LESSONS LEARNED IN THE DEVELOPMENT OF HIGH FIDELITY MAINTENANCE TRAINERS

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ABSTRACT

In the spring of 1989, the Air Force contracted for the development of a suite of high fidelity maintenance trainers to support the training and certification of maintenance technicians for the C-17 air-lifter. This set of 11 trainers encompassed the simulation and replication of every subsystem of the still-in-development C-17 aircraft. The development of the C-17 Maintenance Training Devices (MTD) would be the first attempt on such a large scale to support certification of technicians on equipment other than the aircraft. Tenets of the program included: minimizing the use of aircraft parts, causing a great dependence on aircraft data; no formal training on the aircraft, thus eliminating parsing of tasks between aircraft and trainer; and delivery of the trainers concurrent with deployment of the aircraft to Charleston AFB, SC. As the amount of training time available on modern aircraft decreases, and formal training programs extend to the flight line, training/certification devices with comparable fidelity requirements will proliferate (i.e., MV-22, F/A-18E/F, F-22). This paper discusses some lessons learned from the development and test of the C-17 MTD program, with emphasis on the definition, design, and test of adequate fidelity, to support the certification requirements of the user (specifically, Air Mobility Command). In retrospect, a recurring theme throughout the various phases of the C-17 MTD development, is that the evaluation of higher level requirements and the definition of lower level requirements continues on through the test program. Hopefully, this paper will evoke some thought for harnessing the inevitability of this requirements process so that future programs will result in products that meet the user's requirements and expectations.

ABOUT THE AUTHOR

Mark Adducchio has supported the Air Force acquisition of training systems at Wright-Patterson AFB for 15 years. Mark has just completed front end work on the C-17 Maintenance Training System, having also served as the lead engineer on the original C-17 MTD development from 1989-93, and is currently the Air Force Lead Engineer for the F-15C Aerial Combat Enhanced Simulation (ACES) program. Mark also served as lead engineer on the Special Operations Forces Aircrew Training System, B-2 Training System and Ground Launched Cruise Missile - Missile Procedures Trainer. A native of Dayton, Ohio, Mark is a graduate of the University of Dayton (Bachelor of Technology, 1980; Master of Science, 1989) and resides in the Dayton area with his wife, Bonnie, and their eight children.

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INTRODUCTION

In 1989, the Air Force awarded a contract for the development and production of high fidelity maintenance training equipment to support deployment of the C-17 air-lifter. The C-17 Maintenance Training Device (MTD) program is a fixed price contract to ECC International, Inc. of Orlando, FL. Trainer deliveries began in early 1993. The C-17 aircraft made its first flight in September 1991. The technical requirements of the contract were defined in a system specification that incorporated functional specifications produced from the Instructional System Development (ISD) process performed by the 3306th Training Evaluation Squadron at Edwards AFB. The system specification defined eleven separate devices that would replicate major systems of the aircraft at a high level of fidelity. A major feature of the technical requirements was that the trainers should support the certification of the maintenance technician such that he or she would be fully able to service or repair the aircraft, with little supervision, on their first day on the flight line. This paper discusses some of the observations and lessons learned in the development of these devices.

REQUIREMENTS

Background

The training devices specifically required included:
Simulator for Training Evaluation/Performance (STE/P*)* - The STE/P replicates the aircraft flight deck and supports all system functions, such engine runs, system check-outs, fault detection, etc.

Flight Controls System Trainer (FCST) - The FCST replicates at least one of each flight control surface, including the vertical and horizontal stabilizers, all of which function via inputs form the replicated flight deck. Supports rigging, removal/replacement, checkouts, fault isolation and servicing.

Cargo Door/Rails System Trainer (CD/RST) - Replicates a portion of the cargo floor, the ramp and door. Supports rigging, removal/replacement (R&R), checkouts, fault isolation and servicing.

Auxiliary Power Unit Organizational Maintenance Trainer (APUOMT) - The APUOMT is a hardware trainer that supports R&R tasks on the APU and of the APU itself.

Air Conditioning Maintenance Procedures Trainer (ACMPT) - This trainer supports removal and replacement of air conditioning system components.

Landing Gear Maintenance Trainer (LGMT) - Physically and functionally replicates the right forward main landing gear and the nose landing gear, and includes a simulated flight deck. Supports operation, R&R, fault isolation, rigging and servicing.

UARRSI Trainer (UARRSIT) - Replicates the aerial refueling system in support of operation, troubleshooting, and removal/replacement.

Fuel Tank Maintenance Trainer (FTMT) - Replicates the right inboard fuel tank and functionally supports all fuel system operation and troubleshooting.

Consolidated Maintenance Trainer (CMT) - Mockup of the forward fuselage, replicates crew entry door, maintenance tunnel and flight deck to support removal/replacement, servicing and rigging.

Organizational Engine Maintenance Trainer (OEMT) - Replicates the F117 engine, externally and internally, to support R&R of line replaceable units (LRUs), engine R&R, borescoping, and inspections.

Engine Cowling Maintenance Procedures Trainer (ECMPT) - Engine mockup, including cowling doors to support crew chief training of accessing and servicing the engine.

Specification

As mentioned in the introduction, the training device requirements were defined in the ISD Functional Specifications. These specifications heavily depended upon a series of tables that defined the training objectives, the training tasks, and the level of fidelity of trainer components, that the analysts believed were necessary to support the training tasks and to meet the training objectives. Additionally, there were listings of malfunctions, or "malfunction classes" that addressed the types of simulated malfunctions that would be necessary to support training and the aircraft support equipment that was also anticipated or required to support training. Due to the developmental nature of the C-17 aircraft in the 1987-1988 timeframe when these specifications were being generated, much of the information from which the requirements were derived was quite preliminary. This specification approach leaves the door open for contradictions in requirements, as the performance requirements were defined not only by the training task, but also by the training objective. The problem was further compounded by specifying the solution via the component fidelity table, malfunction requirements and necessary support equipment. Of course, the specification of design solutions goes against the grain of today's acquisition streamlining initiatives, and the Government is out of the business of dictating designs. On the other hand, one can imagine, even in today's enlightened environment, that a maintenance technician involved in this task analysis effort would want to go ahead and define his or her interpretation of the performance requirement rather than leave that interpretation to some engineer who has never set foot on a flight-line or in a training detachment.

Prior to this program, the certification of Air Force technicians had always been accomplished based upon their demonstrated performance on the aircraft. Headquarters Air Mobility Command (AMC) imposed the certification requirement early in the program - before contract award, but after a bulk of the instructional analyses had been accomplished. This certification requirement redefined the fidelity requirements determined through the Instructional System Development process and acted as an overriding influence to the determination of the level of replication of aircraft components. Although never quantified beyond "perform the task as on the aircraft", the Functional Specifications were "fortified" with additional requirements to support certification. Such fortifications included: the addition of training objectives, and in some cases, tasks, to support the certification requirement; the addition of major aircraft components; and the addition of several general and overarching statements that addressed attachment, obstructions and task environment. The addition of the certification requirements further compounded Functional Specification issues discussed above. Although the structure of these specifications had the potential for contradictory requirements, at least there was a logical and systematic process in which the ISD developed the requirements. By piling certification requirements on top of the training requirements, the interrelationship of the various requirement types was compromised.

Certification vs. Training

As the program team embarked on the development of the trainers, the assumption was that the level of fidelity required to support training would also be sufficient to support the certification requirement. This was due to an inability to discriminate the needs of the instructor vs. those of the "certifier". With no experience in certification of technicians using training devices and the fact that the functional specifications really took on no new or unique characteristics, other than more components, the training and certification requirements were treated the same. Even today, there is disagreement on the level of trainer fidelity required to support certification. Training personnel will address high fidelity as the need to closely replicate only the portion of the component that the student "addresses" ("you can use a bowling ball as long as it has the correct connectors and fasteners"), while those interested in certification argue that such an approach is inadequate - that everything about the subject component must match the aircraft. The educator worries about the curriculum and the training objectives, and has faith that the extensive analysis behind the curriculum will produce a technician that will ably transition to the flight line. The certifier worries that the student will not make the transition from the trainer to the airplane and knows of only one way that such a transition will be successful - the trainer has to look, feel, smell and act like the airplane.

Trainer Fidelity

What was learned in the course of developing and testing the C-17 trainers was how to simulate the look, feel and smell of the aircraft. This "physical fidelity" was characterized in the specifications as low, medium or high, but that was not enough information to convey the requirement of the users. In most cases, the physical replication of the aircraft seemed to be more important than the functionality. It may be that the actual level of physical fidelity required here was more difficult for the development team to grasp. For functionality, maintenance trainers have, for a long time, required close replication of aircraft functions. Even in flat panel trainers, where physical fidelity is low, functional fidelity is typically high in support of operation and fault isolation tasks. The level of physical fidelity required to support training is beginning to catch up to the benchmarks set by functional fidelity. Specific examples include:

Color. While the color of a component may seem to be a trivial matter, we found that to the user it helped set a tone of how close the replicated system was to the aircraft. There are some color cues (besides the obvious warning and caution indicators) that the maintainer will encounter, particularly for tubing and ducting. Also colors may cue the maintainer on component location. Even colors in multifunction displays are expected to be true to the aircraft. This provides them with a level of comfort on the accuracy of the display.

Weight. All components removed and replaced in the course of task training/certification should match the weight and center of gravity of the corresponding aircraft components. When an aircraft component is heavy enough that it must be handled with a hoist or lift, the accuracy of the weight is less important. However, center of gravity remains important as it will affect how the component sits in a sling or on a hook. Also, if a component's weight is borderline between being manhandled and being moved with support equipment, then the weight and center of gravity should be accurate, as the possibility exists for the prescribed handling procedure to change.

Attachment. Despite the move to "Best Commercial Practices" in both the trainer industry and to some extent in the aircraft industry, best commercial practices on the flight line is still the use of Mil Spec parts and practices. In a classroom, an instructor may demonstrate to a student that to replace a component four bolts are removed, a connector is removed, and then the black box is removed. When that student is certified to perform this task, his line supervisor would expect him to note the fact that the wrong size bolt is used. For example, after proper application of torque a bolt-end does not adequately clear the nut, the student would be expected to get the proper fastener. When proper fasteners and torque values are not defined in the aircraft data, which occurred when working with aircraft development data, the best source turns out to be (USAF) Technical Order 1-1A-8, "Structural Hardware", in which the maintainers are usually well versed.

Torque Values. Torque values are required to be applied in the course of certification and may be up to the instructor's discretion in the course of training. The instructor will address the proper application of torque to fasteners and may provide demonstrations, or even have the students apply the proper torque. However, this tends to deplete the detachment's bench stock for some fasteners rather quickly, and concentration on fasteners during systems courses consumes class time. Again, it's a matter of how much time there is in the classroom. Commercial fasteners (non-MS) don't stand up to repeated torque applications. Same with couplings for tubing and hoses. Material selections will make a difference. In some areas, stronger materials than what are used in the aircraft may be necessary to sustain repeated application of specified torque values. Where torque values are not identified in the engineering data, (USAF) T.O. 1-1A-8 is a good alternate source.

Dimensions and tolerances. Dimensions and tolerances need to be observed. This is particularly important when components mate or are adjacent. While certification is task oriented, the evaluation is still more holistic in nature. An inspection of the fit, while not defined in the T.O., will be accomplished. The technician should be observant in the work area and identify for correction anything that is not right, gaps in adjoining surfaces, missing safety wire, etc.

Tubing and Cabling. Tubing, hoses, cabling and wiring in the view of the student should match the appearance of corresponding aircraft components. Terminations, connections and couplings should be the same as that used in the aircraft. It is difficult to find commercial versions of these sorts of components that match what you find on an airplane. A typical reaction from the user was: "we don't use that on the airplane". Routings, mounting, clamps, wraps, labels and stanchions should match the appearance, clearance, spacing and means of attachment of that found in the aircraft. One problem of mixing and matching commercial hardware with MS hardware is that the fit may not be just right. The initial use of commercial type ducting with MS clamps, found, the clamps were not tight over the duct when tightened to the correct torque value. Where specific wiring and cabling requirements are not specified, practices and values are specified in (USAF) T.O. 1-1A-14. Also, be careful to not end a cable or tube routing until the component is routed completely out of the maintenance area, not just out of the student's sight. Although the student may not see the termination while performing a task associated with the specific cable or tube, when he or she moves to some other task, the termination may be obvious.

Replication of Manufacturing Processes. Many aircraft components are "trimmed" to minimize weight. Excess metal may be trimmed from valve bodies, structural members such as bulkheads have holes carved in them, etc. Again, this is expected to be replicated on the trainers. For the most part, the use of black appliqués to simulate holes are not a popular approach. Also, some trainer designs originally had incorporated replicated valve bodies that approximated the shape or volume of the corresponding aircraft part (that old bowling ball theory rears its ugly head), which turned out to be inadequate for certification purposes. The user is interested in replications that are not approximate, but include every bump, edge, nook and cranny.

Access Panels. Access panels and doors should be replicated exactly as once the task is accomplished the student will have to close up. If this process is different than what is accomplished on the aircraft, then this is a problem. The number of fasteners should be the same, seals should be in place, etc. Also, remember that these access panels will see a lot more action than their aircraft counterparts.

Control Panels. Simulation of control panels is not new. Even on flat panel trainers, control panels are typically good replicas of aircraft components. One concern in the original C-17 MTD development involved panels in which only a subset of the switches or indicators would be used, with the remainder being depicted pictorially. The users did not want a student directed to the correct switch or circuit breaker by the fact that there is only one or two possible choices on a control panel or breaker panel. As a minimum, when one switch was required on a panel, moveable dummy switches, which did not have to be electrically active, would be placed on the remainder of the panel. Each circuit breaker that was fully simulated was immediately surrounded in all directions by physically functional non-active circuit breakers (can be pushed/pulled). All other circuit breakers were mocked up, but did not have to even be pull-able.

Malfunctions. Simulated malfunctions are traditional with maintenance training simulators. One problem experienced in specifying the original program was that, due to a blanket malfunction requirement in conjunction with a somewhat disjointed task list (due to very immature tech data, and the after the fact addition of tasks to support certification), the malfunction list did not match the tasks. Some specified malfunctions would never be seen because they were not supported by a task. There were also malfunctions that might cause a repair action, but there was no Operational Checkout that would detect the fault to prompt a repair activity. There were also fault isolation tasks with no attendant malfunction. The lesson here, of course is to check the requirements for consistency.

Surround Fidelity. One of the bigger problems during the development of the trainers was the issue of "surround fidelity". This constitutes the replication of the aircraft in the immediate task area, and was expected to match the aircraft just as closely as the specific components involved in the task. Needless to say, this could encompass rather large areas of replication. Without an aircraft to study and possibly photograph, it was difficult for the user to visualize what specifically had to be included, and it was certainly difficult for the designer to assimilate the big picture from the various aircraft installation drawings.

Reduced Fidelity. Reduced fidelity areas may be candidates for cues on familiarization and orientation, and for areas adjacent to the specified tasks. These reduced fidelity components may include pictorial representations, fixed, non-functional mock-ups, dummy switches and indicators, etc. Many trainers successfully utilize multimedia (interactive videodisc, computer graphics, CDROM, etc.) to represent portions of the trainer that were not replicated in 3D. This was not the preferred approach for C-17 MTD as this would require unnatural actions - use of a computer or touch-screen - that the student would not encounter on the flight line.

Support Equipment. Securing the proper support equipment for training is not a simple task and will easily consume more program energy and resources than what is planned. The deliveries of countless maintenance training devices have been delayed due to the unanticipated scarcity of needed support equipment. The Air Force's strategy for acquiring support equipment (in excess of 200 pieces) for use with the C-17 trainers was to make it the responsibility of the trainer manufacturer. This did not make the problem go away! It did off-load a considerable workload from the Government. Contractors need to beware that managing support equipment consumes resources and usually more resources than may be planned. Support equipment is needed in-plant to support integration and test, and ultimately in support of training. For the C-17 MTD program, the contractor was required to procure the support equipment through commercial sources. None would be provided as Government Furnished Equipment (GFE). Due to the developmental nature of the aircraft, support equipment was still being defined as the trainers were being designed. Sources had not, in many cases, been determined. The Air Force Item Managers had not placed orders for equipment and would not be placing new orders for at least a year or two. The MTD contractor had to procure support equipment from vendors much the same as the aircraft manufacturer. Due to the early need of support equipment for the trainers, much of the fielded support equipment would turn out to be of a different version or part number. This was particularly true for support equipment specifically developed for the C-17 aircraft. It would be more cost efficient to minimize support equipment needs during development, however, the requirement at the time was for a full suite of equipment to support simultaneous training requirements.

Simulated Support Equipment. Where the trainer had to electrically interface with support equipment, there were instances that required the support equipment be simulated. The problems presented in support equipment simulation are closely related to those found in simulating the aircraft, only worse. Not only was the aircraft still being designed, the interface with the support equipment was also evolving. At the same time, maintenance procedures that would utilize the support equipment were evolving, and in some cases, a source for the support equipment had not yet been determined. Additionally, the fidelity of the simulated equipment would come into play. First and foremost is the use of the notorious "trainer unique umbilical" that is used to provide the simulation computer the support equipment status regardless of connectivity. Another issue is the functionality of the equipment for other than task related activities.

DEVELOPMENT AND TEST

Aircraft Source Data

All trainer programs have issues with aircraft source data. The overall scope of the C-17 MTD development, coupled with the approach that no or very few aircraft components would be used, made aircraft data particularly critical. Due to streamlining in the aircraft contract and the Air Force's intent to not purchase every possible piece of data that supported aircraft design, the Air Force's access to design data for transfer to the trainer manufacturer was impossible. In turn, the aircraft manufacturer required only vendor data that was necessary for aircraft interface, and had only limited rights to most vendor data. This meant that the aircraft manufacturer could not share such data with other organizations such as trainer developers. The trainer developer was therefore required to go to all the various aircraft vendors to buy data or establish associate contracts to use the design data for the trainers. With some companies this was not an easy process.

Once the data is in hand, sorting through the data is a tedious process. In most cases this is an iterative process, where additional data has to be ordered to get the information needed to complete a design. The trainer manufacturer had a person on site at Douglas Aircraft to support this process, which was very helpful early in the design when a large amount of aircraft data was needed.

Design Reviews

Design activity tends to peak just prior to the various design reviews. Requirements are being evaluated, revisited, clarified, and deficiencies identified. Drawings are being generated, reviewed, and modified. Documentation is being generated for customer review, and in some cases, document rejections, and their impact on scheduled events, are being negotiated. Internal design reviews and "murder-boards" are being conducted, with changes incorporated for commonality and the "good of the program". Engineering specialties are getting in their final licks. Support equipment issues are just beginning to overwhelm program management. Manufacturing is beginning to ramp up and long lead requirements are being defined. Multiply such a scenario by eleven. This was a very active time for the MTD program. The design reviews for the C-17 MTD were, for the most part, held together. A lesson learned is that too much time was spent reviewing the design for the sake of the design and not enough time in interactive discussions between users and designers on how the preliminary designs would incorporate the specific fidelity issues of interest to the team. Detailed designs were reviewed at a low level but relative to the higher level requirements. There was not enough examination of the lowest level requirements (safety wire, fasteners, etc.) at anytime prior to test. Part of the problem may be that there was no real definition of roles and responsibilities in the design review itself - for both designers and customers alike. Certainly the designers should have gone into the review with some need of input from the Air Force - both relative to specific design issues as well as possibly some focus for further design efforts. Since the aircraft was still in its infancy, even the Air Force personnel did not have a complete image of the aircraft and all of its intricacies. More insight of the source data used by the engineers to synthesize a design early in the process may have been helpful to the development process. The Air Force should have spent more time getting into the designers thoughts and intentions rather than what was on paper. If users and designers come to consensus as to what is expected, what is needed (relative to the requirements - of course), then hopefully it becomes academic as to what is on paper, what has to change, and where the design has to go. This cannot be done by attending a PDR, a CDR and test. More interaction is required. This interaction is enabled when all members of the development team understand their role, as well as everyone's role, in the entire development process.

Test

Testing was performed in accordance with the test procedures. Test procedures were based upon the Logistics Support Analysis task - a precursor to the aircraft tech order - in addition to engineering tests that verified various design requirements (spare memory, design & construction, etc.). Aircraft maintenance procedures cannot be incorporated into a test procedure wholesale without some up-front analysis to insure it can be run from end to end on the training device. Regardless of the level of fidelity of the trainer, it is important to review the procedure for applicability. It is also important for a test person to pay close attention to the test procedure in a dry run to insure that every little operation required by the procedure can be performed - safety wiring, torque values, seals, etc. - and make no assumptions that minute aircraft procedures do not have to be followed.

Probably the most frustrating occurrence in test is when a discrepancy is uncovered that should have first been caught in the course of design, and certainly should have been caught either during integration or the contractors own internal tests. One way to prevent this is through user involvement during integration, possibly with incremental reviews of the hardware as it is assembled - with some means to track and correct deficiencies as they are discovered. Doing this, it becomes of the utmost importance that the design team follow through and resolve any issues that are raised. Lack of closure for such issues serves to destroy any confidence the test team has in the development team and in the product. *Close the loop!* Also, the contractor in-house test team and Quality Assurance (QA) team need a good understanding of the requirements at the lowest level, and an understanding of the user's perspective on how the user will interact with the equipment, both during a test and when it is deployed. This requires test and QA floor personnel to be interactively involved in the development, and also to fully understand the user's perspective. Quality Inspectors typically inspect completed work in accordance with approved in-house workmanship procedures and against the governing drawings. As stated above, best commercial practices on the flight line are military specifications and standards. As a result, work that will pass muster in the plant will potentially fail an aircraft maintainer's initial inspection. The workmanship requirements need to be defined and documented such that the inspector uses the same standards as those used on the flight line.

A large amount of time was spent during C-17 MTD test looking up aircraft source data, pulling it from the library, and matching it to the finished product to see how well a component matched the aircraft. In many instances, the time it took to complete this inspection process exceeded the time it took to complete the specific maintenance task. The lesson here is to reference aircraft source data in the trainer documentation, and possibly do some matching and verification earlier in the program, thus lightening the workload during test.

SUMMARY

Level of fidelity issues are a fixture of trainer development programs. Part of the problem is that engineering trade-offs must occur to control cost and schedule. Such decisions can cause problems when the user is not included in the decision making process, or at least, fully informed of the decision when it is made. Another reason is that neither the developers or the users understand the requirements well enough to make definitive requirements statements at the front end of the program. The problem is compounded by failing to establish adequate processes to decompose the requirements to the lowest possible levels early enough in the development process. While the issues discussed above appear to place the C-17 MTD program in a less than attractive light, the achievements of the program far outweigh the problems. A large portion of the C-17 airplane was replicated at a time when the airplane itself was still being designed. There was good user involvement throughout the program and their input was instrumental in determining the final device configurations. The MTD team has provided a significant training capability to the airlift community.

Bringing everyone on board early in the development and hammering out roles and responsibilities is of utmost importance in assuring the finished product meets both the requirements and the expectations of the user. This includes certification requirements as well as the more traditional training requirements. For years, aircrews have demanded high fidelity in flight simulators - to the point of pushing the state of the art in visual and sensor simulations. Why should we expect, or provide, any less for our maintainers?