components of a particular equipment subsystem, and all the "front panel" dials, switches, and meters which are important for performing an operational checkout of the subsystem. The panel contains numerous test points located on or near subsystem components. A small computer controls the signal supplied to each test point, dial, etc., in such a way that the normal operating system can be simulated, or, one of many malfunctions can be simulated. An instructor console is used to insert malfunctions into the trainer; a viewing console is provided to display for the trainee what he would see on his meter when testing at a particular point or when viewing certain components.

The EC-II/EC-3 type trainers are not used to teach or to provide practice on perceptual-motor skills. However, in addition to conceptual troubleshooting skills, they can be used to teach names and parts' locations, and the relation between operational controls and equipment operation (65).

This type of trainer is considered to be "general purpose" because its mainframe can be used to simulate different systems. A simulation package for any particular system consists of a display panel, a visual disk and a computer program on tape. Given that two or more simulation packages are available, it takes a very short period of time to substitute one package for another.

For a variety of reasons the EC-II/EC-3 trainers are considered to be an advance over earlier general purpose or "generalized trainers." Because of advances in miniaturization it now is easier to develop a display panel which represents more realistically a major equipment system. Once the computer program for a system has been prepared, setting up the trainer to simulate a different malfunction can be done by keying in a number which represents the new malfunction. The availability of compact random access visual systems allows for the rapid display of a wide variety of test signals, pictures of equipment components, and so on at a single display point. As mentioned above, once two or more simulation packages have been developed, it is easy to substitute one for the other.

The extent to which the EC-II/EC-3 trainer, and similar flat-panel trainers, should be called "general purpose" is a matter of definition. Perhaps it would be more accurate to describe them as having a general purpose mainframe which employs "systems specific" simulation packages. The flexibility and modifiability of these packages has not been described in the literature. One would like to know how easy it is to change each segment of the simulation package--computer program, visual disk, and display panel. Weapons systems are subject to many changes during their lifetime and simulations of them also should be capable of ready modification.

At this juncture there remain many unanswered questions about computer-driven flat-panel simulators. They may have a greater potential than their forerunners, but, in terms of their malfunction simulation capacity, their capability to be reconfigured to reflect system modifications, and their overall effectiveness, they may not be much of an improvement over their forerunners. In fact, their forerunners may have had certain advantages. For example, the forerunners may have been more reliable; at least some of them were easier to reprogram or reconfigure, and some of them could simulate a very wide variety of malfunctions, at least at the between-stage level. Moreover, earlier versions of flat-panel simulators were much more "general purpose," but this feature was obtained at the price of physical fidelity. It is ironic, but it appears that recent efforts to develop improved troubleshooting trainers have in fact led away from the general-purpose-like trainers of the past, e.g., FORECAST trainer (21) and Generalized Electronic Troubleshooting Trainer (70), to trainers which are quite systems specific or at least use very specific simulation packages.

The EC-II/EC-3 is a two-dimensional trainer, and many persons like the greater physical fidelity provided by three-dimensional trainers. Both the Educational Computer Corporation and Honeywell have developed three-dimensional trainers which are programmed by mini-computers. These devices are full-scale mock-ups of real equipment, but portions of the equipment which are not essential for the troubleshooting problems selected may be simulated by etched front-panel graphics, non-operational hardware, inexpensive plastic forms, and so on. If the equipment being represented contains many similar panels, then only a few panels need be functionally operational while the remainder can be simulated in some inexpensive fashion (44).

Many of the early troubleshooting trainers, like the Optimal Sequence Trainer and the Malfunction Information Trainer (68), were essentially devices for presenting paper-and-pencil troubleshooting exercises. In fact, most, if not all, of the problems simulated on an EC-II trainer could be presented using these simpler trainers, but with less physical fidelity. However, in comparison with their relatively simple predecessors, it is much easier for instructors to set up EC-II-like trainers to represent different malfunctions--the instructor keys into the trainer a number representing a particular malfunction and then the trainer's computer software reconfigures signal generation and display devices to represent that malfunction.

Graphical material can be employed to teach certain aspects of the troubleshooting process. It follows from this that certain of the conceptual aspects of troubleshooting can be simulated using computer-generated graphical displays coupled with a random access slide projector. One example of this type of maintenance simulator is the computer-based training system (55) developed by General Electric. The PLATO system, developed by the University of Illinois in conjunction with Control Data Corporation, also has the capability to use computer-generated graphics to simulate equipment and to present maintenance problems.

Technically speaking, we have arrived at a point where the conceptual aspects of maintenance, especially troubleshooting, can be simulated on paper or by three different hardware systems--flat-panel system simulators, computer-graphics' terminals, or three-dimensional equipment simulators (49). The cost of the products produced by these four approaches varies inversely with the physical fidelity of the simulation produced by each approach. But, aside from certain equipment characteristics or maintenance tasks which are still difficult to simulate, it does appear that the state-of-the-art in simulation technology has advanced to where maintenance simulators can be used to produce a performance capability in course graduates which is not achievable with traditional actual equipment trainers. Unfortunately, the need for or usefulness of this increased performance capability is not perceived by many instructors nor by major segments of the training system or training program acquisition system. This seems to be because the training system seldom has been expected to produce personnel with a practical troubleshooting capability at graduation from a basic (3 level) maintenance course. In our judgement major changes in capability seldom come about through a perceived need. Rather, an improved technology creates a need for more of the technology. As the cost-effectiveness of simulators becomes more widely known, there probably will be increased agitation for producing course graduates who have an increased capability to troubleshoot equipment.

APPLICATION OF SIMULATION TECHNOLOGY TO TECHNICAL TRAINING: RESEARCH FINDINGS

Electronic Troubleshooting Trainers: Pre-1967

In 1968 Valverde (68) published an annotated bibliography which reviewed the important developments and research related to maintenance training from 1950 through 1966. The following section provides a brief summary of the research reported in that source.

According to Valverde:

> Most maintenance trainers were developed for use in the electronic career field because of the need to provide practice in troubleshooting. Due to the great expense of operational equipment and time required to provide practice in troubleshooting, personnel of the Maintenance Laboratory, Lowry Air Force Base, undertook the development of prototype troubleshooting trainers more than a decade ago. The rationale for the use of these trainers, in addition to economy and savings in time, was the fact that the trainers provided trainees more experience in troubleshooting than they could receive under normal training conditions.

Unfortunately, the problems which generated the Air Force's interest in simulators in the early 1950s still persist, and the above quote is equally applicable today.

Most of the electronic troubleshooting trainers developed prior to 1967, and up through 1977 also, concentrated on providing "a realistically complex, relative low cost, reliable substrate on which the tasks associated with electronic maintenance can be performed" (47). Briggs and Duvall (7) demonstrated that the E-4 Fire Control Troubleshooting Trainer was an effective trainers. He noted that performance on the E-4 trainer was faster than on an actual equipment trainer because time-consuming checks were eliminated, and it was easier for the instructor to insert malfunctions. These two characteristics are common to almost all troubleshooting trainers.

In a series of studies using the MAC-1 and MAC-2 trainers (Malfunction and Circuitry Trainer), French (23) demonstrated that students trained on these devices did just as well on a performance test as did students trained on bench mock-ups of real equipment. Other early forms of troubleshooting trainers which have been effectively employed include the Malfunction Information Trainer (14), the Optimal Sequence Trainer (9), and the MTS-1, Maintenance Task Simulator (20).

During the 1950s and early 1960s the Air Force sponsored the development of a general purpose trainer, the GETS or Generalized Electronic Troubleshooting Trainer (70), which was designed to teach a general strategy for troubleshooting electronic equipment. Another trainer, the Checkout and Maintenance Trainer (CAM) (29), was developed as a research vehicle for studying maintenance training.

From 1957 through 1965, Shriver and his colleagues undertook an extensive series of studies concerned with both the development of improved technical documentation and maintenance training devices. The beginning study in this series, one designed to improve training on the M-33 radar system, employed a mock-up of the system that covered about 500 square feet. Using specially developed analysis techniques, the radar system was divided conceptually into troubleshooting blocks such that if the signal into a block was correct but one or more of the block outputs was not, then the fault had to reside in one or more of the parts which comprised the block (60, 62).

The training device developed represented the system at the troubleshooting block level. Each block was simulated by a small metal "black box" named for the troubleshooting block it represented. Each "black box" had a test point which was wired to a large upright instructor panel. The 100-plus black boxes which represented the entire radar system were placed on racks. A simulated oscilloscope was used to display waveform readings at each test point, and a simulated malfunction could be placed within any "black box" by flicking the instructor console switch for that box. If the reading at a test point was supposed to be correct, a glass plate containing an etching of a normal reading lit up within the simulated oscilloscope; otherwise a straight-line "abnormal reading" etching was displayed. Students used this trainer, along with a troubleshooting block diagram of the system, to learn how to troubleshoot conceptually to the small group of parts which comprised each troubleshooting block. Sometimes the troubleshooting sequence began with the student collecting "symptoms" information on an inexpensive front-panel mock-up of the M-33. At other times, an instructor provided the initial symptoms (59).

The original FORECAST trainer was considered to be a general purpose or generalized trainer in that it was fairly easy to modify the trainer to represent another system. To accomplish this, the plates in the simulated oscilloscope and the names of the "black boxes" had to be changed. Of course, before these steps could be accomplished, the system to be simulated had to be analyzed and subdivided into troubleshooting blocks. This step, often the most time-consuming and costly one in the simulator development process, has to occur for any simulator which has been configured to represent a specific system.

A second version of the trainer just described was used to teach maintenance of the NIKE HIPAR system. It too was considered to be a general purpose trainer in that its basic features could be employed to simulate any electronic system once a specially prepared block diagram had been developed for the system (21, 61).

In this trainer the numerous racks of black boxes which typified the original FORECAST trainer were discarded; they were replaced by a block diagram located on the surface of a 2- by 3-foot metal box called a "desk-top" mock-up. Test points, wired to toggle switches located on a control console, came out on each square inch of the top surface of the mock-up. By carefully positioning the blocks of a block diagram it became possible to place the diagram on top of the mock-up such that there was a test point at the input and output of each block. As an added feature, the mock-up unit contained rotary and toggle switches which represented the main operational controls and monitor switches of the system. On this mock-up students could practice the cognitive aspects of troubleshooting--symptom interpretation, the programming of troubleshooting checking sequences, and the interpretation of individual checkpoint information.

A third unit of the above trainer was called a Display or Waveformer Unit. It consisted of a metal matrix of 156 cells each containing a small lamp. Each cell was associated with a particular test point on the mock-up and a particular switch on the control console unit. When a particular test point was touched with a probe, a lamp was lit in the associated cell of the Waveformer Unit. Over the front surface of the Waveformer Unit was placed a photographic negative containing pictures of the normal waveform, voltage or meter readings which should appear at each test point. All incorrect readings were shown as a straight line in one cell of the Waveformer.

In many respects the mock-up just described had less physical fidelity than its predecessor. In particular, the Waveformer had much less physical fidelity than the simulated oscilloscope used in the M-33 study. Despite this, the two trainers seemed to be equally effective, and the low fidelity of the Waveformer had no apparent psychological or behavioral impact on students. From a practical standpoint, the second trainer was as effective as the first even though it was less expensive, smaller and had less physical fidelity.

In a third version of the foregoing trainers the device was designed so that students could insert their own malfunction patterns by pressing keyboard buttons. A manual was produced which gave the initial statements of malfunctions (previously given by the instructor) and the appropriate keyboard button settings. The student then took test point readings to select other test points until they finally had localized the malfunction to a troubleshooting block (63).

In the final version of the FORECAST trainer the entire troubleshooting process was simulated on paper and incorporated into a troubleshooting manual. This manual contained all the scope pictures that previously were displayed on the simulated oscilloscope, all the symptom information that was provided by an instructor or on "initial statements of malfunctions," as well as other information such as location of test points. In addition, troubleshooting exercises in scrambled book format were developed (63).

None of the four versions of FORECAST trainers was compared with another, but all seemed equally effective. All versions taught conceptual troubleshooting skills; all were generalized trainers in that they could be reprogrammed to represent other electronic systems.

Electronic Troubleshooting Trainers: Post-1966

Flat-Panel System Simulators. From the mid-1960s to the present considerable advances have been made in the development of computer-driven 2-dimensional troubleshooting trainers. Earlier versions of these trainers suffered because they could not display all portions of a system relevant to a set of troubleshooting problems, could not show controls graphically, and often displayed test point and symptom information in a binary fashion. Furthermore, until recently even so-called general purpose trainers could not be changed rapidly from one subsystem to another, nor could they easily simulate non-electronic subsystems. Today flat-panel trainers such as the EC-II/EC-3 trainers can easily be changed from one system to another and can represent both electronic and non-electronic subsystems provided that programs are available for doing so. It is worth remembering, however, that this flexibility is obtained by substituting one complete simulation package for another. These packages are costly to prepare, and the ease with which the panels and programs which comprise the package can themselves be modified remains to be determined.

Numerous researchers have investigated the effectiveness of the EC-II. McGuirk, et al (39) simulated the AN/APQ-126 radar and compared its effectiveness for teaching troubleshooting with the effectiveness of Actual Equipment Trainers (AET). They found that the simulator was as effective as the AET, was more reliable, and was much less costly.

Spangenberg (65) demonstrated that the AN/APQ-126 simulator could be used effectively to teach national guardsmen the purpose of controls, the interpretation of normal versus malfunction operation, the performance of system self-checks, and malfunction isolation procedures.

Malone, et al (38) reviewed the effectiveness, usability and cost of a variety of trainers, and concluded that the EC-II should receive top ranking as a troubleshooting skills trainer.

A number of maintenance courses throughout the armed services employ maintenance simulators, the EC-II/EC-3 in particular. Apparently they are effective but there is little published research evidence to confirm this supposition.

Computer-Graphics Terminals. Computer-based instruction (CBI) is used effectively in a number of service maintenance courses. In addition to its use for teaching conceptual material, increasing interest has been shown in the use of CBI for teaching maintenance skills, the use of test equipment (11) being one such example. Stern (66) used computer-graphics terminals to teach the use of the oscilloscope. He found that training using CBI techniques was as effective as using actual oscilloscopes; neither training was very effective in the absolute sense, however. Lahey (35) demonstrated that CBI can be used to teach the use of the multimeter. However, the end-of-training test was verbal rather than psychomotor.

In a study for the Navy, Radsken and Grosson (54) concluded that CBI can be effective in the submarine systems training environment when applied to interactive operator and basic maintenance training tasks.

At the Behavioral Technology Laboratories at the University of Southern California, the use of generative computer-assisted instruction (CAI) for task training is under investigation (57). Two stand-alone CAI systems are being developed for the U. S. Navy; one system to teach maintenance of surface ship electronic equipment, and the other to teach maintenance of the F-14 AWG-9 Weapons Control System. For both projects computer graphics terminals will simulate equipment front-panel configurations. Using a light pen the student will be able to interact with front-panel controls and displays. This type of CAI system can be placed on board ship and eventually should have the capability to serve both as a training device and a job aid.

In a somewhat similar project the Air Force Human Resources Laboratory has developed a "Computer-Assisted Performance Carrel." This device "which consists of a computer terminal (PLATO IV/Magnavox), a digital control processor, and analog interface equipment, incorporates many of the standard features of the EC-II plus interactive instructional programming. This interactive approach provides a self-paced capability thereby dramatically reducing the monitoring functions instructors normally perform in performance courses (45)." The Performance Carrel is designed to teach "hands-on" tasks; its effectiveness for this purpose is the subject of current studies.

Three-Dimensional Trainers. Within recent years a new class of three-dimensional trainers has been developed by a number of corporations. Essentially these are EC-II-like simulators which have been housed in a three-dimensional mock-up of the equipment being simulated. This provides an added dimension of physical realism which probably will increase user acceptance.

The Educational Computer Corporation has developed a 3-D simulator for the Navy's A-7E Heads-Up Display Unit and Test Bench. Not all of the test bench is simulated, but its external appearance is represented very realistically. Honeywell is in the process of developing a three-dimensional simulator of the Air Force's 6883 Converter/Flight Controls Test Station for the F-111D aircraft. To date no research evidence has been reported on the effectiveness of the above two simulators. Although more costly than two-dimensional simulators such as the EC-3, there appears to be no reason why they should not be equally as effective. Whether or not they will be as cost-effective as the EC-II/EC-3 is a question for further research to decide.

Until recently simulators have been used to teach maintenance at the organizational level but not at the intermediate level. Now with the development of three-dimensional simulators for test bench equipment, sophisticated trainers are available for teaching intermediate level maintenance. It is now possible to develop such trainers because of advances in the design of electronic equipment. Recently designed electronic systems tend to be interlaced with sensors connected to front panel displays and built-in test equipment (BITE). The sensors monitor the function of removable modules, drawers, card racks, etc. called "line replaceable units" (LRU). At the organizational level of maintenance the BITE and the front panel displays are used to isolate a malfunction to an LRU. Essentially this involves the performance of a series of operator-like actions. Through the use of sensors within LRUs, and the use of signal generators controlled by a computer, it has become possible to develop test sets and stations which can isolate a malfunction to a small section of an LRU or even to an individual part. This is maintenance at the intermediate level and it too is accomplished via the performance of operator-like tasks. The implication of these developments is twofold. Firstly, troubleshooting at both the organization and intermediate levels of maintenance has become quite similar in nature--they tend more and more to involve operator-like tasks. Secondly, it is easier to simulate operator tasks than other maintenance tasks such as the removal and replacement of components. Moreover, it is quite acceptable to use simulators to teach equipment operation. Therefore, it is becoming more and more acceptable, as well as technically easier, to use simulators to teach fault isolation at the intermediate maintenance level.

A recent report by Parker (51) "found that the commonality is increasing among avionics systems that are members of the same family and among equipments that are members of different families." He suggested that there will be a decline in skill level requirements for avionics technicians because of the increased commonality between equipments and because of the increased modularization, integration and potting of circuits. While investigating the use of CAI maintenance training systems for the Navy, Rigney and Towne (57) concluded that "troubleshooting at the basic circuit level seemed likely, as a consequence of medium and large scale integration of circuits, to become less important." As a consequence they concluded also that troubleshooting on the basis of front panel symptoms will become more important.

Troubleshooting Trainers: Non-Electronic Systems

As mentioned earlier, most troubleshooting trainers have been designed to simulate electronic subsystems. Numerous researchers, however, have demonstrated that mock-ups of front panel displays and controls of radar systems (10, 61), or the instrument panel and driver's control of a tank (17), can be used effectively to teach nomenclature and location, and energizing and shut-down procedures. These trainers, however, could not be used to teach troubleshooting procedures other than the performance of operational checks and symptom gathering. More recently, the EC-II has been used to successfully teach troubleshooting of hydraulic systems and the 53C51 Mohawk propeller system (18). As part of a project for the Navy, Burtek Corporation has developed a simulator for the Hagan Automatic Boiler Control System.

A simulator somewhat similar to the EC-II, the Omnidata simulator, is used by the Navy to teach start-up and running procedures for internal combustion engines. Omnidata simulators are fixed purpose simulators; they lack the programmable features of the EC-II. They can, however, be configured to simulate a variety of equipments and systems to include: two-cycle diesel engines; CTC-85; Ingersol Rand Air Compressor; Automotive Lighting, Indicating and Warning Systems; Aero-47-A Weapons Loader; GTC-100; and the NR-10 Air Conditioning System. The device can be used to demonstrate principles of operation and troubleshooting procedures. A few Omnidata models can be purchased as off-the-shelf items, but most models must be custom designed.

Effectiveness of Low-Cost, Low-Fidelity Aids and Mock-Ups

A number of studies have demonstrated that "very simple, low-cost trainers, or mock-ups having only gross physical fidelity--dummy instrument panels, photos, or line drawings--can be used effectively to train students to perform a variety of procedural tasks (68)." In 1954 Denenberg (17) showed that a very inexpensive mock-up of the instrument panel and driver's controls of the M47 tank was as effective as an expensive mock-up and the real tank for teaching starting and stopping procedures, and, the names, locations, and functions of driver instruments and controls. Cox, et al. (10) were unable to demonstrate a relationship between 12 training devices of varying degrees of reduced functional and physical fidelity and student proficiency or training time on fixed-procedure tasks.

Torkelson (67) compared the effectiveness of cutaways, mock-ups, and transparencies for providing instruction on the Mark 13 torpedo. He found no differences in training effectiveness of the three kinds of media but did find slightly better retention when three-dimensional trainers were employed. He recommended that mock-ups and cutaways be justified on grounds other than training effectiveness, such as requirement for outdoor use, student operation, need to show moving parts, and so on.

As already reviewed in this report, Shriver, Fink, and Trexler found that the conceptual skills of torubleshooting could be taught equally well using scrambled book exercises or a variety of low-cost, low fidelity trainers. In addition, they found that inexpensive mock-ups could be used to teach radar operating procedures (60).

DETERMINATION OF SIMULATION REQUIREMENTS

Current Procedures and Problem Areas

The general procedures for determining simulation requirements are quite easily stated. One first conducts a job and task analysis to identify training requirements. These requirements then are examined to identify those which should be covered during training. This sub-set of requirements is then examined in terms of the training media and methods needed to support training on each requirement. Eventually a smaller sub-set of training requirements is identified which probably can can best be taught through the use of a simulator. Later on, during a trade-off analysis, one identifies those requirements which are not feasible, or which are too costly, to simulate. A decision is made to handle these requirements by some other means, probably OJT, or not to handle them at all. Specifications then are prepared for a simulator. By turning to appropriate reference sources, one can find rather elaborate descriptions for how to perform each of the foregoing steps. But, after digesting all that information, most practitioners still would agree with Bryan and Regan (8) that there are few if any prescriptions for how to identify simulation requirements and to design major training devices.

Most training equipment designers can agree with Modrick (48) that one should not develop specifications for training content and training devices until training objectives have been identified. Almost any document describing the Instructional System Development process will emphasize this point. All efforts to design training programs and devices should begin with a thorough job and task analysis. However, despite continual advances in the state-of-the-art, techniques for accomplishing a job and task analysis are still more of an art than a science. To further compound the problem, it is becoming increasingly obvious that "job-descriptive information alone cannot provide sound basis for translating job requirements into personnel and training requirements (8)."

In recent reports, both Cream, et al. (13) and Eggemeier (19) have discussed the need to develop more efficient means and methods for identifying training device requirements. Cream reviewed the limitations of current methods and found them: not sufficient for the actual design of a training device; difficult to apply by unskilled persons; and apt to emphasize minimally acceptable performance. Eggemeier reported that short term methods for identifying training device requirements result in the adequate specification of training requirements but do not provide satisfactory information upon which to base decisions about what features the training device should possess. Bryan and Regan feel that much more basic research is required to "expand and validate the behavioral information..." provided by job and task analysis. They cite also the need for more information on the relationship between "various kinds of tasks and various kinds of learning."

Current procedures for determining simulation requirements can, with difficulty and often unknown effectiveness, be applied to existing weapons systems. They are much more difficult to apply to new systems still under development. Both Modrick (48) and Cream (12) have expressed the need for methods which will identify training requirements and training device requirements early in the development cycle for a new system. Their review of this problem reveals that we do not have methodology for converting engineering data into training and training device requirements. This problem area has been studied periodically since at least the mid-1950s (58, 59) but few solutions have been forthcoming, at least with respect to maintenance training.

In one of the FORECAST studies (59) Shriver took the position that changes made during the last year before fielding a new electronic weapons system are trivial with respect to the level of detail needed to develop a maintenance simulator which can teach troubleshooting at both the organizational and intermediate levels of maintenance. They therefore designed and built three types of maintenance simulators based on a detailed task analysis of the NIKE HIPAR system as it existed one year before it was scheduled to become operational. The analysis and development process was accomplished within one year, beating the real equipment to the field by several months. The simulators were the only equipment the Ordnance Guided Missile School had to train on for six months, and they served as training equipment for several years after the real equipment became available at the training site.

Both Valverde (68) and Reilly (56) have discussed problems associated with identifying training requirements and devices for new systems. When training requirements and training programs are under development concurrently or in advance of systems in the field, it often is necessary to make a purchasing decision before clearly defined alternatives in the form of simulators or other training media have been developed. This may force the purchase of actual equipment for training. It is easier to order additional equipment from the prime contractor than it is to order training equipment from a separate vendor.

Once training requirements have been identified there still is a need to select those tasks which should be simulated. Miller (44) has discussed one method for doing this. It involves deriving a weighted rank order for each task to be covered during training. Ranks are based on the difficulty, frequency and importance of the task. Those tasks receiving the highest composite rank are given proportionate consideration regarding whether or not they should be simulated, and, the level of fidelity at which they should be simulated. This is a practical way of making decisions about fidelity and about which tasks should be candidates for simulation. Of course, once decisions have been made about which training requirements should be supported by a simulator, one still has to make a host of decisions regarding the feasibility and cost of designing a simulator to accomplish the desired effect. These problems will be discussed in the next section of this report.

Transfer of Training, Learning Stages and Simulation Requirements

What is learned earlier in a course should aid learning during latter stages of the course. When it does, positive transfer of training is said to have occurred. A well-designed training sequence seeks to control the training environment so as to maximize positive transfer (8) from one portion of a course to another, and from the course to the job.

Transfer of training should be viewed with reference to stages of learning. As shown in Table I, a novice repairman enters a training program the general goal of which is to prepare him to the point where he can attain final mastery of his job in the work environment. As the student encounters each new task during his formal training, he progresses through three stages of learning with respect to that task. In this report these learning stages are defined as being very similar to the three stages of learning described by R. B. Miller (47). However, we find it useful to confine Miller's three stages to formal or "schoolhouse" learning, and to recognize that a fourth stage of learning or practice on the job is almost always required.

Numerous authors (33, 43, 47) have suggested that different kinds of tasks and different degrees or stages of learning have different implications for transfer of training. We still do not know enough about these relationships, and it is an area well worth further research. In particular, we need more research on how to determine the transfer validity of trainers before they are accepted (1). In the meanwhile, considerable evidence does exist to support the view that training requirements during earlier stages of learning are different from those of later stages, and therefore require support from devices which have different characteristics. For example, R. B. Miller (47) defined three classes of trainers -- familiarization trainers, constructed-response trainers, and automatized skill trainers. He associated each class with a stage of learning, and pointed out that each class has different characteristics. Kinkade and Wheaton (33) have divided the learning spectrum into five stages and have associated each with particular types of training aids and devices. Collectively the research literature suggests that, as shown in Table II, various types of training devices and media can best be employed to support various stages of learning.

Table I. General Relationship Between Stages of Learning, Training Sites, and Training Objectives

STAGES OF LEARNING	TRAINING SITE	GENERAL TRAINING OBJECTIVES
Novice		
1st Stage	School	Acquire Enabling Knowledges & Skills -- learn names & locations -- become familiar with job requirements -- become familiar with job content
2nd Stage	School	Acquire Uncoordinated Skills and Applicable Knowledges -- learn basic procedures -- learn part-task performance -- learn theory
3rd Stage	School	Acquire Coordinated Skills and Ability to Apply Knowledges -- practice procedures -- practice part-task performance -- practice conceptual skills, such as malfunction location -- practice application of theory
Apprentice		
4th Stage	Job	Acquire Acceptable Job Proficiency -- practice on the job -- participate in on-the-job training
Journeyman		

Training aids, devices and simulators are employed to support the learning process. Their usage also should be viewed in terms of efforts to increase transfer of training. According to this point of view, training aids are used early in the learning process so as to decrease the time and effort required to acquire skills and knowledges later on. Part-task trainers are employed so that trainees need spend less time on job-segment or whole-task trainers. Job-segment or whole-task trainers are used when it is necessary to reduce the amount of time required by course graduates to acquire acceptable on-the-job proficiency. When viewed from this prospective, it becomes apparent that no one class of training aids or devices need carry the entire training load. Furthermore, it becomes obvious that from a cost-effectiveness standpoint the general training strategy should be to obtain full measure from training devices which can support the first and second stages of learning before switching to the more expensive simulators required to support later learning stages. It might be true that more sophisticated, higher-fidelity trainers have the capability of teaching what might be taught by less advanced trainers. However, time thus spent would be taken away from the time during which advanced students could be perfecting skills on the more advanced trainers (47). "A preferred approach (to maintenance training) would be to use the simplest material which meets the training objectives and to select more complex materials only when training objectives cannot be met efficiently by the less costly material" (27).

One often encounters the belief that to insure transfer of training the instructional settings should be similar to the job situation. In fact, this is implied in AFM 50-2 (2). Many persons, especially instructors, believe that if you want to maximize transfer of training to the job, one of the better ways to accomplish this is to design training equipment that is "as realistic" as possible (56). It is difficult to identify the factual basis, if any, for this belief. In the first place, actual equipment trainers are more apt to be used as classroom demonstrators than as trainers for the development of performance skills. Other media such as low-cost mock-ups and films would serve equally well as demonstrators, although their motivational value might be less. The primary objective of many maintenance courses is to train people to perform at an apprentice level. At this level tasks can be performed accurately but in a rather slow, uncoordinated, "unskillful" manner. Many persons, instructors particularly, believe that real equipment is required to teach skills at this level. That belief is erroneous. Low-cost mock-ups and simulators may often be more appropriate.

The official intent of most maintenance courses is to prepare students so that, with additional on-the-job practice and training, they can master their job. For these courses the course performance standards are considerably lower than those required on the job. Moreover, some maintenance courses concentrate on teaching theory and do not even attempt to teach performance skills. Still other courses, especially

Table II. General Relationship Between Stages of Learning, Training Objectives and Types of Training Devices

STAGES OF LEARNING	GENERAL TRAINING OBJECTIVES	TYPES OF TRAINING DEVICES
1st Stage ↓	Acquire enabling skills and knowledges	Demonstrators -- wall charts, films, TV, mock-ups, etc. Nomenclature & Parts Location Trainers
2nd Stage ↓	Acquire uncoordinated skills and unapplied knowledges	Part-task Trainers Procedures Trainers
3rd Stage ↓	Acquire coordinated skills and ability to apply knowledges	Troubleshooting Logic Trainers Job Segment Trainers Skills Trainers
4th Stage	Acquire job proficiency in job setting	Operational Equipment Actual Equipment Trainers

those based on some version of the task oriented training concept, have been so reduced in length that they can only provide students with a brief introduction to the equipment(s) they will maintain in the field. With reference to Table I, such courses cover maintenance skills and knowledges at only the first or second stage of learning. Courses taught at these levels have little if any valid need for actual equipment trainers or even for simulators. Certainly they do not need simulators which can be used to teach the skills of troubleshooting.

Before alternatives to the foregoing approaches to maintenance training are developed, it would seem judicious to reexamine course standards. Should it be the goal of a 3-level maintenance course to prepare students so that, with minimal additional Field Training Detachment (FTD) training and on-the-job training (OJT), they can master their job? If the answer to this question is "yes," then the standards for 3-level courses should be raised. This in turn would make it easier to justify the use in these courses of simulators and even actual equipment trainers.

Assuming that the objective of a resident maintenance course is to provide graduates who have reasonable skills, it then becomes appropriate to develop a media mix of training aids, part-task trainers and simulators which will prepare students so that they can rapidly refine their skills when they have access to real equipment. Whether this access should be provided during resident training, FTD training or OJT should be decided in terms of the difficulty, expense and consequence of training recent course graduates in the field via the use of operational equipment or dedicated actual equipment trainers. For some maintenance specialties it might be less expensive to provide both simulators and actual equipment trainers for resident training so as to reduce the requirement for field training on operational equipment. This approach would take maximum advantage of transfer of training principles and the advantages associated with employment of simulators for training. This approach is based also on a realistic view of how recent maintenance course graduates are used in the field--they are used as aides to senior repairmen until they have demonstrated an ability to work, under general supervision, on specific types of equipment.

DESIGN AND SPECIFICATION OF SIMULATION REQUIREMENTS

Current Problem Areas

Many authors share with Spangenberg (65) the view that "no predictive body of knowledge is available which will insure the adequate design of a simulator for effective training." Both Eggemeier (19) and Cream (12) cite the need for a systematic methodology for matching training requirements with training device features, and it is the opinion of Bryan and Regan (8) that "at the present time most major training device design situations and problems must be treated individually since there are few rules for designers."

Many decisions must be made when designing and writing specifications for a simulator. The physical and functional fidelity level at which various equipment features will be simulated must be decided. Decisions must be made about certain physical features of the simulator; how rugged it will be, for example. Decisions must be made about the instructional features to be incorporated into the simulator, and who will have the final say with respect to these features. Before final decisions are made trade-off analyses must be made to determine if the decisions are made, trade-off analyses must be made to determine if the tions. These and other issues must be resolved on the basis of general guidelines only since no specific rules exist. Especially troublesome to make are decisions about fidelity.

The Fidelity Issue

Much of the acquisition and support costs of training devices can be related to the fidelity, especially the physical fidelity, of the device--high fidelity training devices usually cost more than low fidelity devices. For this reason the Air Force is very concerned with identifying those training situations and conditions where low fidelity devices can be effectively employed.

Three types of fidelity have been identified as being relevant to training devices. They are: physical or equipment fidelity; functional or environmental fidelity; and psychological fidelity. Physical or equipment fidelity refers to the extent to which training equipments duplicate the appearance and feel of their real equipment counterparts (56). Functional or environmental fidelity refers to the extent to which training equipments duplicate stimuli which are present in the operational environment and provide an opportunity for responding realistically to these stimuli. Psychological fidelity refers to the extent to which trainees perceive the training equipment "as being a duplicate of the operational equipment and the task situation." There is widespread agreement that to be effective a training device should possess a high degree of functional fidelity. There is considerable disagreement over the amount of physical or equipment fidelity a training device should possess.

Numerous studies have demonstrated that training devices of low or medium physical fidelity can be effective. Such devices had been especially effective for teaching procedures (41, 67, 69). In many of these studies the training device simulated front panel controls and displays, and allowed for students to practice making responses to these controls. A not unusual finding has been that inexpensive mock-ups were superior to expensive mock-ups and real equipment for teaching equipment start-up or energizing procedures (1, 3, 10). In view of these findings it would seem that "the answer to maintenance training lies not in how much but how little simulation to use. This is not to say that fewer simulators should be used, merely that low-cost, low-fidelity simulators should be employed where they can be made effective." (27)

The Air Force has sponsored the development of a number of trainers designed primarily to teach troubleshooting logic. The early versions of these devices usually included a two-dimensional display which provided symptoms and test point information in binary terms. Despite their obvious low physical fidelity, they were found to be effective for teaching fault location procedures (68).

A more sophisticated version of this type of trainer, the EC-II/EC-3, has been effectively employed to teach nomenclature, operating procedures, and malfunction location at the organizational maintenance level (39, 64, 65, 71).

There now seems to be no question but that training devices which possess a reasonable level of functional validity but which have a low physical fidelity can be very effective. Despite this evidence, most maintenance training devices still possess an overabundance of physical realism, often to the detriment of their effectiveness. In fact, in most maintenance courses today actual equipment trainers are extensively used. Generally they are used as classroom demonstrators not as skill developers. Moreover, they are not very effective for developing skills, at least not at the first and second stages of learning.

During the first stage of learning both physical and functional fidelity can be rather low. However, it appears that as students progress through the second and third stages of learning, the functional fidelity of supporting training devices should increase more rapidly than the physical fidelity of those devices (33). It appears also that a point will be reached beyond which increases in either functional or physical fidelity will not increase training effectiveness.

Miller (47) has postulated that as the fidelity of a training device increases, the amount of transfer of training to operational equipment also will increase, but at some point will level off despite increases in the fidelity of the training environment. The relationship postulated by Miller (Figure 2) further suggests that at some point the additional amount of transfer of training obtained from additional training device fidelity becomes much less cost-effective.

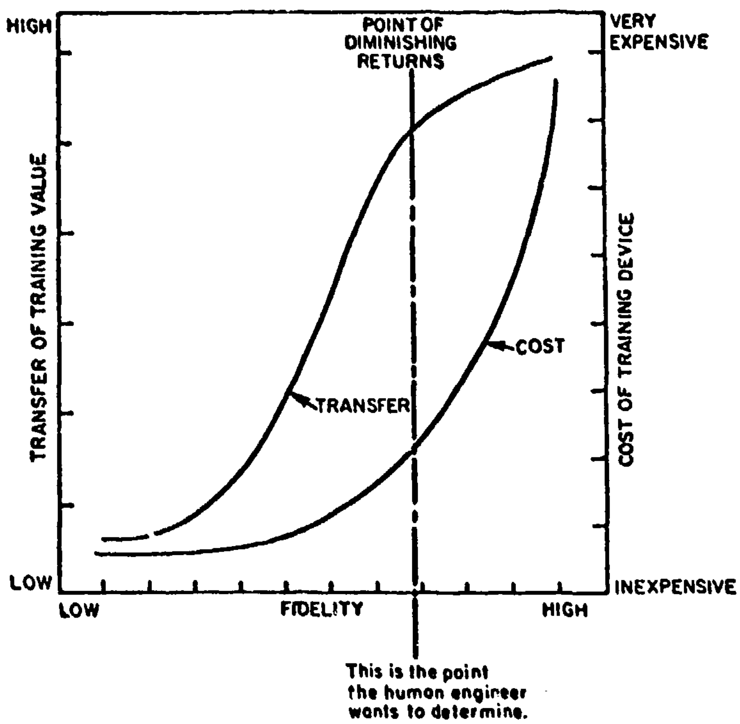

Figure 2 Interrelationship Between Cost, Fidelity of Simulation, and Training Effectiveness (Modified from Miller, 1954).

Eventually, students must acquire the ability to perform efficiently on operational equipment. It might be argued therefore that, at some time during their formal resident training, students should be provided with the opportunity to practice on either actual equipment trainers or on simulators which possess a very high degree of physical and functional fidelity. This argument is valid to the extent that resident training must prepare students to perform skillfully in the job setting without benefit of additional field training. This seldom is a requirement of resident courses. Therefore, resident maintenance courses seldom have high performance skill objectives. Rather, they tend to be theory and knowledge oriented, assuming that skills will be acquired in the field. Because of this, during resident training it often is sufficient to demonstrate equipment operation and maintenance actions as opposed to teaching students how to operate equipment and perform maintenance tasks.

There may be a few advanced (5- and 7-level) maintenance courses which have terminal objectives identical to job performance requirements. The need for such requirements must be determined on the basis of a job analysis and an analysis of the potential for on-the-job training and practice. When the requirement does exist, there will also exist a requirement for the use of actual equipment trainers and possibly very high fidelity simulators. More commonly, the objectives of an initial (3-level) resident maintenance course will be to prepare students so that via FTD training and on-the-job training and practice they can perform at the journeyman level after some months on the job. For such courses a high degree of transfer of training between resident training and the job is not expected. Therefore, there is only a minimum requirement for using actual equipment trainers or high physical-fidelity simulators during training.

During the early stages of learning, the use of high fidelity simulators may interfere with effective learning (3). While learning nomenclature and the location of front panel controls and displays, or when learning the relationship between controls and equipment operation, there is little need to represent all the other competing stimuli and response options which may exist in the operational environment. Their presence would only confuse the students and slow up their learning process.

Learning to perform portions of a complicated procedure on a specially constructed part-task trainer has been found to be an effective way to learn complicated procedures. For example, it would be both impractical and ineffective to teach the use of an oscilloscope while teaching also the procedures for locating a particular class of malfunctions.

Reilly (56) has provided a list of 21 characteristics for describing training devices (Table III). Each characteristic describes a feature which might be incorporated into a simulator. For example, to the extent possible, training devices should have structural or physical fidelity, functional fidelity, and provide for the learning of both motor skills and cognitive skills. In addition, it is advantageous to develop simulators which are student-proof, allow students to interact with the simulator and to receive feedback, can be used extensively throughout a course, are relatively inexpensive to purchase and maintain, and so on. Obviously, no one training device can possess all 21 characteristics in favorable amounts. Actual equipment trainers possess

Table III List of Training Device Characteristics
(Adapted from Reilly)

1.	Structural Fidelity	11.	Safe Usage
2.	Functional Fidelity	12.	Student-Proof Ruggedness
3.	Motor Skill Teaching Capability	13.	Student Accessibility
4.	Motor/Cognitive Skills Teaching Capability	14.	Student Input Capability
5.	Cognitive Skills Teaching Capability	15.	Feedback-to-Student Capability
6.	Fault Insertion Capability	16.	Noise Level/Environmental Factors
7.	Programmability	17.	Multi-System Flexibility
8.	Update/Modifiability	18.	Self-Paced Usage Capability
9.	Reliability/Maintainability	19.	Lock-Step Usage Capability
10.	Availability	20.	Usage Rate
		21.	Cost

high amounts of structural and functional fidelity and allow students to practice motor skills. They are not, however, studentproof, easily modified or updated, easily maintained, etc. It cannot be overstated that characteristics which make equipment effective in the operational setting often are those which make it ineffective as a trainer.

Desired Physical and Instructional Features

Well-designed training equipment intentionally deviates from reality (8). To promote learning, it should possess certain features not possessed by its real equipment counterpart. To withstand heavy use by both students and instructors it should be constructed differently than the equipment it represents. To prolong its usefulness it should be capable of being modified to reflect later versions of the equipment it simulates.

Some of the instructional features which should be incorporated into a simulator include the capability to provide prompts and cues; to provide feedback to the learner; to allow the instructor to vary the difficulty level of problems; and to allow for variations in the training sequence in order to adapt training to the present state of the trainee (8). In addition, Kinkade and Wheaton (33) mention the capability to teach specific tasks, and to allow practice on difficult components of a lengthy procedure, as useful instructional features. Some special features which seem desirable (8) are (a) the ability to set the device so that it will demonstrate both proper and improper operations and common mistakes; (b) the capability to record student performance on video for playback purposes; (c) the capability to provide for practice and drill on difficult segments of a procedure; and (d) the capability to exercise individual positions in a team trainer. Which of these many features should be incorporated into any specific trainer is a matter of opinion; most decisions are made on the basis of educated guesses.

An especially troublesome decision area, at least to the authors of this report, concerns whether or not to incorporate into a simulator the capability to simulate many malfunctions. Some people feel that there is little, if any, need to increase the troubleshooting ability of course graduates. This opinion seems based on the fact that present 3-level course standards seldom require students to be proficient troubleshooters at the end of the course. In theory, this skill is acquired in the field. In practice this policy is likely to produce graduates with so few practical skills that field personnel dislike trying to teach them on the job.

Another version of this opinion has been expressed by Cream (12) who has suggested that training device designers should not incorporate into their device a large malfunction insertion capability. Rather, he proposed that designers first determine the amount of course hours available for troubleshooting practice. Since these hours will not be enough to cover a large number of malfunctions, he recommends that designers identify critical malfunctions and simulate only those. Our objection to this position is based on the belief that maintenance course graduates should have some reasonable ability to troubleshoot when they arrive at the field so that job incumbents will regard them as worthy at least to be helpers. We agree with Malone that "troubleshooting training must include as many as possible critical and/or frequent failure modes." (37)

The authors feel that current courses have slighted troubleshooting training because of difficulty in inserting malfunctions into real equipment. Under current conditions it often is too much trouble to teach practical troubleshooting skills. This need not and should not be the case. Moreover, we feel that the advantage of simulators should be viewed with respect to the total training system, both the schoolhouse and the field. We think it is important and cost-effective to raise formal course standards when the raised standards can be met at no or only slight increases in training costs. This may not provide a payoff to ATC Technical Training Centers, but it might considerably reduce the cost of FTD training. In addition, it should increase the operational capability of field units, and perhaps save money which otherwise would have to be spent inefficiently on on-the-job training.

In addition to instructional features, the well-designed simulator should possess a number of physical characteristics. Of course, it should represent its equipment counterpart in a manner that will promote the acquisition of job-oriented training objectives. Moreover, special efforts should be made to functionally represent those tasks which will be taught on the trainer. In addition, the device should provide easy access; be rugged or student-proof; be reliable and easily maintained; be as simple as possible; and be able to withstand unusual use patterns (33). To this list Bryan and Regan (8) would add that the device should be easy to reprogram; be constructed in a module or building-block design; and when possible, be designed for multiple usage by different types of trainees. As discussed under the section on fidelity, Reilly (56) has provided a list of 21 characteristics which can be employed to both describe and review the design requirements for simulators. Some of these characteristics are mutually exclusive, and there are no hard-and-fast rules for deciding the degree to which they should exist in a training device.

Procedures for Selecting Requirements

Despite the lack of rules, decisions eventually must be made about the design and specifications for simulators. Bryan and Regan provide a useful discussion on the use of trade-off analyses. These will help one identify the costs and benefits of a training device which will support various training requirements, simulate various equipment functions, and have certain instructional features. Their discussion offers a few guidelines but no prescriptions. They also point out that the trade-off analysis should not stop after comparing training device options. Rather, non-hardware alternatives also should be considered. For example, perhaps a training requirement can be more cost-effectively handled by low-cost aids or mock-ups. Perhaps training should be conducted on the job. Perhaps no training is required at all; instead, well-constructed job aids might be used to guide performance on the job (22, 50).

Shriver et al. (61) used the exemplary model approach to identify the requirements for a simulator of the NIKE HIPAR system. Based on prior research, they already had identified the functional characteristics of the operating and maintenance mock-ups they felt were needed for training on new radar systems. Further, they ascertained that the data required to develop these devices and their supporting documents existed in manufacturers' manuals used for "Key Personnel" training. Also, they found that prototype equipment was available for study at test and evaluation sites. Most importantly, they found that these information sources were available at least one and one-half years before student training had to begin. This gave them ample time to develop a system simulator, supporting maintenance documents and classroom lesson plans. This illustration serves as a reminder that the information needed to make decisions about the purchase of simulators can be different from, and must be available earlier than, the more detailed information upon which the engineering features of the simulator are based. To anticipate a later discussion, we feel that the exemplary model approach does allow one to make simulator purchasing decisions early in the new equipment development cycle. Development of specifications for the functional characteristics of the simulator then can await the production of an advanced prototype of the new equipment.

While reviewing the use of part-task trainers for maintenance, Reilly (56) noted that new trainers such as the EC-3, and trainers based on Honeywell's Automated Electronic Maintenance Trainer (AEMT) concept, have been designed to provide a multi-system application capability. For example, the EC-3 trainer can simulate equipment at all levels of maintenance.[1] Given the capability to rapidly change

[1]Besides the Educational Equipment Corporation and Honeywell, there are many other companies which have a capability to produce either or both two- and three-dimensional maintenance trainers. These companies include Autonetics, AVCO, Boeing, General Electric, Parsons and Sylvania.

from one level of simulation to another, there is no need to incorporate both levels into the same simulation package. Also, there is no need to try to simulate two or more subsystems with the same simulation package. It sometimes is cheaper to use two simulators to meet all simulation requirements than it is to develop a single simulator which meets all requirements. In a similar vein, the EC-3 uses different panels and programs to simulate different subsystems.

Sometimes equipment consists of many parts which are virtually identical to one another. When this situation exists, one or two parts can be functionally simulated and photos, mock-ups or dummy components used to simulate the remainder (44). This technique was followed in order to lower the cost of the Air Force's 6883 Converter/Flight Controls Test Station Simulator.

There seems to be some disagreement over the relative role various groups should play in the selection of simulator characteristics. Most authors agree that there should be an interaction between the user (instructors who use the simulator), simulation engineers and training psychologists. Cream (12) proposes that instructors make many of the final decisions on the basis of information provided by engineers and psychologists. In part, this would be an effort to ensure appropriate instructor usage of the simulator as well as to lessen their negative feelings about the device. The authors of this report recognize the problem of obtaining instructor cooperation but would prefer to search for solutions elsewhere. We would prefer to obtain inputs from instructors but then let training psychologists and engineers knowledgeable about simulation techniques make the final decisions on the basis of trade-off analysis. Training psychologists are more apt to know about the cost and benefits of a variety of features which can be incorporated into simulators. Moreover, they are more apt to consider low-cost training alternatives as well as non-training alternatives such as more "human engineering" of equipment. Engineers expert on simulation techniques are more apt to know the feasible techniques for simulating various equipment features and maintenance tasks, and the approximate cost of various simulation approaches.

In a previous section on the determination of simulation requirements this report briefly discussed the possibility of copying exemplary training devices employed to teach the maintenance of other similar weapons systems. We find this an attractive approach and suspect that it is followed rather extensively, the flaw in its application being that the simulator copied probably are not especially exemplary.

USER ACCEPTANCE OF MAINTENANCE SIMULATORS

Research Findings and Problem Areas

During recent years there has been an increased realization that the effectiveness of training devices depends on how they are used and accepted by instructors and students (40). Instructors, however, are the more important of these two user groups because they are in a position to defeat the purposes of training devices and to govern the attitudes of students toward them.

According to anecdotal evidence, training devices are continually misused, and usually underused, by instructors. Instructors ignore many of the capabilities built into flight simulators. They used maintenance simulators as classroom demonstrators, showing students how to locate malfunctions instead of allowing them to practice a skill. When viewed from a different perspective, instructors berate simulator designers for developing over-elaborate training equipment whose many "nice to have" features have no practical value in the classroom or training lab. Both parties to this dispute can cite arguments in their favor (8).

The few research findings that relate to this problem area indicate that instructors favor the use of maintenance simulators so long as their use is under the control of instructors, and so long as simulators are not used to reduce the inventory of actual equipment trainers. McGuirk (39) reported that the EC-II troubleshooting trainer was well received by instructors and students and subsequently was incorporated into a Weapons Control Systems' Mechanic Course concerned with the AN/APQ-126 Radar System. Spangenberg (65) found that national guardsmen were impressed with the effectiveness of the EC-II trainer but felt that it was better overall to use actual equipment for training. Biersner (6) found that Navy instructors and trainees favored use of the EC-II for troubleshooting training over use of actual equipment trainers. The Automated Electronic Maintenance Trainer (AEMT) concept has been used to simulate the AN/ALQ-100 airborne electronic warfare transceiver and Navy instructors found the simulator to be acceptable so long as it was not used to replace actual equipment trainers (16).

Modrick (48) admitted that trainers based on the AEMT concept attempt to provide a high fidelity simulation of how equipment "looks" and "feels" in an effort to safeguard against negative attitudes of instructors and other opponents of simulation. He noted also that Navy reviewers agreed that the AEMT appeared capable of teaching troubleshooting procedures but felt that a "trainer should be an aid to the instructor rather than a replacement for him."

Even flight simulator advocates continue to experience user acceptance resistance. According to Killian (30) the extensive use of simulators requires "a step-by-step program of proving and selling each new concept to the pilots who are involved, the management who must support the developments, the approval and authorizing agencies, and the instructor groups who can make or break a program."

Much of the resistance to simulation is based on the belief that high physical fidelity of a training device is necessary. Neither instructors nor students can readily understand how training on simulators, and especially low fidelity simulators or mock-ups, can prepare students to work on actual equipment. As mentioned earlier in this report, perhaps the use of simulators has been oversold or mis-sold in the sense that proponents of them sometimes imply that all training can best be conducted using simulators and other training devices. We do not subscribe to this view, and neither do many simulator advocates; instructors should be informed of this. In our view, a cost-effective maintenance program is most apt to be one that employs a mix of training aids, simulators, and actual equipment trainers; one type of training aid or device would not be eliminated in favor of other types. Rather, low-cost, low fidelity aids and devices would be employed where possible so as to reduce, but seldom eliminate, the number of more expensive simulators and AETs required to support training.

Techniques for Obtaining Instructor Acceptance

Bryan and Regan (8) have reviewed the features which should be possessed by simulators, and these features, when present, should make simulators more acceptable to instructors. The features include: high reliability, ease of programming and reprogramming, ease of access and use. Also, the simulator should employ an instructor station which allows the instructor to be a "good" instructor. That is, the station should provide information about the range of problems available to and for use by the instructor; it should be easy to load programs into the simulator; it should be easy to reconfigure the trainer to meet the needs of individual students or a particular section of a course; and information about student performance should be provided. To this list it should be added that the simulator should not be over-elaborate, should not overload the instructor, should not collect useless data, and should provide feedback to the student. Of course, the simulator should have a high degree of functional fidelity and a medium amount of physical fidelity. Unfortunately, the definitions for "high" and "medium" fidelity are not clear.

Cream (12) is of the opinion that instructors should have the final say with respect to the design of a simulator, and should be responsible for preparing the plan for integrating the device into the training program. He feels that this is the best way to assure that the device will be acceptable and be used. He notes also the need for communication between instructors, simulator designers and training psychologists during the design stage of the simulator. These are the persons who should be involved in the trade-off analysis which should be conducted before the functional specifications for a simulator are finalized. Bryan and Regan (8) apparently feel that less reliance should be placed on instructor decisions. However, they do emphasize the need for communication between simulator designers and instructors, and recommend that instructors have some say regarding design parameters. They recommend also that a joint committee composed of instructors, simulator designers and instructional psychologists be established for the purpose of developing instructional material and the plans for incorporating the device into a course.

There is some disagreement regarding who should prepare the utilization guide for a simulator, although there is agreement that one should be prepared. Cream (12) feels that it should be prepared by instructors, while Bryan and Regan (8) feel that simulator designers, with the cooperation of users, should be responsible for the utilization guide.

THE COST-EFFECTIVENESS OF MAINTENANCE SIMULATORS

The Potential and Reality of Simulators

So far in this report we have reviewed numerous studies, many of which claim that simulators and/or low-cost training devices are more cost-effective for training than are actual equipment trainers. Siecko (64) noted that the EC-II usually cost only a fraction of the cost of the real equipment it represented. Spangenberg (65) reported on how effective and relatively inexpensive was the EC-II trainer. French (23) noted that the MAC-1 and MAC-2 trainers were much less costly than the systems they represented, and were more effective. The Automated Electronic Maintenance Trainer (AEMT) is rather expensive, yet one report noted (15) that it was less than half the cost of the system (AN/ALQ-100) which it simulated.

Another group of authors have reported on the cost-effectiveness of training aids and mock-ups. Torkelson (67) doubted if the use of three-dimensional mock-ups could be justified when wall charts or transparencies served equally well at much less cost. Vris (69) concluded that cutaway charts and transparencies were economical and effective substitutes for more expensive three-dimensional cutaways. Grimsley (25) varied the appearance and functional fidelity of a panel used to train soldiers to operate the Section Control Indicator Console of the Nike Hercules guided missile system and found all three versions of the panel to be equally effective. As noted already, Cox (10) could find no difference in the effectiveness between various training devices which differed in cost.

The evidence seems convincing: simulators are more cost-effective for teaching malfunction location techniques than are actual equipment trainers; low-cost, low fidelity mock-ups for teaching nomenclature, parts location and procedures may be more cost-effective than more expensive three-dimensional aids, animated cutaways, or real equipment trainers. Surely, the time has now arrived for the wholesale adoption of simulators and low-cost training devices, or has it? Has the use of maintenance simulators resulted in the use of lesser numbers of actual equipment trainers. Has their use resulted in a decrease in course training time? Has any course been able to reduce its requirement for instructors because of the use of simulators? These are the basic ways to reduce course costs, yet there is no published evidence to indicate that these costs have been lowered by the use of maintenance simulators. The literature does contain estimates of the amount of money which might be saved through the use of simulators (48) and many authors have speculated that it should be fairly easy to obtain cost savings through the use of simulators. However, the literature does not contain reported examples of such savings in cost. It is difficult and time-consuming to evaluate the effects of training devices and perhaps it is for this reason that cost advantages associated with the use of simulators have not been reported. In addition, the extensive use of maintenance simulators is a very recent phenomenon and their effectiveness is still undergoing evaluation. We can only hope that those involved with current and future maintenance simulator studies will publish their results so that the presumed cost-effectiveness of maintenance simulators can be adequately documented.

Moving on to the topic of effectiveness, what evidence is there that maintenance simulators have resulted in greater end-of-course student proficiency which in turn has transferred to the field in some noticeable fashion? The authors of this report know of no studies on maintenance simulators which have addressed the transfer of training issue in this fasion, although anecdotal evidence exists that students trained with simulators can perform acceptably in the field. An an example, in the early 1960s a course developed under the direction of Shriver, Fink, and Trexler (61) was forced to train students to maintain the NIKE HIPAR radar system before the real equipment showed up at the training site (a not unusual occurrence). A series of specially designed simulators, based on a detailed task analysis, was used instead of real equipment as training devices. The first few classes of students were trained with these devices with no known damaging impact on field operations. However, no data were collected to identify what, if any, problems course graduates did experience in the field. Eventually the HIPAR equipment showed up at the school. The course then became quite conventional, employing both real equipment and the specially designed simulators for training. In so doing the course became more costly, possibly more effective, and in all probability, less cost-effective.

The typical study of maintenance simulators compares students trained on a troubleshooting simulator with students trained to troubleshoot on actual equipment. Training on the simulator is supplemented with nomenclature and parts location training. Both groups receive special training on the use of test equipment. Both student groups then are tested on some type of troubleshooting test which usually emphasizes the application of troubleshooting logic, a skill which can be taught well using a maintenance simulator. Invariably students trained on the maintenance simulator perform better, or at least equally as well, on the test as do students trained on actual equipment trainers.

After the usual simulator experiment is terminated, the troubleshooting simulator may be incorporated into the regular course and the course Plan of Instruction (POI) adjusted so that students now troubleshoot on both the simulator and on actual equipment trainers. The course is never shortened because of this, and little attention is paid to the increased proficiency which the students may now have. It is doubtful if field supervisors are even aware that students are now being trained slightly differently. From the standpoint of school policy, the course now is producing students which exceed course requirements, but this is an acceptable situation so long as it doesn't cost much. In fact, if training personnel like the new simulator, they may order more of them. Eventually they may end up with a course which is considerably more costly in terms of training equipment requirements, and which over-trains its students, at least with respect to current course standards.

Despite claims for their cost-effectiveness, the published facts indicate that the advantages to be gained through the use of maintenance simulators remain as a potential; the potential gains have yet to be translated into practical impacts. The challenge for the future, then, is not one of showing that maintenance simulators are potentially cost-effective. Rather, it is to identify the training conditions and assumptions which must be changed so that this potential can be realized, and to actually effect these changes.

Realizing the Potential of Simulators

If simulators are cost-effective, what must be done to demonstrate this in a practical fashion? Let's consider the possibilities. Consider a course where course standards are not to be changed and where simulators are to be used to teach troubleshooting skills. The increased effectiveness of the simulator may allow one to shorten the length of the course. Perhaps 40 hours of POI time are devoted to troubleshooting training. Using a simulator this may be reduced by one or two days with no loss in effectiveness, not much of a cost saving unless the course trains large numbers of students.

Perhaps the course employs two or more actual equipment trainers during the troubleshooting exercise. Using simulators, one or more of these AETs may not be needed. Perhaps they can be completely dropped from the training equipment inventory, but probably not. Instructors will still want AETs to serve as demonstrators to both students and visitors. To a visitor the presence of actual equipment trainers is more impressive than the mere presence of low-cost simulators. AETs give the impression that students actually are taught to maintain them. The facts may be quite different, but the visitor does not stay long enough to learn of this.

Perhaps by using simulators the instructor requirements for maintenance courses can be decreased. This might be difficult to accomplish because troubleshooting occupies only a small percentage of time in the typical maintenance course, and instructors are needed for the "information pumping" aspects of the course. However, if the simulator is designed to take over the giving of instruction, as in the CAI mode, for example, the requirement for instructors could decrease.

So far then it seems that the use of simulators instead of real equipment for troubleshooting will effect cost savings if an actual equipment trainer can be dropped from the course, or, if the simulator takes on some of the instructional load so that instructor requirements can be reduced.

Consider now a course where both course costs and standards can be changed, where it is permissible and even judged worthwhile to produce graduates who have an increased troubleshooting proficiency. To obtain this increased proficiency usually will require an increase in training equipment costs. The impact of the increased proficiency may be that course graduates are now able to more readily assume their duties in the field. The operational readiness of the units to which they are assigned actually may be increased, but this would be extremely difficult to prove. It might be less difficult to demonstrate that lesser amounts of on-the-job training now are required to bring course graduates up to a required proficiency. This may result in a cost savings to field units but not to the training center.

For courses already in existence, the addition of simulators will increase training center costs unless they can eliminate certain numbers of actual equipment trainers, or can shorten training. Some courses only employ one actual equipment trainer so there seems little chance of eliminating the use of that trainer. Those courses which employ two or more AETs may be able to eliminate one or more of them, and effect a considerable savings.

Taking another approach, the standards of a course can be examined more thoroughly, especially with respect to their job relevance. Is it the objective of a maintenance course to teach job-relevant skills and knowledges? If so, perhaps the course should concentrate more on teaching students to do something as opposed to teaching them about something. Maintenance simulators are most effective when used to teach and to provide practice on job-oriented skills; they will be cost-effective to the extent that course objectives emphasize the acquisition of job performance skills. Despite the emphasis on the ISD approach to course development, most maintenance courses still are oriented toward the acquisition of theoretical knowledges as opposed to job-relevant skills.

To summarize the arguments presented here, the authors are of the opinion that published research to date has only suggested that maintenance simulators are potentially cost-effective. Furthermore, we feel that the potential benefits of simulators cannot be achieved unless certain fundamental changes are made to maintenance courses. These changes involve one or more of the following:

a. changing course standards to emphasize the acquisition of proficiency as opposed to knowledges.

b. raising course standards to the point where it will take a mixture of simulators and AETs to achieve them.

c. requiring that course lengths be reduced with no loss in course graduate proficiency.

d. specifying that for any particular course only one copy of the actual equipment can be used for both operator and maintenance training, and that simulators and other training devices must be used instead of additional actual equipment trainers.

SUGGESTIONS FOR FUTURE RESEARCH

The research evidence has demonstrated that "many procedures and troubleshooting tasks can be effectively simulated with relatively low levels of fidelity" (25, 26). Further, this evidence indicates that "as training requirements move from the 'nuts and bolts' toward the more cognitive aspects of understanding electrical, electronic and hydraulic systems and the acquisition of diagnostic and troubleshooting skills, programmable computer-operated devices become more appropriate than actual equipment (37)." Regardless of the evidence, however, the use of simulators for maintenance training has not received widespread support, and many questions about the use of and effectiveness of maintenance simulators still remain. The paragraphs that follow describe much of the research which should, according to recent articles and reports, be performed with reference to maintenance simulators and other media for maintenance training.

Because of the current pace of maintenance simulator development and implementation, we feel that it will be difficult for research to stay ahead of implementation. We suspect that for some time to come researchers will be reacting to hardware developments rather than identifying the directions these developments should take. Despite this, further research must at least prepare the right questions to be asked of implemented products, especially as they pertain to product evaluation. Such questions should improve the next iteration of maintenance training devices and point future simulator R&D in more cost-effective directions.

Evaluating the Cost-Effectiveness of Simulators

Those who advocate the use of simulators for maintenance training believe that simulators can both increase the effectiveness of training and decrease costs. Maybe so, but convincing evidence to support these claims has still to be offered. Simulators are effective during training; at least they are more effective than are actual equipment trainers for teaching troubleshooting skills. However, there is little evidence regarding the degree to which simulators promote transfer of training to the field (24, 39). More evidence is needed in this area. In particular, we need more information about what can best be taught by the use of simulators, procedures or cognitive troubleshooting skills, with "best be taught" evaluated in terms of transfer of training to the field.

Simulators usually cost less than the equipment they represent. It follows then that training costs should be reduced when simulators are used in place of real equipment. The flaw in this logic is that it is based on the potential of simulators. So far few maintenance courses have substituted simulators for actual equipment trainers. Instead, simulators have been added to the course equipment inventory. Further studies, either on new systems or on extant ones, must actually do without real equipment and demonstrate that the impact is not detrimental. To quote from King (31), "What seems to be needed are adequate demonstrations, to the user communities, of those cost reductions and training benefits that are likely to accrue from the use of these new technologies. The time is right for putting together the best of each of the different approaches (Tech Pubs, simulations, CAI) into one or more advanced systems. The objective of each would be to provide the user community with the experience and data they need to commit to an investment in the newer methods."

Before the cost-effectiveness of simulators can be demonstrated, the indices of training costs and effectiveness of training must be reexamined, and the methods for conducting evaluative studies reassessed. As an example, training effectiveness can be defined in terms of within or end-of-course proficiency, proficiency during early weeks on the job, or proficiency after some months on the job. So far transfer of training research has demonstrated that simulators can increase proficiency during and at the end of resident training. A variety of research also has demonstrated that major variations in resident training cannot be correlated with job proficiency after a year or more in the field. It still remains to be shown conclusively that transfer of training affects performance during the first weeks and months on the job. If transfer of training does occur, it should have its most important and noticeable impact during these weeks. There is a need therefore for studies which examine the relationship between resident training, especially that supported by simulators, and on-the-job proficiency during the first one to three months on the job. In addition, there is a need for more research in the field of trainer evaluation, especially the evaluation of training effects resulting from the manner in which a trainer is used versus those effects related to the trainer itself (53).

Proficiency during early weeks on the job can show itself in a variety of ways; these indices should be identified and incorporated into evaluation studies. As examples, has the pattern of job assignment been changed? Has FTD training or on-the-job training been shortened? Has the time required to certify recent graduates at the "5" level been decreased? These are some of the data that should be collected in future transfer of training studies.

Those persons conducting evaluative studies of simulators should be alert to the possibility that supervisors will not be aware that recent course graduates may now have increased capabilities and can be given more difficult assignments during their early months on the job. Assuming this to be the case, it may be necessary to educate supervisors regarding these new capabilities and to suggest to them that they employ recent graduates differently than they did formerly.

With reference to training costs, it seems quite possible that simulators may lead to only slight cost reductions for school training but may provide the potential for substantially reducing the cost of FTD and on-the-job training. As an illustration, it may be more cost-effective to employ simulators to reduce the need for actual equipment training but not to reduce course length. Probably this would lead to the overtraining of students, at least with respect to current course standards. In turn, this might necessitate raising the standards. The practical implication of the foregoing approach is that simulators might reduce somewhat the cost of resident training, but that the major cost impact might be felt elsewhere. It is our view that the cost-effectiveness of simulators should be evaluated in terms o, the total impact on the personnel selection and training system, and on the logistics system instead of merely the impact on a particular course or Technical Training Center.

Comparing Simulators

Despite appearance, there is little evidence that the application of simulator technology has increased the proficiency of maintenance course graduates. New simulators have been evaluated by comparing students trained on them with persons trained in the classroom or on real equipment. Montemerlo (49), Spangenberg (65) and others have severely criticized this research paradigm, pointing out that this type of research does not increase our understanding of the conditions for which simulators best can be employed. Furthermore, research comparing simulators with actual equipment trainers has implied that simulators can be substituted for actual equipment trainers _in toto_. There is no evidence that this is possible. It is worth noting, however, that it is useful to conduct a few simulator studies solely for the purpose of demonstrating that simulators can be effective trainers. Such public relations efforts can pave the way for further studies which employ more suitable research paradigms.

In general, studies on the effectiveness of maintenance simulators have compared persons trained to troubleshoot on a simulator with persons who have not been trained to troubleshoot but who perhaps have talked their way through a few troubleshooting exercises in the classroom. With rare exceptions, the "new trainer" always wins. Students trained on the EC-3 or the AEMT have not been compared with students taught on the EC-II. Even worse, they have not been compared with students taught on the MAC-1 malfunction and circuitry trainer or any of the other trainers developed years ago. For all we know we may have gained nothing, at least with respect to course graduate proficiency, despite recent advances in simulator technology. Research is required to examine this possibility.

It may be difficult to win support for comparative research on simulators because no precedent has been established for conducting this type of research. Moreover, there is some question as to whether or not ATC schools should have the responsibility for producing graduates with practical troubleshooting capabilities. Some feel that this should be the responsibility of field training. On the other hand, a capability that actually exists can create a need in ways that a conceptual capability cannot. Now that there are simulators that can be used effectively to teach troubleshooting skills during resident training, more and more persons may agree that this should be allowed even though it necessitates an upgrading of course standards.

Supposedly recently developed trainers and simulators have a number of favorable characteristics not possessed by simulators of the fifties and early sixties. Presumably they can cover a wider variety of malfunctions than trainers of the past. It is claimed that they are less subject to obsolescence because they can be modified more readily. New simulators possess somewhat higher degrees of both functional and physical fidelity and therefore should be more effective. These are some of the arguments offered in favor of recent trainers and simulators. The validity of these arguments remains unknown and should be the subject of further research.

Determining Training Requirements

A number of authors have proposed research programs which might lead to a better identification of training device requirements. As mentioned earlier, Bryan and Regan (8) feel that more basic research should be performed on job and task analysis techniques, especially on what additional information might be gathered to support later decisions about training requirements and media support requirements. They also recommend more research on how to teach various tasks which are common to many maintenance job positions.

Both Cream et al. and Eggemeier (13, 19) have suggested that more research is needed on "short-term" methods for identifying training objectives and requirements. G. G. Miller (44) has discussed one technique for selecting from a pool of requirements those which should be simulated. More research is needed on the effectiveness of this and alternate methods. Modrick (48) has discussed the need for more research on the methodology for converting engineering data into training and training device requirements. The foregoing research problems are especially acute with respect to new weapons systems; there is a need to develop improved techniques for identifying training and training device requirements early in the weapons systems development cycle so that decisions can be made about the types of trainers to purchase.

In a recent paper, Klein (34) noted that ISD procedures were not developed to provide data in support of the design of simulators. In particular he felt that "ISD procedures do not adequately describe complex motor coordination tasks, nor tasks requiring complex perceptual-cognitive decisions. Questions of necessary fidelity, criteria for selecting part-task vs. full mission simulators, or types of instructional features are not addressed." It seems probable that the initial steps in the ISD process can be modified or elaborated to provide information needed to design simulators. This possibility should be examined.

A practical approach to some of the above problems has been proposed by Cream et al. (13) and others, and is based on the observation that new weapons systems seldom are completely new but rather are improvements to present systems. Cream proposed that, when identifying training and training device requirements, one should look at how training is conducted on similar equipments and tasks. Extensions to this approach will be discussed later on.

Determining Simulation Requirements

Principles for determining training content and simulation requirements for various learning objectives exist only in rudimentary form, and need much more development. We need better data regarding what simulators and actual equipment trainers can best be used for, and at what stage in the training process each should be used separately or in various mixes (49, 52, 56).

Research relating to the degree to which simulators should physically and functionally represent equipment should receive continued support, since it is arguments about this issue that often lead to the non-acceptance of low-cost training devices and simulators (33).

Just who should be involved in the determination of simulation requirements, and especially which group should make the final decision, is a matter for further study. Most authors agree that simulation engineers, instructors, and training psychologists should be involved, but there is disagreement regarding the roles they should play and the decisions they should make.

Numerous authors have discussed the need for determining simulation requirements on the basis of a trade-off analysis. The literature, together with military documents, is replete with guidelines, usually quite general, for how to conduct such an analysis and to make decisions regarding the design of simulators. In addition, there are many military persons and civilians in the Air Force who have participated in this decision-making activity. It would seem useful to collect and codify this expertise and these guidelines, and to incorporate them into a manual for the design of maintenance simulators. We admit that this would not lead to simple formulas which could be followed by the uninformed. However, it should at least collate the state-of-the-art and help spot more precisely the gaps in it.

Developing Exemplary Simulators

One way to identify training device requirements for new weapons systems is to examine how training is conducted on similar extant systems. An extension of this approach is to identify tasks common to many systems and then to identify exemplary training devices already in existence which can be used to teach those tasks. Complementing this approach is one which attempts to develop exemplary training devices for common maintenance tasks or common equipments or equipment subsystems.

The approach to simulator development currently followed by the Air Force involves the identification of common, costly equipments which might be simulated for the purpose of maintenance training. The development of a simulator for the 6883 Converter/Flight Control Test Station for the F-111D aircraft is an example of this approach. In addition, the authors of this report currently are conducting a study which will attempt to identify other common Air Force equipments or weapons subsystems which might be simulated cost-effectively during training.

For selected subsystems which appear in many equipments, exemplary materials for teaching maintenance should be developed. One should select subsystems where heavy use currently is made of actual equipment trainers. The goal of the research effort would be to reduce, but not entirely eliminate, the use of actual equipment trainers, and in their stead develop one or more simulators and perhaps lower cost training devices to prepare students for the simulators.

The approach just described should receive continued support. But, in addition, for each simulator developed a more detailed documentation should be made of such activities as the identification of training requirements, the selection of training requirements to simulate, the trade-off analysis process, and so on. This documentation should make it easier to develop future simulators, and should provide the information which eventually should be incorporated into official Air Force maintenance simulator development documents and regulations.

Various authors (48) have suggested that generic training modules should be developed to cover tasks that occur across many equipment systems. Expanding on this notion, many Air Force weapons systems and equipments have one or more of the following subsystem--electronic, electrical, hydraulic, mechanical or optical. It would seem worthwhile to develop model approaches and simulators for teaching these subsystems. Moreover, it would seem useful to investigate the possibility of developing exemplary approaches to teach various maintenance activities--removal and replacement of parts, inspection and preventive maintenance, troubleshooting--on common equipment subsystems. The goal would be to develop exemplary packages or modules which could be copied by new weapons systems. This would allow the developers of a training program for a new weapons system to specify, at least in general terms, the type of trainers they wanted to purchase and the probable trainer costs.

Developing Exemplary Mixes of Maintenance Training Media

It has been suggested by many that training aids, simulators and actual equipment trainers are most effective at specific stages in the learning process, and this supposition has been adopted in this report. There is considerable need, however, for more data on what maintenance skills and knowledges various aids, trainers and simulators can support most effectively, and at what point(s) in the training process each should be used (49, 56). This information could be developed as part of the proposed development of exemplary approaches to teach various maintenance activities for various types of equipment. In addition to investigating what types of simulators are most appropriate, it would seem appropriate to develop exemplary media mixes for various systems and subsystems and their supporting equipment.

In a recent report Montemerlo (49) contended that studies which compare the effectiveness of simulators with that of actual equipment trainers are based on the wrong research approach. Rather, he feels that research efforts should be concentrated on the identification of the mix of training media--training aids, mock-ups, simulators, and actual equipment trainers--which are more cost-effective for maintenance training. Montemerlo also pointed out that with one exception, the Apollo moon landing project, simulators always have been used in conjunction with actual equipment trainers, and that this will be the case for many future years. "Given that simulators are an adjunct to actual equipment in training, the question of whether one is better than the other becomes spurious, whereas the problem of allocating training objectives between the two rises to a position of pre-eminence." He concluded his report by stating that the goal of future research should be to determine the types of training objectives and conditions which are conducive to each type of training media, and that research should be designed to determine: the unique contribution each type of training device can make; the ways each can complement the other; the training methods which amplify the advantages of each; and the types of training objectives most conducive to each.

In addition to supporting the use of a variety of training devices, the present authors feel that the effectiveness of simulators can be increased by more closely intertwining the acquisition of maintenance knowledges and skills. We feel that knowledges should be learned in the context of their application; this is the essence of the "functional context" approach to learning.

In the traditional maintenance course knowledges are taught early in the course and skills are acquired later on. Considerable time is devoted to providing instruction about equipment but little time is devoted to the practical application of what was learned previously. The problems with this approach are many. In particular, the practical application portion of the course often is slighted. As a result students are required to remember instructional material for a considerable time before applying it to real equipment in the field. This temporal gap between instruction and its application places too much of a burden on long-term memory; by the time course graduates arrive in the field, they have forgotten much of the application-oriented knowledges they once had learned. There is no apparent advantage to storing verbal content in long-term memory. This practice appears to be an artifact of educational practices which do not prepare people for specific equipment-oriented jobs.

An alternative approach combines knowledge learning with its practical application. This should be a more effective approach since it reduces the requirement for long-term memory for instructional material to a short-term one--the short gap between instruction and its practical application. In addition, this approach may lessen the amount of nice-to-know information offered in most maintenance courses. Moreover, memory will be improved with the mix of verbal and spatial processing.

CAI programs which employ computer-graphics terminals offer one means for teaching related knowledges and skills in close temporal sequence. Recent efforts to incorporate CAI capabilities into maintenance simulators may provide another technique for keeping the instructional and application process intertwined.

Bryan and Regan (8) believe that inadequate support has been provided for basic research on simulators, and feel that an effort should be made to identify more precisely the simulator characteristics required to support the learning of various maintenance tasks as various stages in the learning. They feel also that more reserach should be conducted which compares the cost-effectiveness of simulators with nonhardware alternatives such as low-cost media, job performance aids, and on-the-job training.

Obtaining User Acceptance

There is continuing evidence that instructors do not believe in the effectiveness of simulators and do not properly utilize them even when they are supplied in adequate numbers. Concrete suggestions as to what to do about this situation seldom appear in the literature, probably because the problem is not one that is subjected easily to research. Rather, it is more of a public relations problem.

Some of the techniques which might be employed to obtain user acceptance should be described more fully, and instances where one or more of these techniques have proven successful should continue to be reported in the literature. Mackie, et al. (36) have made a good start on this. They identified six factors which lead to the acceptance or rejection of training devices. These simulation factors are: specific trainer features, characteristics of the users, characteristics of the instruction, pattern of use, and the manner in which the device is introduced to the user. Some of the practical ways to obtain better acceptance of simulators by instructors have been described by Cream (12). They include efforts to: assure continuity of the user; assure user participation in test and acceptance of device; carefully plan delivery of the device to the training setting, to include the development of a utilization plan; and provide adequate operator and maintenance documentation at time of delivery. Continued studies are required to determine how these and other factors affect simulator acceptance. Eventually a handbook of case studies might be published. In the meanwhile, advocates of simulators must continue to discuss the advantages of simulators with all those who will listen. In particular, an effort should be made to win the support of senior Air Force officers for the use of maintenance simulators; it is the attitude of these officers that establishes the "party line" throughout the training establishment.

The means by which groups of designers, psychologists and instructors should jointly develop the functional specifications for simulators merits further study and documentation. At the very least, instructor needs and biases should be considered when designing simulators. Senior instructors should play a major role in the trade-off analysis process which establishes the final functional requirements for simulators. Also, senior instructors should be recruited to publicize the advantages of simulators. Finally, it would seem mandatory that a utilization guide be prepared for each major simulator, and that instructors should have considerable involvement with its preparation.

Impact of Automatic Test Equipment (ATE)

It has been predicted that beginning in the 1980s considerable diagnostic and fault isolation of line replaceable units will be performed by automatic test equipment. The Navy is well along in its effort to implement this maintenance philosophy on board ship, especially submarines (55). The more advanced automatic test equipments employ computer-driven software packages to both diagnose and check out LRUs, and to isolate malfunctions to a replaceable module. However, because of the wide mix of equipment which must be maintained by many technicians, it is still not possible to develop accurate diagnostic software for many of them or for portions of them. Therefore, in many instances at present the fault-locating portion of Fault Detection and Isolation (FDI) packages must be supplemented by the use of documented manual procedures with or without the use of external test equipment. In a few instances the entire troubleshooting process must be based on improvised troubleshooting supported by general procedures, drawings and references.

Implications stemming from the extensive use of automatic test equipment are many. First, much of current maintenance training still is oriented towards teaching the basic theoretical background required to develop "improvised" troubleshooting procedures. This training approach is based on an outmoded maintenance philosophy, at least with respect to the use of automatic test equipment for organizational and intermediate level maintenance.

Second, as the maintenance of equipment becomes increasingly systematic based on self-diagnostics, it will become increasingly important that technicians be highly skilled operators of test equipment, especially its set-up.

Third, it appears that technician training will become "increasingly dependent upon systems knowledge and front panel/keyboard manipulations to isolate failures to an individual module or a group of modules." (55) This implies that technicians will be much more dependent on their knowledge of functional or signal-flow theory as opposed to an understanding of the equipment in terms of electronic theory.

Ironically, the use of automatic test equipment may both increase and decrease the need for persons who can improvise troubleshooting procedures. With respect to electronic equipment, ATEs eventually should be able to diagnose and locate faults in 95 percent of the equipment 95 percent of the time. However, when this potential is achieved, the problem of false diagnosis will become more critical--the technician will have to decide if the unit under test contains a malfunction or if the test equipment itself is malfunctioning. King & Tennyson (32) predict that such problems will "trigger more widespread use of manual backup techniques to find 'those five percent of the glitches' that the machine won't catch."

Possible solutions to the above problems are being explored by the Navy. These possibilities include the use of less skilled first-enlistment technicians who, should they decide to re-enlist, would be given extensive technical training. Supplementing this would be the extensive use of improved maintenance manuals coupled with the heavy use of stand-alone, compact computer-based simulators which can be used both as training and maintenance aids.

In light of the foregoing discussion, and the interest of the Air Force in the use of automatic test equipment, it would seem appropriate to identify more precisely the job requirements of technicians who will employ automatic test equipment. Based on this analysis, the entire approach to the training of these technicians should be re-examined. It seems probable that the training approach currently planned for these technicians is inappropriate. Moreover, it seems probable that these technicians will need to be provided with improved job performance aids, aids that can be used to identify false diagnoses and to handle the problems which the test equipment cannot handle. Finally, there is some evidence that the use of automatic test equipment will lead to the use of troubleshooting procedures which are more like those now used for organizational level troubleshooting--reliance on the use of front panel indicators and a functional knowledge of signal flow. If this is so, then the use of flat-panel, computer-driven simulators or computer-based simulation may be more cost-effective than the use of three-dimensional simulators such as those currently planned for the 6883 Converter/Flight Control Test Station.

Developing Improved Regulations for Maintenance Simulators

Better and more detailed procedures must be developed for integrating maintenance trainer design into the weapons system development cycle. As it is now, decisions about maintenance training devices often are made before alternative approaches to training have been examined. As a result actual equipment trainers are ordered instead of less costly and probably more effective simulators (37).

Currently Kinton is under contract with the Technical Training Division of the Air Force Human Resources Laboratory to investigate the procedures by which simulators are obtained for new weapons systems. What is obvious so far is that there are more detailed procedures for securing flight simulator than maintenance simulators. Procedures for integrating the design and procurement of maintenance simulators and other types of maintenance trainers should be developed. In addition, there is a need to identify the points in the weapons system development cycle where cooperation between maintenance simulator designers, training psychologists, instructors, and other important groups should occur. These points could be written up as requirements in future regulations. We can agree with Aultman (4) that "if the proper mix of training mock-ups, actual hardware and other training aids is to occur, early interface between the ATC and the operational command is required. Using commands must be involved in the training area from the very beginning of new equipment acquisition."

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