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Technical Report NAVTRAEQUIPCEN 77-D-0028-1

AIRCRAFT MAINTENANCE EFFECTIVENESS SIMULATION (AMES) MODEL

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This report covers a project to develop and test a functional simulation model of aircraft maintenance. The model is called AMES, which means Aircraft Maintenance Effectiveness Simulation.

AMES is a computer model that simulates the operation and maintenance of an aircraft squadron. It is different from other aircraft models in that it measures the effects of human errors in maintenance (maintenance accuracy).

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AMES is a potential tool for managers to help identify those aspects of maintenance with large payoffs for improving operational readiness and/or mission completion rate. Additionally, AMES can be used to evaluate quantitatively the effects of human factors improvements on aircraft readiness.

AMES is important to the maintenance community because of its treatment of maintenance error rates. Maintenance errors are known to have a large impact on many other factors in the maintenance performance equation, e.,g., elapsed time, consumption of spares, aborted missions, etc. However, this knowledge has seldom been put to good use. One reason is that errors are difficult to measure. Another reason is that the effects of errors are highly interactive, and not easily traced by conventional analysis techniques.

AMES addresses both of these problems.

1. The measurement of error is accomplished by a special data analysis procedure, which employs engineering inference to extract error incidents from 3-M records and squadron operating records.

2. The interactive effects of errors are handled effectively by the computer, based on prior analysis of functional relationships in the operation and maintenance environment.

Preliminary AMES results show the enormous magnitude of maintenance errors. The following results were obtained for the F-14A in the base years of 1976 and 1977.

- Eighteen percent of maintenance actions resulted in errors. This number is very conservative because many errors cannot be detected with the 3-M data.

- A 90 percent reduction of these errors increases mission completion rate from 49.6 percent to 57 percent. This is equivalent to having 1.8 percent additional aircraft in each squadron of 12.

- When missions must be flown, mission completion rate may be a better measure of system performance than operational readiness. As maintenance improves, more missions are flown which in turn results in more malfunctions. The additional missions flown are reflected directly in mission completion but only indirectly in operational readiness.

The 90 percent reduction in errors is believed possible using state-of-the-art aiding/training technology. Study of the efficacy of aiding/training seems to be an area of research that could lead to potentially very large cost benefits.

In addition to human performance variables, AMES includes as inputs, operating schedules, parts availability, equipment item realiability values, maintenance manpower levels, and time-to-repair values. All such data are directly available from existing records.

AMES has now been taken through the prototype phase of model development. It has been shown to perform as intended relative to the F-14A aircraft. Recommendations for future use include: systematic model improvement, extension to other weapon systems, and involvement in trade-off studies indicating potentially cost effective human factors research.

PREFACE

The Naval Training Equipment Center (NAVTRAEQUIPCEN) has a continuing interest in the application and evaluation of the methods used in training design and development. Intrinsic to that interest is the need to measure performance, both within the training process and within the work environment supported by training.

The project described here concerns performance measurement in aircraft maintenance.

This project is part of a larger effort to establish a quantitative relationship between the effectiveness of maintenance and the operational readiness of Fleet units served by maintenance personnel. Two other projects deal with factors known to influence maintenance effectiveness. Such factors include quality of training; availability and usability of technical information, and maintainability of the hardware.

In the first, a study performed in the period 1978-1980, the relationship between maintenance effectiveness and maintenance training was explored. A connection was established between the performance problems of maintenance technicians and the methods employed in the training of such personnel. This study was funded by NAVTRAEQUIPCEN under Contract N61339-77-0166.

In a second study, the relationship between maintenance effectiveness and equipment design for the maintainer is being explored. Using the AMES model as a processing tool, an effort will be made to predict the impact on system cost/readiness where design-for-the-maintainer remedies are postulated. This study is funded by the Naval Air Development Center (NAVAIRDEVCEN) under Contract N62269-79-62-93093.

The work for the AMES program was performed by the Xyzyx Information Corporation, under contract N61339-77-D-0028. Close cooperation was rendered by the Maintenance Support Office Department in Mechanicsburg; the OPNAV Instruction Office in Washington, D.C. F-14A squadron personnel at NAS Miramar; and SH-2F detachment personnel at NAS, North Island.

There were three objectives for the project. One objective was to provide a basis for training new maintenance managers to understand the maintenance functions collectively as a system. A second objective was to provide a tool enabling R&D managers to assign higher priorities to people-related efforts in maintenance research.

The third objective was a research and development objective. This objective was to create a prototype functional simulation model for studying aircraft maintenance effectiveness.

We gratefully appreciate the efforts of Commander E. H. West, Maintenance Officer, Fighter Airborne Early Warning Wing, U.S. Pacific Fleet, NAS Miramar. Commander West provided us with information about maintenance and procedures which considerably simplified model development.

We would also like to thank the Maintenance Support Office Department, Defense Activities in Mechanicsburg, PA, especially Mr. Mansuato Pierucci. He provided the necessary 3-M flight and maintenance records.

Additional thanks go to Henry Kleine, for his help in the design of the model and in construction of a general plan for model development. The use of his Software Design and Documentation Language (SDDL) was most helpful in analysis of the model design and computer coding.

We would also like to thank Jan Clarke, Julie Engelschall, and Lou Pennie for respectively typing, editing and producing the art work for this report. Their helpfulness and care have made our task much easier than it might have been.

Finally, we would like to thank David Bronstien and Dominique Inaba. David served as our excellent programmer. He also wrote utility programs, procedures, and reports, and kept our files in good order. All of his work was extremely helpful; but in the end, it was his perceptive observation of inconsistencies that helped the most. Dominique was our program secretary and librarian. On a model as large as this, organized and updated records are imperative. With Dominique on the job, we had no problems.

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SECTION I

INTRODUCTION

It is reasonably well known that maintenance technicians commit errors. Even the general consequences of these errors are fairly well known. These consequences include damaged equipment, wasted materials, accidents and injuries, excessive use of spare parts, and most prominently, the persistent need for rework.

Curiously, however, the problem has not been studied very systematically. Major efforts have been made to measure and control performance time, but performance quality has gone unquestioned. In this respect, the maintenance research community has taken the same path as was taken earlier by the reliability community. Neither has constructed a viable method of dealing with the errors they know are occurring.

What is needed is a practical way of measuring both performance time and performance quality, including the interrelations they represent. These are the elements that comprise the true variable, maintenance effectiveness. Given those measurements of performance time and quality, it is necessary to be able to relate them to a higher-level variable of great importance, such as operational readiness. Finally, there is a need for an economical method of exercising this relationship under varied conditions.

Such a method would make it possible to study alternatives when seeking ways to improve performance at the operational level. The effects of changes in the personnel subsystem could be examined quantitatively, thus putting them on an equal footing with proposed hardware solutions. This capability would have large implications for the training community, which has always had difficulty in demonstrating impact at the bottom line.

OBJECTIVES

Our immediate goal is to study the relationship of maintenance effectiveness to system performance. A functional simulation model of the aircraft flight and maintenance process can be used to quantify this relationship. The immediate objective of this project is then to create a prototype functional simulation model for studying aircraft maintenance effectiveness.

A more distant goal is to provide tools and techniques to improve maintenance. The long term objectives should be chosen to use the functional simulation model as a first step. The two long term objectives are as follows:

- to provide a basis for training new maintenance managers to understand the maintenance function as a system.

- to provide a tool enabling R&D managers to assign higher priorities to people-related efforts in maintenance research.

ORGANIZATION OF THIS REPORT

This report describes the AMES Model. The report is organized in the following way:

- The first three sections provide an introduction and overview of the project. Section I provides a brief overview. Section II describes errors and their effects on maintenance. Section III discusses the modeling approach and why it was chosen.

- The second three sections describe various aspects of the AMES Model. Section IV describes the procedures used to design, construct and test AMES. Section V describes the additional information required to use the model. Section VI describes the AMES Model itself.

- The final two sections provide results, conclusions and suggestions. Section VII describes results of our study and preliminary results obtained from the model. Section VIII presents conclusions and suggestions for improvements, modifications, and potential uses of the model.

- The Appendix describes the model in much greater detail.

SECTION II

MAINTENANCE ERRORS

Maintenance errors are discussed under the following headings:

- Kinds of Errors
- Effects of Errors
- Measurement of Errors

The dynamics of errors tend to be similar in nature, regardless of the maintenance environment. However, the discussion here applies specifically to the area studied; that is, organizational maintenance on carrier-based Navy aircraft.

KINDS OF ERRORS

As shown in Table 1, maintenance errors may be conveniently sorted into three categories: Type I, Type II, and Type d.

A Type I error occurs when the technician troubleshoots the equipment and concludes that a particular unit has failed when, in fact, it has not.

A Type II error occurs when the technician troubleshoots the equipment and concludes that it is okay when, in fact, it contains a defect.

A Type d error occurs when the technician damages the equipment or performs a corrective or preventive maintenance action improperly. Examples would be loose connectors, mismatched parts, improper alignment, and inadequate lubrication.

The method of categorization used here reflects the manner in which records are kept in the Navy Maintenance and Material Management (3-M) System. This is very important to the modeling effort. Any measurement method seeking to impact the Naval Air Maintenance community must be as consistent as possible with the 3-M System and its associated data base.

TABLE 1. KINDS OF MAINTENANCE ERRORS

TYPE OF ERROR	EXPLANATION OF ERROR	TYPICAL SOURCE OF ERROR
I	Technician replaces a unit that has not malfunctioned.	Troubleshooting
II	Technician fails to recognize a unit that has malfunctioned or been improperly handled.	Troubleshooting; checkout
d	Techician fails to accomplish a corrective or preventive action properly.	Removal/installation; service; repair; adjust/align.

A key fact seen in Table 1 is that each type of error tends to be associated with its own particular maintenance function or functions. This is a crucial property in the design of the AMES Model. The functions themselves are identified as parts of the maintenance system being simulated. The presence of three kinds of technician errors, occurring at unique points within that system, provides the basis for a logical network. Within that network, errors can be expressed quantitatively and their side effects traced and measured.

EFFECTS OF ERRORS

This discussion of the effects of errors is an overview to show the general behavior of errors in the maintenance environment.

The effects of the three types of maintenance errors are summarized in Table 2. As shown there, errors may be discovered during post-job inspection, before a flight, or during a flight. Following discovery, the effects may be to abort the flight, repeat the maintenance function, use spare parts wastefully, place an unnecessary load on intermediate maintenance, and, of course, incur a risk of injury or accident.

Abort Flight

Other than the risk of injury or accident, which is present whenever an error is committed in aviation maintenance, the most serious effect of error is an aborted flight. All equipment items do not share equally in this risk. Flights are aborted only when critical components are involved. Criticality is determined by a pre-established list. Note that errors detected and corrected during post-job inspection normally do not cause a flight to be aborted. Note also that the (abort) effect is identical for all three types of error.

Repeat Function

This effect points up the cardinal rule of maintenance productivity: "Every error, regardless of the circumstances, creates a need for rework. Errors thus represent sheer dead weight in the system."

The extent of the necessary rework varies with the type of error. For Type II and Type d errors, rework is usually limited to the offending maintenance function, i.e., checkout or repair. For Type I errors, however, the rework is usually more extensive. Not only does troubleshooting have to be repeated, but the associated corrective action must be repeated.

TABLE 2. EFFECTS OF MAINTENANCE ERRORS

Kind Of Error	When Error Is Discovered	Effects				
		Abort Flight	Repeat Function	Use Spare Wastefully	Place Load On IMA	Risk Injury/ Or Accident
I. Good Unit Replaced	Post-Job Inspection		● (B)	●	●	●
	Before Flight	● (A)	● (B)	●	●	●
	During Flight	● (A)	● (B)	●	●	●
II. Bad Unit Not Replaced	Post-Job Inspection		●			●
	Before Flight	● (A)	●			●
	During Flight	● (A)	●			●
d. Repair Done Incorrectly	Post-Job Inspection		●	● (C)	● (D)	●
	Before Flight	● (A)	●	● (C)	● (D)	●
	During Flight	● (A)	●	● (C)	● (D)	●

(A) Flights aborted by critical equipment items only.
(B) "Function" includes troubleshooting & repair.
(C) Spare parts wasted only when broken.
(D) Load placed on Intermediate Maintenance Activity (IMA) only when broken part repairable.

Rework produces two kinds of negative results. First, and most obviously, it increases the direct cost of maintenance by requiring the presence of a larger-than-optimum staff. Second, it impedes the work schedule, thus fostering the creation of queues, wherein jobs are waiting for people. In this latter sense, excessive demands for rework always impinge upon aircraft availability.

Use Spare Wastefully

Spare parts are used wastefully in two of the three types of error situations, regardless of the time of discovery. The parts problem is avoided only in those cases where the error is failing to see that a replacement is necessary.

The greatest waste of spare parts probably occurs in troubleshooting because of the trial-and-error approach taken by so many technicians. It is true that good units removed in error may be used again after being re-cycled through Intermediate Maintenance Activity (IMA). Nevertheless, while they are in that (re-cycling) mode, they are not available for re-issue. Temporary shortages are thus generated, often leading to reductions in aircraft availability.

The waste may be less in the "improper repair" category, because so many repairs can be corrected without the need for new parts. However, that situation is counterbalanced by the occasional repair error that causes such serious damage that the broken parts cannot be mended, even in IMA. In such cases, the spares inventory is impacted permanently.

Place Load on IMA

Intermediate maintenance shops are burdened unnecessarily every time a part is replaced in error. This contribution to the problem is the Type I error committed in troubleshooting. IMA must handle all such parts as though they were defective. In fact, only after inspection and/or testing at IMA is it safe for the parts to be declared ready for issue. Since such parts enter IMA without defect, all work done on them must be regarded as wasted effort. The result is an increase in the direct cost of maintenance.

The dynamics are slightly different when repair is done incorrectly at the organizational level. In such cases, parts go to IMA only if they are damaged. The nature of the waste lies in the time spent by IMA in mending the broken parts. This waste is relieved only when the parts are broken so badly that they cannot be repaired.

Risk of Injury or Accident

As indicated earlier, the risk of injury or accident is present every time an error is committed in aircraft maintenance. Depending on severity, injuries and accidents may impact all aspects of maintenance and operational productivity. That is, they can affect direct costs, aircraft availability, personnel availability, the spares inventory, support equipment availability, and even facility availability. They are also known to be highly disruptive of normal operations.

MEASUREMENT OF ERRORS

The topic of error measurement is treated in detail in Section V of this report. The purpose of the present discussion is merely to show that error measurement is entirely feasible, given real-world data of the quality provided by the 3-M System.

All of the error measurements prescribed for the AMES Model can be obtained from the 3-M data and many can be identified by number in the 3-M Catalog. Where necessary, additional procedures are provided by Xyzyx to guide the analyst in extracting error data from those records.

Type I Error — Good Unit Replaced

Information on Type I errors is obtained from a 3-M report generated in IMA. The report is MSOD 4790.A2551-01, "No Defect Item Analysis Summary." This report summarizes equipment items processed by Aircraft Intermediate Maintenance Departments for which reported defects could not be duplicated. Such items thus reflect erroneous removals from the aircraft.

Type II Error -- Bad Unit Not Replaced

Information on Type II errors is obtained by a time sequence analysis of 3-M records CT11, CT21 and CT41. The analysis is inferential in nature. Where successive flights are accompanied by corrective maintenance actions on the same system, and those actions suddenly stop, a particular condition may be inferred. That is, the final corrective action was successful, but each preceding action must have been in error. Analysis for Type II errors requires engineering knowledge covering system equipment, operating theory, and maintenance practices.

Type d Error — Repair Done Incorrectly

Information on Type d errors is obtained from malfunction codes exercised on 3-M records CT11 and CT21. Two subsets of the Malfunction Code list appear in Tables 3 and 4. The codes shown in Table 3 indicate the definite occurrence of a Type d error. The codes shown in Table 4 indicate a probable Type d error.

Probable errors must be verified through reverse time sequence analysis wherein records are checked for prior maintenance actions. If the equipment has been worked on in the two days immediately preceding discovery of the problem, the defect is assumed to have been induced by maintenance rather than by equipment failure. Engineering knowledge is needed to distinguish between equipment failure and maintenance error.

TABLE 3. MALFUNCTION CODES ON RECORDS CT11 AND CT21 INDICATING DEFINITE TYPE d ERROR

CODE	DESCRIPTION
086	Improper handling
087	Improper identification
246	Improper or faulty maintenance
301	Foreign object damage (FOD)
304	FOD-Self inducted
651	Air in system
931	Inadvertent operation

TABLE 4. MALFUNCTION CODES ON RECORDS CT11 AND CT21 INDICATING PROBABLE TYPE d ERROR

CODE	DESCRIPTION
093	Missing part
105	Loose bolts, nuts, screws, rivets, fasteners, etc.
106	Missing bolts, nuts or screws
108	Broken, faulty, or missing safety wire or key
127	Adjustment or alignment improper
135	Binding, stuck, jammed
410	Lack of, or improper lube
730	Loose

SECTION III

GENERAL DISCUSSION OF MODELS

INTRODUCTION

The goal of all aircraft maintenance is to provide aircraft capable of flying missions. Therefore, the effectiveness of maintenance should be measured in terms of system performance, i.e., how well the aircraft system performs its mission. Figure 1 shows the factors that contribute to or affect such system performance. In the figure, the complicated set of interactions involved in aircraft maintenance is included in the circle labeled "AIRCRAFT FLIGHT & MAINTENANCE SYSTEM".

The outputs of the "AIRCRAFT FLIGHT & MAINTENANCE SYSTEM" circle are two system performance parameters: operational readiness, and mission completion rate. Flight and maintenance are included together since both are required to produce successful missions as well as to maintain a reasonable level of operational readiness.

The most obvious way to determine the extent to which system performance is affected by change of the factors is to observe an actual squadron. However, the primary purpose of aircraft is to fly; it is not to study maintenance. The high cost of aircraft prevents the exclusive use of a squadron for the study of maintenance. Therefore, we need some other ways to determine how the various factors mentioned above affect the aircraft flight and maintenance system. Two important properties of a maintenance system need to be considered:

- Complex Interactions Between Factors
- The Random Nature of Aircraft Component Failure

Complex Interactions Between Factors

Each of the factors shown as inputs in Figure 1 is related to some part of the flight and maintenance process. The immediate effects of each of the factors can be expressed in a relatively simple manner. For instance, if personnel required to prepare an aircraft for flight are not available, the aircraft cannot be made ready to fly. However, because of the complex interactions between the factors, it is extremely difficult to determine how they will affect the overall performance of the system, as expressed in terms of operational readiness and/or successful mission completion.

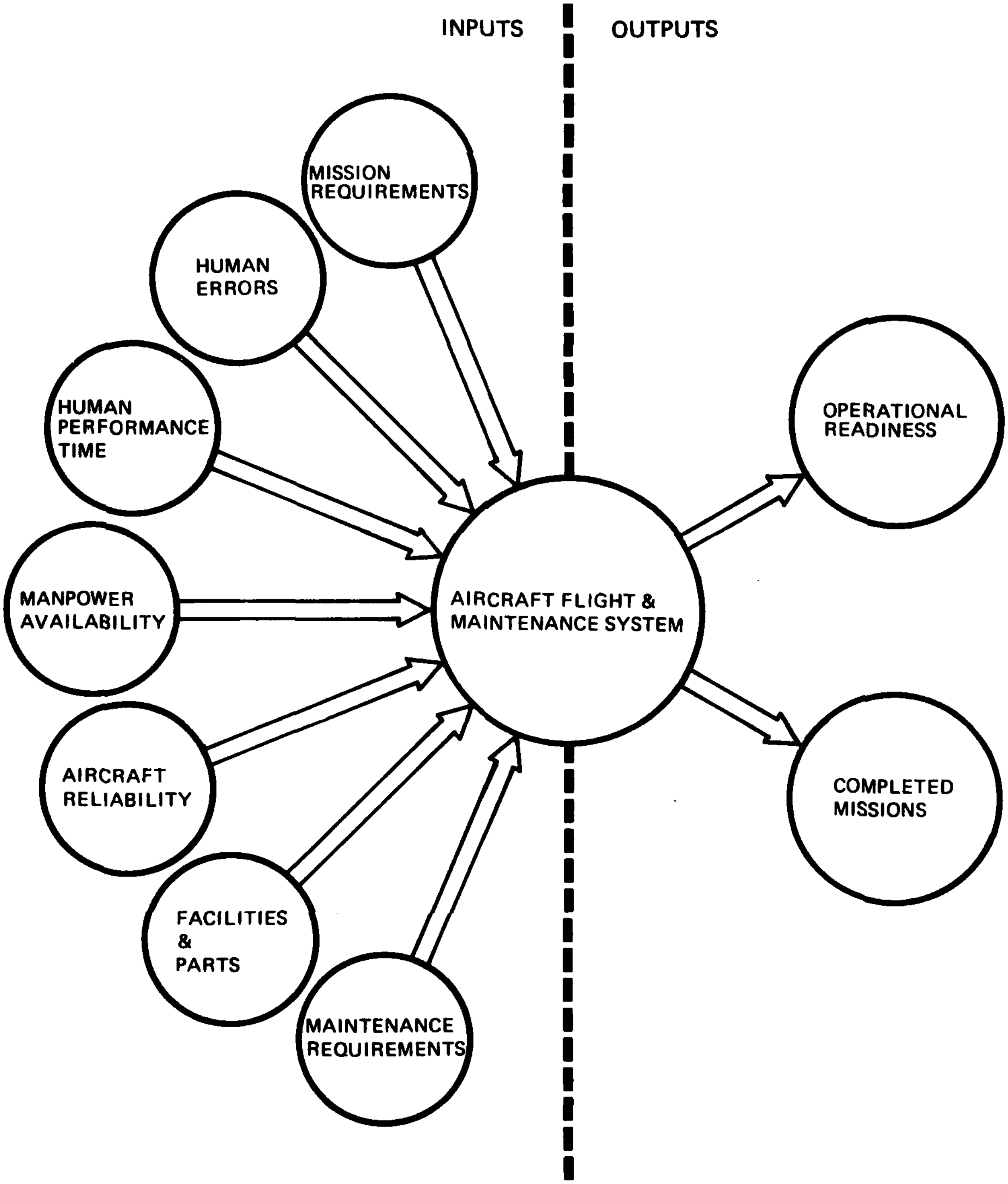


Figure 1. System Approach To Aircraft Maintenance

Maintenance has seldom been studied as a bona fide system. The complex interactions between the factors have made it difficult to gain meaningful insights from the uni-variate studies so common in maintenance studies. Consequently, little is known about the sensitivity of system performance parameters to changes of the factors. To compound the problem, some variables affect not only the system performance parameters but the demand for other factors as well. For instance, a reduction in human errors that damage components should increase operational readiness. However, it should also reduce requirements for such factors as spare parts, maintenance facilities, and personnel.

The Random Nature of Aircraft Component Failure

The primary reason why maintenance as a system is so complex is that it is a stochastic system. That is, it is a system "driven" by random events. The random events driving the system are the failures of the system components. The maintenance system is "driven" by the failures in that it must respond to the failures and correct the malfunctions.

The random distribution of the failures complicates the system in two ways. First, the specific time of failure cannot be predicted. The only prediction possible is the total number of failures over an expected period of operation. Thus, resources for corrective maintenance cannot be scheduled in advance.

Secondly, the random distribution usually results in work demands occurring in batches. That is, the average time between failures for a given component may be long but the actual time between two failures may be quite short, followed by a very long interval for the next failure. When hundreds of components are involved, the slack and busy times become mixed together, thus, the "balancing" of resource utilization and queues becomes quite complex.

ALTERNATE APPROACH: A COMPUTER MODEL

The two properties discussed above make it quite difficult to learn the characteristics of a maintenance system by systematically observing an actual maintenance operation. Such systematic observations become quite time-consuming, expensive, and often disruptive.

An alternative to the observation method must be a method that handles the complex interactions properly and can properly handle the random occurrences. The method must also provide quantitative information. Computer modeling, using Monte Carlo simulation techniques, satisfies all of these requirements.

COMPUTER MODELING WITH MONTE CARLO SIMULATION

A model is a representation of a theory or an empirical system. To be useful, the way in which the model works must correspond to how the real system works. The system to be modeled was shown in graphic form in Figure 1. The model is intended to represent the "aircraft flight and maintenance system" portion. The inputs and outputs remain basically the same. Given the selected set of inputs in Figure 1, the model generates the outputs.

The Monte Carlo simulation technique is especially suited for modeling a maintenance system. The suitability is discussed in terms of the two important properties discussed earlier, i.e., complex interactions and randomness. The unique feature of the Monte Carlo technique, and the basis for its name, is its ability to simulate randomly occurring events. Some precautions about the model are also presented.

Complex Interaction

The modeling method is well suited to systems with many complex interactions. The volume of information necessary to handle all of the many details of the interactions requires that the model be implemented on a computer.

For a squadron of 12 aircraft, each with more than 100 units, and approximately a hundred men distributed over 11 work centers, the computer can simulate a month of flights and maintenance in a few seconds. The several million calculations and manipulations that a month of simulation represents could not be accomplished in any other way.

Randomness

Because aircraft failures occur randomly, the computer model must be able to simulate such random failures. The Monte Carlo technique generates randomly occurring failures.

In the Monte Carlo technique, the probability of component failure must be provided as an input. This input is expressed as the probability that a particular component will fail per flight hour. To determine, on a particular occasion, if the component fails, the computer selects a random number from a long list of random numbers between zero and one.

For example, the probability that a coin flipped will be "heads" is 0.5. To simulate the flip of a coin, the computer selects a number from a list of random numbers between 0 and 1. If the random number is less than .5000, the computer treats the result of the coin flip as a head. Otherwise, the result is treated as a tail. The example simulates a random coin flip using Monte Carlo techniques.

In a similar way, the model simulates random failures, using the probability of failure per flight hour for each of the components on the aircraft. The probabilities currently in the model are based on the actual failure rates for the F-14A units. Let us assume that the probability that a particular unit will fail in a given hour of flight is 15 percent or 0.15. After an hour of simulated flight, the computer selects a random number from the random number list. If the random number is less than 0.15, the unit is considered to be a failed component. If it is greater, the unit is still considered good. After each hour of flight, the next random number in the list of random numbers is selected.

This approach has two advantages. For one, it provides the randomness required by actual aircraft failure rates. Just as important, it also allows a repeatability not possible in the real world. For instance, by starting the computer again, at the beginning of the random number list, one can repeat exactly each component failure at identical times in the run. Thus, the computer run may be repeated exactly with an identical number, order, and timing of failures.

Obviously there is no advantage to repeating a run if nothing is changed. However, there are times when it would be of tremedous advantage to repeat a run or portion thereof and examine the run in greater detail. This is particularly useful when trying to isolate problems with model operation.

Due to the randomness of failures, the week-to-week or month-to-month variation of system performance parameters is very high. This means that an average of many measurements taken during a reasonable period of time is needed to obtain a representative figure. Usually, this period is six months or more.

This high variance makes it impractical to study the sensitivity of the system to specific changes by using the actual system. With the model, six months of actual time can be simulated in about a minute of computer time. Thus, the model can be used to test the potential of proposed changes before actually implementing such changes. In addition, model runs, with systematic changes of the factors, can determine the extent to which the system is sensitive to changes in the individual factors.

PRECAUTIONS

There are several difficulties with models. Most systems worthy of modeling are very complex. In comparison, the AMES type of model is quite simple. In fact, the strength of the model lies in its simplicity. However, the simplicity is also its point of vulnerability — if the model is not used properly.

In reducing the complexities to the relatively simple model, it is necessary to make abstractions and take shortcuts. For example, an actual aircraft has millions of components. In a model, these components are grouped together into a few hundred units or about a hundred subsystems. The variations in failures, errors, time, maintenance manhours, etc., between components (within a subsystem) are "treated" with a distribution.

A similar reduction process is applied to the other system resources. For example, human performance is a highly complex process. Yet, the process is represented by only three parameters, i.e., time, error rate, and number of personnel (per job).

These simplifications should not be a problem if the user recognizes the level at which the system and its resources are represented. For example, the model cannot help determine the effect of stress on an individual technician. However, the model can help determine the effect of stress on system performance if the stress can be expressed in terms of some change in performance of technicians.

SECTION IV

DESIGN, CONSTRUCTION, AND TESTING OF THE AMES MODEL

The implementation of complex computer models is a large effort. Choosing the proper technique saves time, and produces models that are easier to understand, build, and fix. This section describes the considerations and procedures used to design, construct, and test the AMES Model.

INTRODUCTION

The principal difficulty encountered in building a model is communication -- both verbal communication and the ability to understand various documents produced. The information required to design and construct the AMES Model is distributed among different people as follows:

Naval Aircraft Maintenance Experts - They have an understanding of how the maintenance system operates. Their direct knowledge of procedures, decision criteria, and priorities must be reflected in the workings of the model. The maintenance experts have a knowledge of available 3-M statistics and what the statistics indicate. Because these experts are also potential users, the outputs should be understandable to them.

NAVTRAEQUPCEN Personnel - The project is funded and technically monitored through NAVTRAEQUIPCEN. They must be able to understand how the project has proceeded and what the model does.

Model Designers - The model designers have a knowledge of the pitfalls and capabilities of models. In order to complete the design they need to understand the nature of aircraft maintenance, the nature of 3-M statistics, and the nature of model trade-offs.

Model Programmers and Testers - These people may occasionally be those who design the model. When they are not, they need an understanding of design as well as knowledge of the computer language required to implement the model.

Model Modifier - Frequently in the life cycle of a computer program, requirements of the model change, either because demands on the model change or the modeled maintenance procedures are altered. As model usage is extended to new situations, new bugs invariably are discovered. Model improvements are discovered as the model is used. Model modification requires that the model be easy to follow. A knowledge of computers and of the proper languages is necessary; however, no other knowledge should be necessary to quickly understand and alter the model.

Model Users - The users of the model represent the most diverse group. It is anticipated that users will be either researchers or maintenance personnel.

The wide variety of background and training among those involved means that techniques to facilitate communication and understanding are essential. This subsection covers design, construction and/or testing techniques under the following additional headings:

- Design and Construction of the Model
- Design of the Model Outputs
- Testing and Validation

The first subsection discusses techniques and methods used to create the computer model. Techniques of documentation and communication are also discussed.

The second subsection discusses consideration given to the outputs of the model. The outputs vary depending on the intended use and audience. The outputs, with only slight changes, may be useful for entirely different applications, e.g., research or training.

The third subsection reviews the procedures used to test the model and assure its validity. A discussion of the meaning of testing and validation is included.

DESIGN AND CONSTRUCTION OF THE MODEL

The subsection discusses techniques and procedures to aid in communication, documentation, design, or construction. The following are discussed:

- English language design
- Software Design and Documentation Language (SDDL)
- Top-down design
- Modular design
- Structural language - Simscript II.5

Each of the above techniques or procedures is described below.

English Language Design

To satisfy the need for communication among people of different backgrounds, the language used for the design of the model is English. English is readily readable by all those involved with the project. The English description is collected into small modules so it is structured very much like a computer program.

Designing in English has the following advantages:

- Facilitates communication with maintenance personnel to allow feedback from model designers.

- Permits simpler understanding of the details of the model by managers or users of the model.

- Simplifies efforts to modify and repair the model.

Software Design and Documentation Language (SDDL)

The English language design formulated in small modules can be indexed and cross-referenced using a computer language processor called Software Design and Documentation Language (SDDL). SDDL was written by Henry Kleine. The design and the indexed cross-reference are combined to form the Design Document. The Design Document is the intermediate between spoken English and the computer code. It is English-like, yet, because it is indexed and cross-referenced, it is useful for both the design phase and the eventual translation of the design into computer language.

Top-Down Design

"Top-down" design is the division of the model into several levels of detail. First a top level (without detail) design is produced. At each succeeding level more detail is included.

Top-down design is primarily a design tool. It prevents the important concepts from becoming lost in the mass of details. Problems that arise in the design can be corrected at the highest level first. After designing the program from the top down, translation into computer language proceeds similarly. Serious flaws can be cured while the model is relatively simple. Frequently, with top-down design, as the complexity of the program grows, the magnitude of the errors is diminished.

A second benefit of top-down design is to explain the workings of the model. It allows those learning about the model to understand one level at a time. Since few want to understand all the details, when the desired level of detail is reached, one need not continue. (The description of the model in Appendix A is constructed in a top-down manner.)

A final benefit of top-down design lies in modification of the program. Selection of the areas that must be modified proceeds at the highest levels of detail (very general). When the section that requires modification is pinpointed, it can be studied selectively in much more detail.

Modular Design

The human mind cannot grasp large amounts of knowledge easily. To avoid this problem, the design (and eventual program) is composed of many small (about 1 page maximum) modules. Each is, in so far as possible, self-contained. Those parameters that must be exchanged between these modules are specified. At each level of increasing detail, each module is broken into several more detailed modules. The modularity of the design foreshadows the eventual modularity of the computer program. When the program is written, each design module becomes a computer program. Modularity also simplifies modification and testing because problems frequently can be isolated to a single module.

Structured Language - Simscript II.5

Modern computer languages are designed using new techniques to speed up the programming process. These languages are found to be easier to use, understand, and modify. Such languages are referred to as structured. The language chosen for the implementation of the model is Simscript II.5. Simscript II.5 is a modern language. Its programming elements are structured.

As an additional advantage, Simscript II.5 has been designed to be as close to English as possible. The actual computer language code in most cases reads like English. Since the names in the design document are the same as in the coded Simscript II.5 statements, many times the actual computer instruction can be understood by one with no computer experience.

Finally, the combination of SDDL and Simscript II.5 is ideal: the indexing and cross-referencing feature of SDDL can also be used on the computer program. Having a cross-reference and index for the actual program simplifies repair and modification.

DESIGN OF THE OUTPUTS OF THE MODEL

The outputs of the computer model perform two functions: they present results to the user, and they aid those who test the model. For much of the presentation to the user, only general outputs are necessary. For most uses the monthly average percentages of operational readiness and missions completed are the only necessary outputs. If monthly status reports are added, the general outputs amount to only several pages of data for each month of simulated time.

In contrast, very detailed specific outputs are necessary for most of the tests. For example, the aircraft number, time of day, and total flight hours to date for each takeoff and landing, might be required for testing. These detailed outputs require several hundred pages of output per month. This amount of output is expensive, and tedious to go through.

For the two separate needs, (presentation to the user and testing of the model), two different kinds of output are required. These are permanent outputs and temporary outputs (traces). This subsection describes the two different types of outputs as follows:

- Design of Permanent Outputs
- Design of the Trace Outputs

The first describes the permanent general outputs. The second describes the detailed outputs which can be selected before each run. These detailed outputs which can be selected are called traces.

The outputs of the model do not affect its operation. Thus, new outputs giving additional information are easily added.

Design of Permanent Outputs

Permanent outputs will be used by persons who may not be familiar with model concepts. Thus, the permanent output reports must be easy to understand.

The form of the 3-M summaries has been chosen as a prototype for the more complicated summaries that the model produces. This assures that those familiar with aircraft maintenance can easily understand model outputs. Comparison of the outputs of the model with actual 3-M summaries is facilitated.

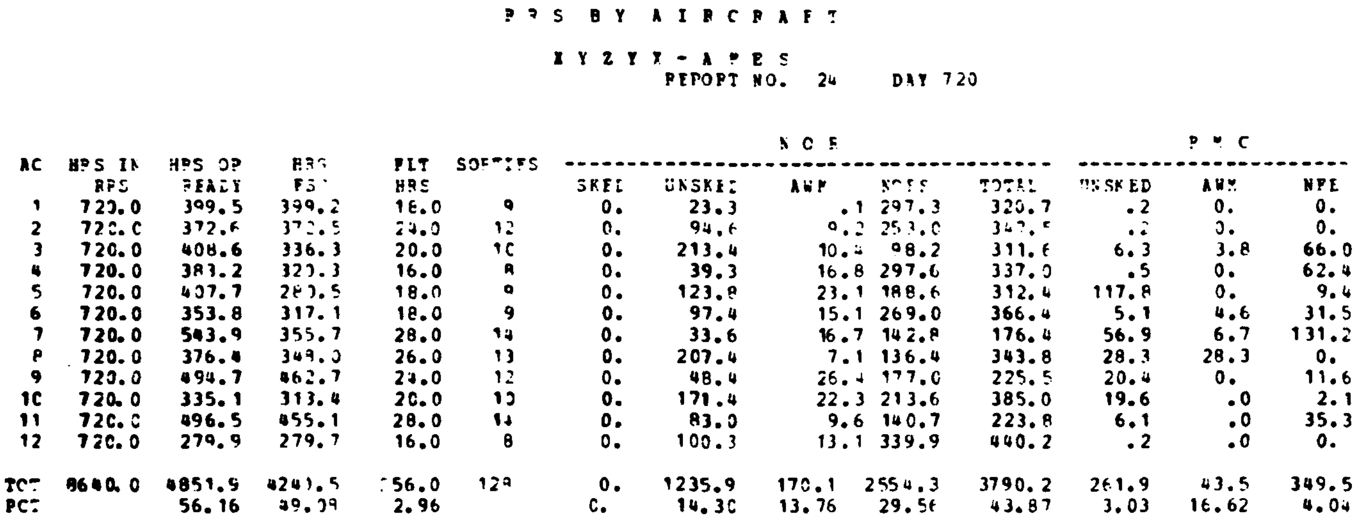
The following reports are available whenever the model is run:

- Monthly Readiness Reporting Status (RRS) Report by Aircraft
- History of RRS (12 month)
- Manhour Summary
- Additional Reports

Monthly Readiness Reporting Status (RRS) Report by Aircraft - A typical example of the monthly RRS Report is shown in Figure 2. The report includes all categories on the corresponding 3-M report (CNAP Gen Form 4790/6) except for Reduced Material Conditions because of scheduled maintenance. Entries to this column can never occur; therefore the column was deleted.

The entries in the row labeled TOT are the totals for all of the aircraft. With the exception of the AWM percentages, the entries in the row labeled PCT are the ratio of the column totals to the total HRS IN RRS (column 2). The AWM-NOR is the ratio of the total AWM-NOR to the TOTAL-NOR. The AWM-RMC is the ratio of the total AWM-RMC to the sum of the total UNSKED-RMC and the total NFE-RMC. These AWM percentages are respectively the percentage of the NOR time or RMC time spent waiting for maintenance personnel or facilities.

History of RRS - (12 month) - A yearly summary of the important parameters of the RRS is shown in Figure 3. This report contains RRS percentages, total flights, and total flight hours during the period, as well as aircraft utilization.



```
                               R R S   B Y   A I R C R A F T

                                    X Y Z Y X - A P E S
                                          REPORT NO.  24     DAY 720

                                                               N O R                                 R M C
 AC  HRS IN   HRS OP     HRS      FLT  SORTIES  ------------------------------------------   ----------------------
       RRS     READY     FSC      HRS            SKED   UNSKED      AWP   NORS     TOTAL    UNSKED     AWM     NFE
  1   720.0    399.5    399.2    16.0      9      0.     23.3        .1 297.3     320.7       .2      0.      0.
  2   720.0    372.6    372.5    24.0     12      0.     94.6       9.2 253.0     347.5       .2      0.      0.
  3   720.0    408.6    336.3    20.0     10      0.    213.4      10.4  98.2     311.6      6.3     3.8    66.0
  4   720.0    383.2    320.3    16.0      8      0.     39.3      16.8 297.6     337.0       .5      0.     62.4
  5   720.0    407.7    280.5    18.0      9      0.    123.8      23.1 188.6     312.4    117.8      0.      9.4
  6   720.0    353.8    317.1    18.0      9      0.     97.4      15.1 269.0     366.4      5.1     4.6    31.5
  7   720.0    543.9    355.7    28.0     14      0.     33.6      16.7 142.8     176.4     56.9     6.7   131.2
  8   720.0    376.4    349.0    26.0     13      0.    207.4       7.1 136.4     343.8     28.3    28.3     0.
  9   720.0    494.7    462.7    24.0     12      0.     48.4      26.4 177.0     225.5     20.4     0.     11.6
 10   720.0    335.1    313.4    20.0     10      0.    171.4      22.3 213.6     385.0     19.6      .0     2.1
 11   720.0    496.5    455.1    28.0     14      0.     83.0       9.6 140.7     223.8      6.1      .0    35.3
 12   720.0    279.9    279.7    16.0      8      0.    100.3      13.1 339.9     440.2       .2      .0     0.

TOT  8640.0   4851.9   4241.5   256.0    129      0.   1235.9    170.1  2554.3    3790.2    261.9    43.5   349.5
PCT             56.16    49.09    2.96            0.     14.30    13.76   29.56     43.87     3.03   16.62    4.04
```

LEGEND

AC	AIRCRAFT
RRS	READINESS REPORTING STATUS
OP	OPERATIONALLY
NOR	NOT OPERATIONALLY READY
RMC	REDUCED MATERIAL CONDITION
FSC	FULL SYSTEMS CAPABLE
SKED	SCHEDULED MAINTENANCE
UNSKED	UNSCHEDULED MAINTENANCE
NFE	NOT FULLY EQUIPPED
AWM	AWAITING MAINTENANCE
PCT	PERCENTAGE
TOT	TOTAL
FLT	FLIGHT
HRS	HOURS
NOTE	MOST UNITS ARE HOURS EXCEPTIONS ARE SORTIES & PERCENTAGES

Figure 2. Example Of Monthly RRS Report

```
                    A I R C R A F T   R E A D I N E S S   H I S T O R Y

                                   A N D   U T I L I Z A T I O N

                                        X Y Z Y X - A N E S

PAST 12 PERIODS            1      2      3      4      5      6      7      8      9     10     11     12
(12=MOST RECENT)       -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----

NO. OF AIRCRAFT           12     12     12     12     12     12     12     12     12     12     12     12
% OP READY              54.9   56.0   46.0   60.5   54.4   60.5   54.7   53.2   52.0   50.0   52.0   56.2
% FULL SYS CAP          47.3   47.6   39.6   55.0   49.4   53.6   48.2   46.8   47.8   46.8   46.8   49.1
% NOR SUPPLY            31.6   35.3   36.7   25.4   34.5   29.5   32.9   37.0   34.1   33.6   33.2   29.6
% SKED MAINT              0.     0.     0.     0.     0.     .0     0.     0.     0.     .0     0.     0.
% UNSKED MAINT          13.5    8.7   17.3   14.1   11.2   10.0   12.5    9.9   13.9   16.4   14.8   14.3
% NOR AWM MAINT         15.0   24.2   12.3   24.2   19.1   21.2   17.4   21.2   14.0   14.3   12.2   13.8
% NOT FULLY EQUIPPED     4.9    7.2    2.7    4.7    4.3    5.8    5.6    5.9    3.9    1.3    3.6    4.0
% RMC MAINT              2.7    1.3    3.7     .8     .7    1.1     .9     .5     .3    1.8    1.6    3.0
% RMC AWM MAINT         35.3   29.6    7.6   15.9   61.1   30.9   54.8   12.5    2.4   17.8   21.3   16.6


TOTAL FLIGHT HRS       280.0  256.0  260.0  280.0  240.0  256.0  276.0  236.0  232.0  288.0  276.0  256.0
TOTAL SORTIES            140    128    130    140    120    128    138    118    116    144    138    128

AC.UTILIZATION          23.3   21.3   21.7   23.3   20.0   21.3   23.0   19.7   19.3   24.0   23.0   21.3
```

LEGEND:

AC	AIRCRAFT
OP	OPERATIONAL
NOR	NOT OPERATIONALLY READY
RMC	REDUCED MATERIAL CONDITION
SKED	SCHEDULED MAINTENANCE
UNSKED	UNSCHEDULED MAINTENANCE
AWM	AWAITING MAINTENANCE

Figure 3. Example Of Twelve Month History Of RRS

The percentages are taken from the bottom of the RRS report for each of the preceding 12 reports. Aircraft utilization is the average number of flight hours per aircraft during the period. The column labeled 12 above the dashed line is the most recent report. This yearly summary presents information found in two 3-M reports (CNAP Gen Forms 4790/7 and 4790/5).

Manhour Summary - The manhour summary (see Figure 4) records manhour statistics by manhours of maintenance time required. The manhours and manhours per flight hour are given by 3-M records (CNAP Gen Form 4790/11). The manhour summary of the model does not go into the same detail with Preventive Maintenance (PM) as do the 3-M reports. PM is not considered in great detail because it is not the focus of the model.

The manhour summary also includes miscellaneous information applicable to model operation: number of II/d errors; number of missions flown, scrubbed or deferred; and the averages of the percent of time OR, and percent of missions flown. The last two are the system outputs described in Section III.

Additional Reports - Two additional status reports are the final permanent reports. These two reports include the total number of jobs by type, total elapsed maintenance time (EMT), total flights, total flight hours, and the location of each aircraft at the time of the report. These reports are useful for comparison when error rates are changed. Figure 5 shows typical examples of these reports.

Design of the Traces

The traces are outputs which are selected at the time the simulation is begun. At present, the traces are planned only for testing. For future training, such traces are useful for examining in detail the workings of the model. A typical example is shown in Figure 6. The figure shows model outputs with only pure traces selected (takeoffs, landings, aircraft movement, aircraft NOR job report, and mission deferral). The model offers more than 30 traces. These traces include detailed information on inputs, CM jobs, inspection reports, component failures, etc. The traces are essential for model testing. Traces are discussed further in the following subsection.

```
DIRECT MAINTENANCE MANHOURS PER FLIGHT HOUR
                    BY AIRCRAFT

                    XYZYY-AMFS

                  REPORT NO  25    FROM    0 TO 720
AIRCRAFT    TOT DAYS   TOTAL MANHRS    UNSKED       SKED       FLT HRS    DMMH/FH

    1         720.0       13656.0      2606.0    11052.0       568.0      24.05
    2         720.0       16300.0      5673.0    10627.0       532.0      30.64
    3         720.0       14905.0      3757.0    11148.0       530.0      28.12
    4         720.0       11845.0      1769.0    10076.0       498.0      23.79
    5         720.0       11719.0      2021.0     9698.0       478.0      24.52
    6         720.0       13570.0      2982.0    10588.0       558.0      24.32
    7         720.0       12591.0      1708.0    10883.0       544.0      23.15
    8         720.0       13374.0      2942.0    10432.0       504.0      26.54
    9         720.0       13159.0      1936.0    11223.0       562.0      23.41
   10         720.0       13669.0      2878.0    10791.0       526.0      25.99
   11         720.0       19046.0      8316.0    10730.0       548.0      34.76
   12         720.0       14283.0      4645.0     9638.0       464.0      30.78

  TOTAL      8640.0        1.7E 05    41233.0    1.3E 05      6312.0      26.63

  733TYPE IID ERRORS DISCOVERED TO DATE

        NO. OF MISSIONS (TOTAL)
SCHEDULED   FLOWN   DEFERRED   SCRUBBED
   2884      1578      2282        1306



                AVERAGE
    PCT OF READY              PCT MISSIONS FLOWN
  54.2  +/-      3.9         52.6
```

LEGEND

UNSKED	UNSCHEDULED MAINTENANCE MANHOURS
SKED	SCHEDULED MAINTENANCE MANHOURS
DMMH/FH	DIRECT MAINTENANCE MANHOURS/FLIGHT HOUR
+/-	INDICATES STANDARD DEVIATION
IID	TYPE II/D ERROR
E	INDICATES EXPONENTIAL NOTATION, I.E., 3.E01 = 3 X 10^{01} = 30

Figure 4. Example Of Maintenance Manhour Summary

```
                 STATUS REPORT AT 2880.0000 HOURS
NCR.POOL:  AIRCRAFT        FLIGHT HOURS        FLIGHTS
                  8             561.400            281
                 11             471.100            235
                 12             559.500            280
                  2             492.600            246
                  7             491.900            246
                 10             565.100            282
OP.MAINTENANCE:
                  9             461.000            231
                  1             477.000            238
                  6             525.900            263
FSC.POOL:
                  3             562.400            282
FLT.CERTIFIED.AIRCRAFT:
FLYING.AIRCRAFT:
TA.WORKSHOP:
                  5             614.700            307
                  4             811.400            406
PRIORITY.REPAIR:
```

```
                    AIRCRAFT STATUS REPORT FOR 2880.0000 HOURS

                                         TOTAL TIME (HOURS) SPENT:
     TOTAL JOBS OF TYPE:       WAIT   WAIT   WAIT   WAIT                WAIT    CDI
AC    TS   RIP   RR   ND       PERS   PAC    PARTS  MPERS    WORK       CDIS    WORK

 1     1    84   53   26        5.2  114.6  1483.3     .7    218.4      1.4     8.8
 2     1    99   40   31       26.0  102.0  1613.2   25.5    387.4      1.9    12.8
 3     2    83   54   26       34.7  134.4  1276.7    4.2    299.8      1.6    11.2
 4     1    62   49   19        5.7   98.6  1303.8     .3    165.4       .3     7.0
 5     0    64   39   11        2.4   57.0  1137.2    2.1    142.7       .7     6.5
 6     1    66   58   28        6.5   45.8  1073.3     .3    246.2      4.2    10.2
 7     1    71   69   18        4.7   40.6  1760.5    1.0    186.1     13.8     7.4
 8     0    56   56   29        8.2  108.0  1263.3   22.4    259.8       .3     9.3
 9     1    78   63   32       14.0   47.9  1317.8   12.2    229.5      1.3     9.5
10     0    72   58   20       16.5   17.6  1077.8    3.1    234.3      5.0    10.6
11     0    79   42   18       25.1  115.1  1249.4    1.4    385.7      4.1    14.6
12     2    58   41   18       18.8   65.8  1091.6   28.5    277.1      2.4    11.5
TOT   10   872  622  276     2.E 02 9.E 02 2.E 04 1.E 02 3.E 03 4.E 01 1.E 02
```

LEGEND:

E INDICATES EXPONENTIAL NOTATION, I.E.,
$3.E\ 01 = 3 \times 10^{01} = 30$

Figure 5. Examples Of Additional Status Reports

```
NCR JOBS FOR AC   1:    1
PLANE CANNOT BE REPAIRED WITH NOR FM JOBS

-< TAKE-OFF: AC  2  TIME  661.3000 HOURS

-< TAKE-OFF: AC  3  TIME  661.3000 HOURS

>- LANDING: AIRCRAFT   4  TIME  662.0000 HOURS  WITH 116.80 FLIGHT HOURS AND   69 FLIGHTS TO DATE.

>- LANDING: AIRCRAFT   5  TIME  662.0000 HOURS  WITH 117.40 FLIGHT HOURS AND   70 FLIGHTS TO DATE.

>- LANDING: AIRCRAFT   2  TIME  662.0000 HOURS  WITH 118.20 FLIGHT HOURS AND   68 FLIGHTS TO DATE.

>- LANDING: AIRCRAFT   3  TIME  662.0000 HOURS  WITH 114.50 FLIGHT HOURS AND   68 FLIGHTS TO DATE.


MISSION   745832 DEFERRED AT  662.0000 HOURS
NOR JOBS FOR AC   4:    0


MISSION   745832 DEFERRED AT  662.0030 HOURS
FAILURE: CT  1 AC  5 CRIT NOR  JOB   753048
NOR JOBS FOR AC   5:    2
INDUCTING AIRCRAFT   1 FROM FSC
PLANE CANNOT BE REPAIRED WITH NOR FM JOBS
NOR JOBS FOR AC   2:    0

-< TAKE-OFF: AC  2  TIME  662.0030 HOURS

-< TAKE-OFF: AC  4  TIME  662.0030 HOURS
NOR JOBS FOR AC   3:    0
NOR JOBS FOR AC   1:    0

-< TAKE-OFF: AC  3  TIME  663.5000 HOURS

-< TAKE-OFF: AC  1  TIME  663.5000 HOURS

>- LANDING: AIRCRAFT   2  TIME  663.5030 HOURS  WITH 119.70 FLIGHT HOURS AND   69 FLIGHTS TO DATE.

>- LANDING: AIRCRAFT   4  TIME  663.5030 HOURS  WITH 118.30 FLIGHT HOURS AND   70 FLIGHTS TO DATE.
```

LEGEND:

CT	COMPONENT TYPE
CRIT	CRITICALITY OF JOB WHETHER THIS JOB RENDERS THE AIRCRAFT "OR" OR "NOR"

Figure 6. Example of Traces

TESTING AND VALIDATION

Testing is a process to expose problems with the model. When the testing has been completed, validation of the completed model can proceed. Validation is a check of the consistency of the model outputs with actual flight records. Before the model can be trusted as a predictor, it must be shown to reproduce relevant features of known results.

This sub-section describes briefly some of the procedures used in testing the model:

- Top-down testing
- Manipulation of input data
- The use of traces

Top-Down Testing

Top-down testing follows from top-down design. In top-down design (described earlier in this section and demonstrated in Appendix A), the important general features are designed first. Details are added in successive stages later. Top-down testing proceeds parallel to the design as the design is implemented.

The most important advantage of top down testing is that the large mistakes that affect most of the model are discovered at an early stage in program development. As implementation and testing of the model proceed, the detected mistakes are smaller, hence easier to correct.

Manipulation of Input Data

While the top-down testing explained in the last two paragraphs provides the basic testing philosophy, most of the actual errors are detected by systematically varying the input data. Systematically changing the inputs changes the output. Only in rare cases is the output known for a given set of inputs, therefore, the output must be estimated. The following techniques to estimate change in output for a given input change have proven helpful:

- Using simple data
- Using small variations
- Using extreme data
- Using known data (validation)

Using Simple Data - It is very difficult to estimate how 12 aircraft with hundreds of components and several hundred men will interact. However, it is often possible to understand how a single aircraft with only two components and two maintenance personnel will react. By using very simple data, in combination with the following techniques, many problems can be isolated and corrected.

Using Small Variations - The purpose of these techniques is to predict specific levels of an output. If such a prediction is not possible, a reasonable substitute is to predict general changes of an output with a controlled change of input. By changing only a single parameter, a qualitative change in output can often be estimated and used as a basis for determining gross errors.

For example, suppose manpower is the only input parameter changed. It is reasonable to assume that a 10 percent increase in personnel should probably increase operational readiness by only a small amount. Therefore, model outputs showing a large change in operational readiness, with a 10 percent change in personnel suggest probable errors in the program. The errors can be isolated by further systematic changes in the input.

Using Extreme Data - Occasionally, making very large changes in the input produces output values that can be estimated. Input data are considered extreme if they are so large (or so small) that further changes will not affect the output. In many cases, extreme data eliminate complexity in the model. In the simpler extreme case, outputs can be predicted and compared with actual model results.

Extreme data can be entered for the number of personnel at the work centers. If there are no people assigned to any of the work centers, there should be no maintenance work done. The other extreme is 200 men at each work center. Assigning 200 men to each work center (normally there are 2 to 10 men) assures that maintenance personnel will always be available. With so many people at a work center, no delays should be caused by lack of maintenance personnel.

Using Known Data (Validation) - Using data from actual statistics is validation. In addition to normal validation procedures, actual statistics can serve as a baseline from which to use the techniques previously mentioned: small variations and extreme data.

The Use of Traces

Normally only the output reports are produced by a model run. More detailed descriptions of the workings of the model are occasionally desirable to check out the model. Earlier in this section, the nature of the trace outputs was described. The property that makes traces useful for testing is the ability to duplicate runs exactly, including random failure (described in Section III).

When additional detail is required, the identical simulation can be rerun, obtaining more detailed output. If, for example, a particular month has very few flight hours, the same simulation can be rerun, but with output information on the times of all take offs and landings. Examination of the outputs at the more detailed level facilitates isolation of errors or anomalies.

c

The types of information available using traces include detailed information on the following:

- jobs (start-time, duration)
- manpower requirements and allocation
- inspection results and component failures
- PM scheduling and requirements
- model inputs
- mission scheduling

The traces can be indexed by aircraft or job. Histories of a single aircraft or a single job can be followed in great detail during a model run.

SECTION V

INPUTS REQUIRED FOR THE MODEL

INTRODUCTION

Before the simulation is run, details of the aircraft, maintenance personnel, planned maintenance, etc., must be supplied to the computer. Input data typical of actual flight and maintenance conditions are used for baseline studies and to check out the model. These typical data have been derived from analysis of Naval 3-M reports. Model runs with data from actual flight statistics provide a frame of reference. Subsequent runs with systematic changes of input parameters provide insight into the maintenance process and indicate quantitatively the effect of the hypothetical input variations.

The discussion of inputs in this section is divided into the following subsections:

- Model Input Requirements
- Data Sources
- Estimation of Corrective Maintenance Error Rates
- Generating Component Failures

The first subsection, Model Input Requirements, includes detailed information about the nature of the inputs and about how the inputs are derived.

The second subsection, Data Sources, describes the sources used to discover proper inputs. These sources of the input data frequently do not give the precise information required by the model. Therefore, the relevant information must be extracted from available statistics.

The third subsection, Estimation of Corrective Maintenance Error Rates, shows how quantitative values were obtained for the errors made by personnel involved in organizational maintenance. The majority of these errors are not explicitly indicated in 3-M statistics. They must be inferred.

The fourth subsection, Generating Component Failures, discusses how component failures are generated by the model. Using the error rates explained in the previous subsection, component failures can be separated into those caused by actual component failure and those caused by human error.

MODEL INPUT REQUIREMENTS

In order to set up and execute a simulation run, the model program requires six types of input data. The model program requires that each data type be represented by specific characteristics with each characteristic in a specific form.

There are four specified forms of input data. Each unit of data must take one of the following forms:

- Integers - integers are whole numbers (no fractional part). They are used to describe a particular quantity or identification number. For example, 3 maintenance personnel and aircraft number 124 are integers.

- Real numbers - the real numbers include numbers with a decimal fraction. They may describe quantity or probability. Examples of real numbers are 12.86 hours as the mean time between failures, and .64 as the probability that the failure of a particular component renders the aircraft NOR.

- Compound variables - compound variables express the probabilities of occurrence when several alternatives are possible. An example is the probabilities determining which type of job will be generated when a component fails. There are three possible types of jobs: troubleshoot, repair-in-place, and remove/replace. The probability that each occurs can be input to the computer using a single compound variable.

- Distribution - a distribution is a set of values which could be displayed graphically. A distribution expresses the possible value a variable can have as well as the probability that each of the values occurs. Elapsed maintenance time (EMT) for each component is described by a distribution. The distribution of elapsed maintenance times for a particular component gives the probability that the EMT will be between 4 hours and 4.5 hours, for instance. Distributions are frequently derived from 3-M statistics, although nonempirical distributions can be used as well.

An example of a distribution is shown in Figure 7. The figure shows a cumulative histogram of the elapsed maintenance time (EMT). The ordinate is the number of hours required to complete a job; the abscissa is the probability that the job could be completed in less than a given time. For instance, in the figure, the probability is .75 that a job could be completed in less than 5.1 hours (see point A of Figure 7). These probabilities are referred to as cumulative because the probabilities for all lesser times, added together, constitute the cumulative probability. The maximum possible cumulative probability is 1.00.

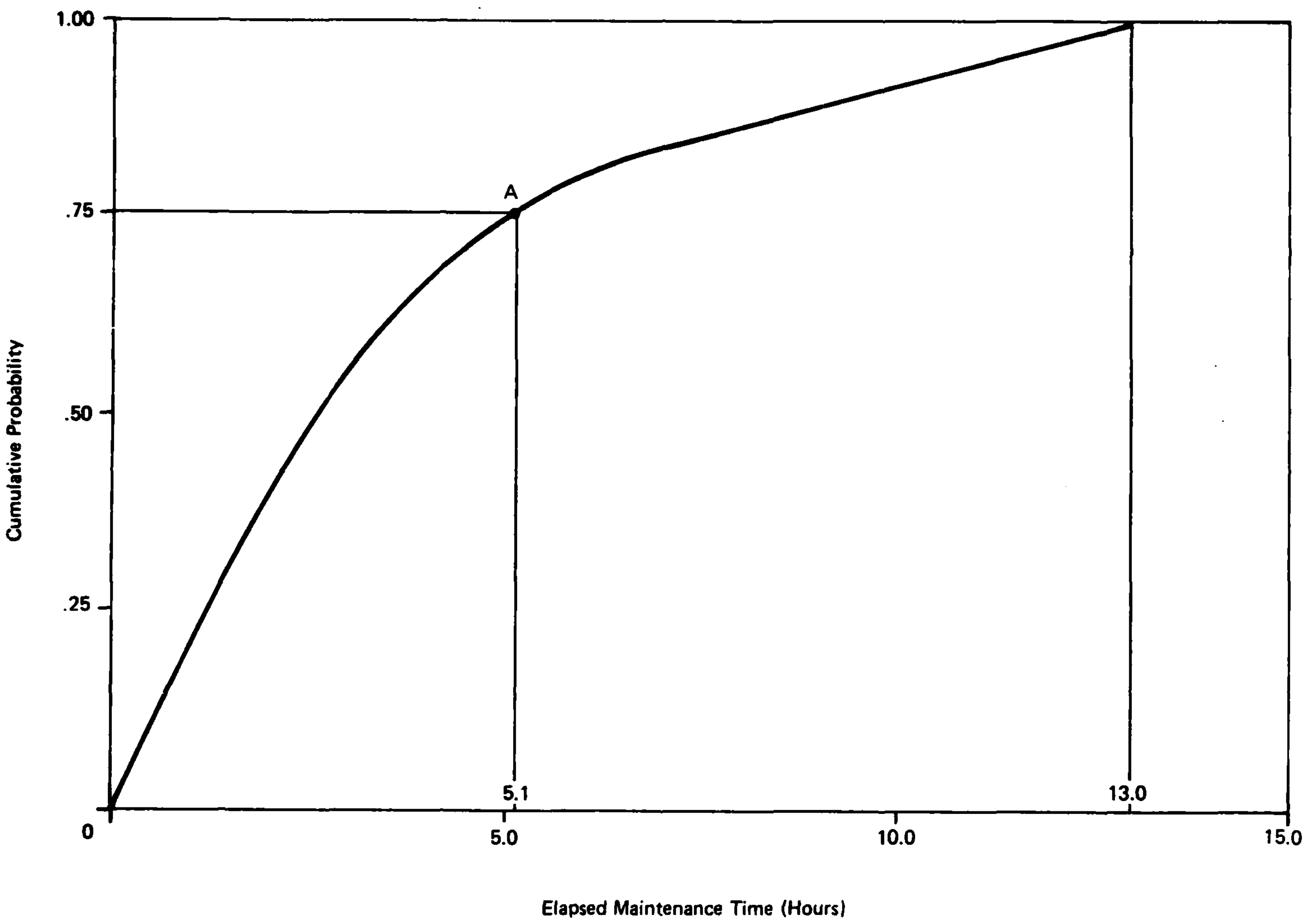


Figure 7. Example of a Cumulative Distribution

The six types of input data required by the model program to set up and execute a simulation run are discussed below. They are:

- Subsystem Data
- Component Data
- Manpower Data
- Planned Maintenance Data
- Multipliers Data
- Run Data

Subsystem Data

For model runs, the computer requires three variables for each subsystem of the aircraft:

- Criticality
- Facilities
- Facilities Delay Time

The data necessary to determine the values of these variables for actual flights are obtained from the Readiness Reporting Status (RRS) statistics by Work Unit Codes. The RRS is part of the 3-M Data Summary.

1. The first variable, CRITICALITY, expresses the probability that a particular component failure in the subsystem causes the aircraft to be NOR (not operationally ready). CRITICALITY is a real variable.

CRITICALITY is the quotient of a fraction whose numerator is the number of times the aircraft is not operationally ready because of unscheduled maintenance (sum of NORM-U and NORS). The denominator is the number of times a readiness reporting status is recorded (total RRS). The calculated value cannot exceed 1.00. It is rounded off to the nearest .01.

2. FACILITIES expresses the probabilities that facilities required to perform maintenance on the subsystem are not available. Like criticality, it is a real variable that cannot exceed 1.00 and rounded to the nearest .01.

The FACILITIES entry is the quotient of a fraction whose numerator is the number of times the aircraft is awaiting maintenance because facilities are not available. (AWM codes 1, 2, and 5). The denominator is the total RRS. The calculated value cannot exceed 1.00.

3. FACILITIES DELAY TIME expresses the probabilities associated with delay times when facilities are not available. FACILITIES DELAY TIME is a distribution. The distribution is formed by making a graph of cumulative probabilities against delay time using AWM codes 1, 2, and 5 from the 3-M summary.

Component Data

A component is a subsystem combined with a work center (a technical maintenance specialty area). Each component requires the following 14 variables for definition.

1. SUBSYSTEM is an index number identifying the subsystem to which the component belongs. Subsystem is an integer variable.

2. WORK CENTER is an index number identifying the work center that maintains the component. Work center is an integer variable.

3. RIP INVENTORY expresses the probabilities that a part required for a Repair-In-Place (RIP) action is not available (Missing) for at least six days. RIP INVENTORY is determined from the 3-M action codes for repair-in-place actions: B, Q, and C. RIP INVENTORY is determined by dividing the number of B, Q, and C actions to the particular subsystem at a particular work center. B, Q, and C are 3-M action taken codes. RIP INVENTORY is a real variable given to the nearest .01.

4. RIP PARTS DELIVERY TIME expresses the distribution of delays (in days) required in awaiting parts for repair-in-place actions. The distribution is determined by compiling a histogram of times spent awaiting maintenance using the repair-in-place action codes B, Q, and C that were discussed in connection with RIP INVENTORY.

5. RR INVENTORY expresses the probability that a part required for a Remove/Replace (RR) action is not available within six days. It is calculated in the same manner as the real variable RIP INVENTORY. The necessary data are obtained from the action taken codes for remove/replace actions.

6. RR PARTS DELIVERY TIME is a distribution. It is analogous to RIP PARTS DELIVERY except R and U codes are used for remove/replace actions.

7. RR INVENTORY PART BAD expresses the probability that a part obtained from inventory for a remove/replace action is NOT BAD (good). RR INVENTORY PART BAD is a real variable. The value is calculated by first dividing the number of times a bad part has been encountered by the total number of remove/replace actions and then subtracting this value from 1.00.

8. ACTION TAKEN has three steps, designated "1" through "3", that express the probabilities that a maintenance problem requires either Troubleshooting (T/S), Repair-In-Place (RIP), or Remove/Replace (RR) actions. ACTION TAKEN is a compound variable.

The T/S probability is calculated by dividing the recorded troubleshooting actions by the sum of troubleshooting, repair-in-place, and remove/replace actions for a particular component. The RIP probability is calculated by dividing the recorded repair-in-place actions by the same sum. The RR probability is calculated by dividing the number of remove/replace actions by the sum. The sum of these three probabilities is 1.00.

9. ERROR I (unjustified removal) expresses the probability of committing a Type I error for the specified component in an RR action. ERROR I is a real variable.

10. ERROR II/D (undetected error/damage) expresses the probability of committing a Type II/d error in any corrective maintenance action. ERROR II/D is a real variable.

11. MEAN TIME BETWEEN FAILURES (MTBF) is the number of flight hours between component failures for a given component. MTBF is a real variable. The value is the quotient of a fraction whose denominator is the total number of flight hours of the sample used. The numerator is the number of Corrective Maintenance Actions (CMAs) for the component of concern during the flight hours mentioned above. Failures include corrective maintenance actions resulting from Type I and Type II/d errors. The total flight hours are obtained from Flight Records Statistics. For the purposes of this report, MTBF and Mean Time Between Corrective Maintenance Actions (MTBCMA) may be considered equivalent.

The number of actions resulting from Type II/d errors is determined by multiplying the total corrective maintenance actions by the II/d error rate. The number of Type I errors is obtained by multiplying the Remove/Replace actions by the Type I error rate. Using the number of Type I and Type II/d errors, the Mean Time Between Actual Defects (MTBAD) is determined in the computer. The MTBAD is the MTBF with CMAs resulting from errors excluded.

12. MEAN TIME BETWEEN NO DEFECT (MTBND) is the mean number of elapsed flight hours between each two occurrences when the component is erroneously declared bad. The value is determined by dividing the total number of flight hours by the number of no discrepancy reports against the component. MEAN TIME BETWEEN NO DEFECT is a real variable.

13. MEAN TECHNICIANS is the average number of personnel needed to perform corrective maintenance on the component of concern. MEAN TECHNICIANS is a real variable.

14. ELAPSED MAINTENANCE HOURS (EMH) is a distribution of the elapsed maintenance times (in hours) for a particular component. The values are calculated from actual component elapsed maintenance time data that has been processed to obtain cumulative percent of occurrence values for increments of 0.5 hours.

Manpower Data

In the model, personnel is represented as belonging to work centers. A work center identifies a group of specialized personnel responsible for a designated area of aircraft maintenance.

1. NUMBER OF WORK CENTERS is an integer variable.

2. NUMBER OF SHIFTS is the number of different shifts of maintenance personnel that work during a given day. It is an integer variable.

3. LENGTH OF SHIFT is the duration that each shift must work. It is a real variable.

4. NUMBER OF CDIs is the number of Collateral Duty Inspectors (CDIs) available to work at a given work center for a given shift.

5. NUMBER OF SENIORS is the number of senior technicians available to work at a given work center for a given shift.

6. NUMBER OF JUNIORS is the number of junior technicians available to work at a given work center for a given shift.

Planned Maintenance Data

Planned Maintenance (PM) data cover the planned maintenance actions that must be performed on a regular basis. These actions are included in the model because they impose a significant workload on the work centers.

The model performs the following six types of planned maintenance:

- Special Inspection - determined by flight hours
- Special Inspection - determined by calendar time
- Special Inspection - determined by flights
- Phased Inspection - determined by flight hours
- Turnaround Inspection - determined by flights
- Daily Inspection - determined by calendar time (may also depend on flight hours and occurrence of maintenance)

The model identifies the different planned maintenance requirements by performance intervals. Each planned maintenance requirement is divided into several segments. Each segment requires a specified amount of time for the work to be performed. The work done in a segment may require work at several work centers. Before a new segment can be started, work at all of the work centers of the previous segment must be completed. The following characteristics are required to describe each PM requirement:

1. PM TYPE designates which of the six types of PM mentioned above applies; e.g., Daily Inspection. A number is assigned to each of the six types. PM TYPE is an integer variable. Although PM TYPE is not actually input to the computer, the information is required to group the PM requirements by type.

2. NUMBER OF SEGMENTS is the number of different segments in a PM requirement. NUMBER OF SEGMENTS is an integer variable.

3. SEGMENT TIME is the time (in minutes) required to complete each of the segments. SEGMENT TIME is a real variable. Each of the segments has a SEGMENT TIME.

4. NUMBER OF WORK CENTERS for each segment is the number of work centers where work must be done during the segment. NUMBER OF WORK CENTERS is an integer variable.

5. PM WORK CENTER is the work center where work must be performed for each of the various jobs in a particular segment. PM WORK CENTER is an integer variable.

6. PM NUMBER OF MEN is the number of maintenance personnel required at a particular work center for a particular segment. PM NUMBER OF MEN is an integer variable.

Multipliers Data

Multipliers can be used to make uniform changes of human performance variables. For each of the components or subsystems, the chosen variable is multiplied by the data multiplier in question. A data multiplier of 1.00 leaves values unchanged. For example, the Type I error rate for all components can be reduced to one-half of its original value by setting the ERROR TYPE I MULTIPLIER equal to one-half. For each variable, a data multiplier will modify the associated variable for all components in a uniform manner. The following multipliers are used for data inputs:

- ERROR TYPE I MULTIPLIER
- ERROR TYPE II/D MULTIPLIER
- ELAPSED MAINTENANCE HOURS (EM HOURS) MULTIPLIER
- PARTS BAD FROM SUPPLY MULTIPLIER
- NO DEFECT (UNDISCOVERED PILOT SQUAWKS) MULTIPLIER

The multipliers can be used to reduce or increase any of the above parameters for all of the components. They are real variables.

Run Data

The run data include other miscellaneous entries such as mission schedule, report intervals, traces, and RUN DURATION. Mission schedule includes a MISSION START TIME and a MISSION DURATION for each mission. The report intervals are variables that adjust the time between reports. Traces are for testing and have been previously discussed. RUN DURATION is the duration of the simulation in days.

Summary

For convenient reference, the prominent data types and the forms they take are shown in Table 5.

TABLE 5. PROMINENT DATA TYPES

FORMS OF INPUT DATA	VARIABLE	DATA TYPE
Integer Variables	Subsystem	Component
	Work Center	Component
	Number of Work Centers	Manpower
	Number of Shifts	Manpower
	Number of CDI's	Manpower
	Number of Seniors	Manpower
	Number of Juniors	Manpower
	PM Type	Planned Maintenance
	Number of Segments	Planned Maintenance
	Number of Work Centers	Planned Maintenance
	PM Work Center	Planned Maintenance
	PM Number of Men	Planned Maintenance
Real Variables	Criticality*	Subsystem
	Facilities*	Subsystem
	RIP Inventory*	Component
	RR Inventory *	Component
	RR Inventory Part Bad*	Component
	Error I*	Component
	Error II/d*	Component
	MTBF	Component
	MTBND	Component
	Mean Technicians	Component
	Length of Shift	Manpower
	Segment Time	Planned Maintenance
	Error Type I Multiplier	Multiplier
	Error Type II/d Multiplier	Multiplier
	Elapsed Maintenance Hours Multiplier	Multiplier
	Parts Bad From Supply Multiplier	Multiplier
	No Defect Multiplier	Multiplier
Compound Variable	Action Taken*	Component
Distribution	Facilities Delay Time*	Subsystem
	RIP Parts Delivery Time*	Component
	RR Parts Delivery Time*	Component
	Elapsed Maintenance Hours*	Component

* = probability

DATA SOURCES

The Navy 3-M System contains a Maintenance Data Collection Subsystem that furnishes statistical data products to the Naval Aviation Maintenance Program (NAMP). Six categories of maintenance data are collected and processed. Two of the categories, Maintenance Data Reporting (MDR) and Aircraft Statistical Data (ASD), have information useful to the AMES Project.

The collected data are transcribed onto specific electric accounting machine (EAM) cards. These cards are submitted monthly to the maintenance Support Office for updating of the MDR History File.

A brief description of the selected data records is presented below in the following sequence:

- Support Action Record
- On Equipment Action Record
- Removal Action Record
- AIMD Action Record
- Technical Directive Compliance Record
- Aircraft Statistical Data Record
- Aircraft Flight Data Record

Support Action Record

This record is Card Type 01. It documents maintenance manhours expended on repetitive nonrepair type maintenance which are not recorded on the Visual Display System/Maintenance Action Form (VIDS/MAF). The following Level 1 information on the record is of interest to the AMES Project:

- Both the Support Code and the Type Maintenance Code show the repetitive type maintenance performed.

- The Number of Items Receiving Maintenance entry is used to determine hours per item.

- The Work Center entry shows the technical skill category that accomplished the work.

- The Total Number of Hours Expended by Maintenance Personnel entry shows how many manhours were needed to accomplish the work.

On Equipment Action Record

This record is Card Type 11. It documents corrective and planned maintenance actions performed on a specific aircraft. The following Level 1 information on this record is of interest to the AMES Project.

- The Work Unit Code (WUC) shows how often maintenance was performed on a system, subsystem or component.

- The When Discovered Code shows how often a need for corrective maintenance occurred when performing a scheduled maintenance function.

- The Action Taken Code shows the WUCs requiring troubleshooting and/or repair. The codes also show the different repair actions such as repair-in-place, remove/replace, cannibalization, awaiting parts, and adjustments.

- The Number of Items Receiving Maintenance entry helps in evaluating actual number of manhours expended on one item.

- Manhours and Elapsed Maintenance Time entries show information on number of personnel used and how long it took to accomplish the maintenance task.

- Malfunction Codes, in particular the conditional codes, help identify errors committed at the organizational maintenance level.

Removal Action Record

This record is Card Type 21. It documents the scheduled removal components and the Level 1 corrective removal actions for repairable components sent to the supporting Aircraft Intermedite Maintenance Department (AIMD). The maintenance actions are documented for specific aircraft. This record is of interest because it will provide the corrective removal actions requiring repair by a supporting AIMD. Scheduled removal actions specify the repair or disposal action.

AIMD Action Record

This record is Card Type 31. It documents the work performed on repairable components received from the Organizational Maintenance Departments supported by the AIMD. Maintenance actions performed are recorded using the same Job Control Number (JCN) assigned by the supported organization. This record is of interest because it will provide what was the final result of the corrective organizational removal actions. Information provided will assist in identifying organizational maintenance errors and their causes.

Technical Directive Compliance Record

This record is Card Type 41. It documents completed technical directives issued for the aircraft and the maintenance performed to accomplish them. Technical directive requirements include all types of changes which affect the maintenance and operation of aircraft equipment. Effect on maintenance work load and effectiveness measures for the operating unit will be provided by this record. The following Level 1 information is of interest to the AMES Project.

- Work Unit Code identifies equipment affected by technical directives.

- Items Processed, Manhours, and Elapsed Maintenance Time entries show the number of men assigned and elapsed time to accomplish the technical directive.

- Work Center Code shows the technical skill category of assigned personnel.

Aircraft Statistical Data Record

This record is Card Type 71. It documents the number of hours a Not Operationally ready (NOR) or Reduced Material Condition (RMC) status existed for a specific aircraft. Also shown are any awaiting maintenance time, the reason for the wait, and the equipment responsible for the NOR or RMC status. This record shows the equipment items that frequently impact the performance measures of an operational unit.

Aircraft Flight Data Record

This record is Card Type 76. It documents the number of flights, the total flight hours and the type and number of landings that occurred on a specific date for a specific aircraft. Information on this record can be used in the development of data required by the Flight Orders input to the AMES Model.

ESTIMATION OF CORRECTIVE MAINTENANCE ERROR RATES

Human errors are responsible for a significant fraction of the total number of aircraft corrective maintenance actions. Our conservative estimate is that at least 20 percent of the non-cannibalization corrective maintenance actions on aircraft equipment are caused by human errors. Treatment of human errors when performing corrective maintenance has been included in the AMES model.

Before the effect of maintenance errors can be studied with the model, a baseline needs to be established, i.e., the current level of errors. Other human performance variables such as elapsed maintenance time (EMT) or maintenance manhours are determined routinely by the 3-M system. As part of this project, corrective maintenance error rates have been conservatively determined at the subsystem level of aircraft equipment. Knowledge of error rates permits calculation of improvements in equipment performance that result from a reduction in human errors.

All of the errors discovered in our analysis are errors that resulted in the generation of additional jobs. Errors which are detected by the CDI or the maintenance technician before completion of the job result in increased performance time. These errors were not detectable by the analysis methods used. Also, Type I errors during Repair-in-Place (RIP) actions cannot be detected with normal 3-M data. Since RIP actions comprise over half of all corrective maintenance actions (excluding cannibalization), the baseline for maintenance errors is understated. The methods for determining error rates are described briefly under the following headings:

- Database
- Measurement of Type I errors
- Measurement of Type II and Type d errors

Database

Data collected and processed by the 3-M System is used as the database to estimate the organizational level aircraft maintenance error rate. 3-M data records provide a dynamic history of aircraft maintenance actions. The maintenance actions are recorded for equipment in its intended operational environment and controlled by the maintenance organization. Maintenance actions are recorded daily as they occur and compiled monthly for machine processing into various reports.

The data and reports are designed to provide timely information to Naval Aviation Maintenance Program managers in order to evaluate, correct and improve maintenance performance. A representative sample of 3-M data records was obtained and subjected to careful analysis and processing.

To determine the equipment error rate statistic, we used a sample of one year of data records for a specific type of aircraft, maintained and operated by six organizations over the same period. Also, one 3-M report was processed to determine the error rate statistic for the Type I error category. Data records and 3-M reports used are described in Table 6. A more complete description can be found in an earlier report, Acquisition and Analysis of Navy 3-M Data.

Error Rate is defined as a statistical measure of the occurrence of one or more of the defined error categories. It is expressed as a percent of corrective maintenance actions (E/CMA) performed. Error rates are grouped for Work Unit Codes (WUCs) at the subsystem level by action work center. For this project, the subsystem level is identified by the first three digits of the WUC.

Measurement of Type I Errors

The Type I error rate for aircraft equipment was calculated from data provided by 3-M report MSOD-4790.A2551-01, No Defect Item Analysis Summary. This report indicates those items removed from the aircraft that were found to function properly (No Defect) by intermediate maintenance. The percentage of A799 (No Defect) items reported represent a portion of the Type I error rate.

The percent No Defect items are the declared bad but actually good repairable equipment items removed by organizational maintenance personnel, expressed as a percentage of the unscheduled repairable items removed. The percentage is for all organizational maintenance work centers in all organizations maintaining the specified aircraft.

The Type I error rate calculated from this report does not include false removals of nonrepairable equipment or erroneous repair-in-place actions. The latter ommission is important since repair-in-place actions represent 60-65 percent of corrective maintenance actions (excluding cannibalization actions). The number of Type I errors noted would nearly double even if errors during repair-in-place were only one-half of the errors during remove/replace. Unfortunately, errors during repair-in-place cannot be detected with the current 3-M data.

TABLE 6. SELECTED 3-M DATA RECORDS AND REPORTS

CARD TYPE	RECORD NAME	RECORD DESCRIPTION
11	On Equipment (Maintenance) Action Record	Prepared from information on the VIDS/MAF. Documents corrective and planned maintenance actions. Actions are documented for a specific organization and for a specific aircraft.
21	Removal (Maintenance) Action Record	Prepared from information on the VIDS/MAF. Documents scheduled component removal and corrective maintenance actions involving removal of repairable components. Actions are documented for a specific organization and for a specific aircraft.
76	Aircraft Flight Data Record	Prepared from information on Part C of Naval Aircraft Flight Record. Documents flight information for a specific day and aircraft. Includes number of flights and total flight hours.
Report MSOD4790. A2551-01	No Defect Item Analysis Summary	Prepared from Card Code 11, 21, 31, and 34. The report identifies the No Defect Actions for a given repairable component as a percentage of the total no defect actions, processed at intermediate level maintenance activities.

The report summarizes the percent of No Defect items to the fourth digit (component level) of the Work Unit Code (WUC) for the equipment. Since the AMES Model simulates maintenance only to the third digit (subsystem level) of the WUC, the report data was converted to present the percentage of No Defect items at the third digit level of the WUC.

Measurement of Type II and Type d Errors

The manifestation of both Type II (undiagnosed failure) and Type d (damage) errors is the same in the 3-M statistics. Both error types have the same symptoms. A corrected discrepancy is followed soon by another discrepancy of the same or related component. An engineering analysis of both discrepancies determines if an error was made or if the two discrepancies were independent. In some error occurrences, Type II error can easily be distinguished from a Type d error. However, many error occurrences require engineering analysis to differentiate between error types. Because Type II and Type d errors both have similar effects and are treated in the same way by the model, it was not necessary to separate the two error types.

Figure 8 describes briefly the process used to identify the errors. The first step (labeled 1) is to choose a sample aircraft. Recall that the data base contains maintenance records for six squadrons, or approximately 72 aircraft. To reduce the error analysis to a manageable task, a minimum sample of 24 aircraft (four from each squadron) was established. The aircraft flight records were examined to eliminate atypical aircraft (those with too few flights).

The remaining aircraft were listed by squadron and aircraft bureau number i.e., a number unique to each aircraft. Bias in selection of sample aircraft was eliminated by developing a random selection scheme. A table of random numbers was used to rearrange the aircraft in each squadron in a random sequence. The first four aircraft in the random sequence were used for error analysis.

The next step (labeled 2 in Figure 8) was to obtain a hard copy time ordered history of the 3-M flight and maintenance records. The flight record information was arranged in a column-row matrix by use of a computer. The columns contain the information on the flight record. Each row (or line) represents one flight record sequenced by flight date.

Unscheduled maintenance (3-M type Maintenance Code B) record information was also arranged in a column-row matrix by use of a computer. The columns contain selected information on the maintenance record. Each row (or line) represents one maintenance record of the corrective maintenance action (CMA) performed to clear a discrepancy against the aircraft. The CMA's are listed in a time ordered sequence of WUC numbers by action date. The list results in a time ordered sequence of CMAs performed on each aircraft system.

Starting with the first record for each system, succeeding records are examined in sequence (step 3 in Figure 8). The flight list is checked for total number of flights between action dates. If two or fewer flights have taken place, a possible Type II or Type d error has occurred (step 4). Both CMAs are then analyzed (step 5) to determine if an error has occurred. Analysis includes:

- Check Job Control Number (JCN) date and sequence to verify latest CMA occurred after previous CMA was cleared on action date.

- Determine if CMAs are related by analyzing information listed for each CMA, (i.e. equipment WUC, manhours, elapsed maintenance time, When Discovered (WD), Malfunction (MALF), Action Taken (AT), and Items Processed.) Check action taken column of previous CMA for letter A (no repair required). When letter A is recorded, a possible D error has occurred. Another D error symptom is when CMAs are performed on a system after successive flights and then cease or return to the usual discrepancy pattern.

- If not familiar with equipment, check the aircraft maintenance manuals for system theory and maintenance procedures to determine if latest CMA is related (i.e. functional dependance, directly connected or removed for access) to previous CMA. When an error is found (step 6), the CMAs are recorded as a D/d error (step 7).

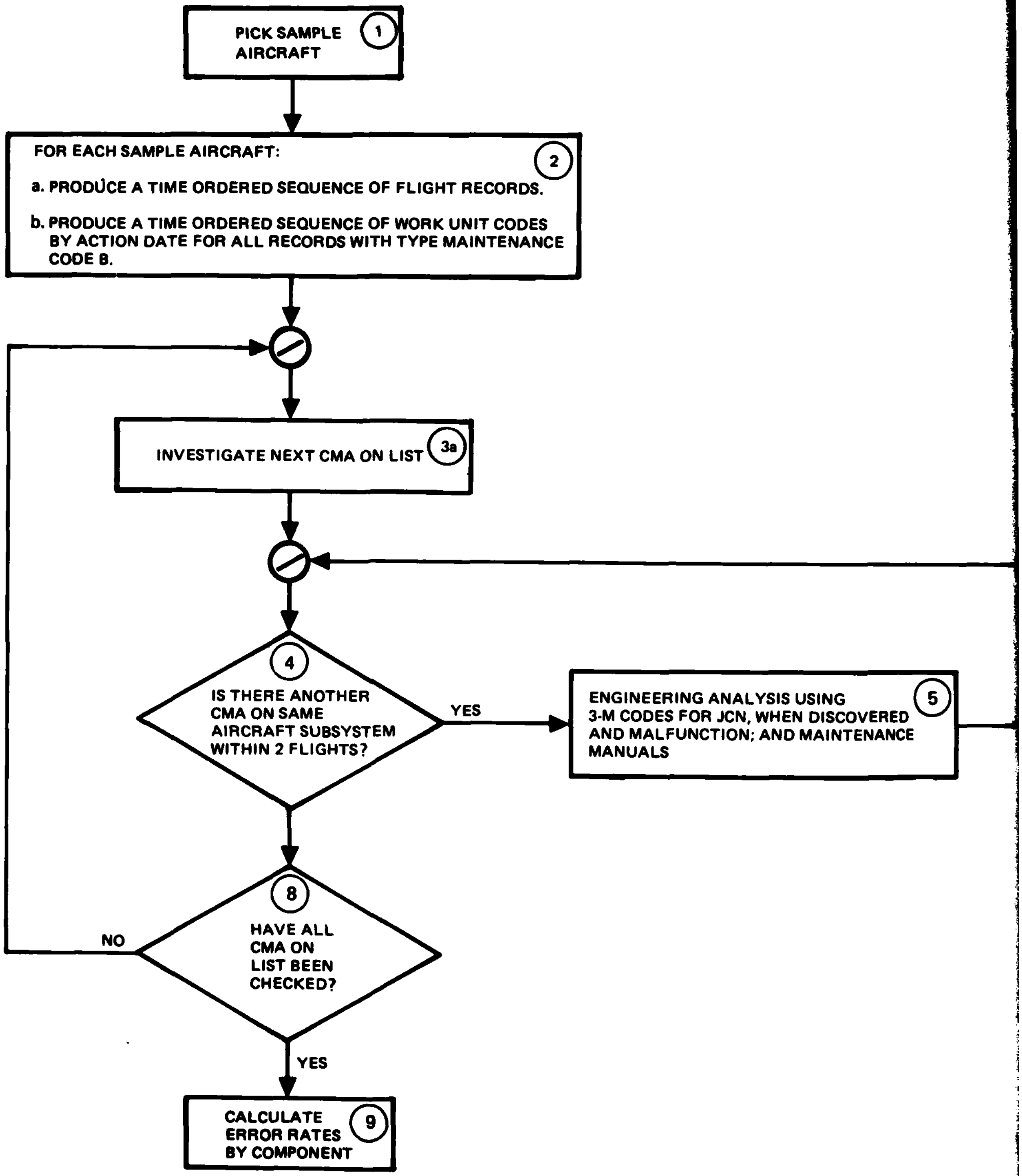
After analysis of all sample aircraft are complete (step 8), the errors and CMAs are totalled and recorded for each aircraft equipment subsystem. For each equipment subsystem, the total errors are divided by the total CMAs to obtain the estimate of the subsystem error rate (step 9).

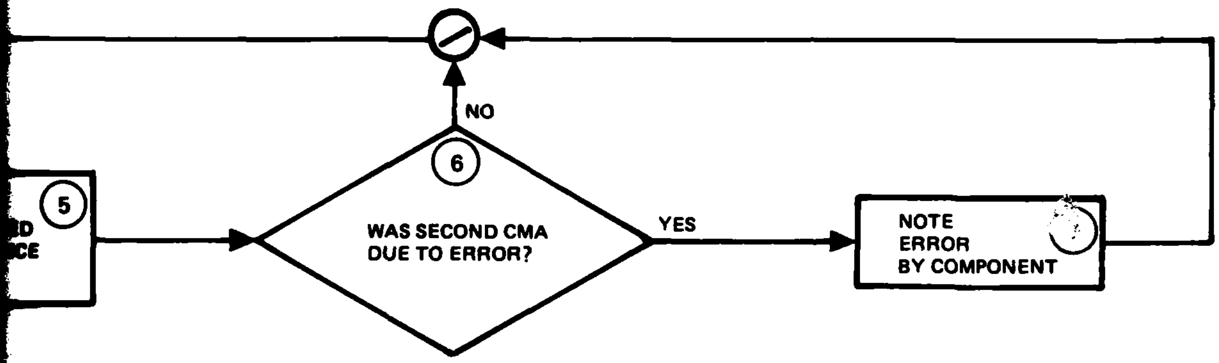
GENERATING COMPONENT FAILURES

Any reported problem with the aircraft (not including technical directives, corrosion control, or planned maintenance) results in a 3-M report. The problems are called discrepancies. Figure 9 shows how reported discrepancies result in jobs. Briefly some of the terms can be explained as follows:

No Defect Squawk - if a pilot reports a discrepancy that cannot be found by organizational maintenance. A report is filed indicating that no defect could be found.

Repair-In-Place (RIP) Job - the discrepancy is verified and can be corrected by organizational maintenance without a spare Line Replace (RR) Job -able Unit (LRU).


PICK SAMPLE AIRCRAFT
1
FOR EACH SAMPLE AIRCRAFT:
2
a. PRODUCE A TIME ORDERED SEQUENCE OF FLIGHT RECORDS.
b. PRODUCE A TIME ORDERED SEQUENCE OF WORK UNIT CODES BY ACTION DATE FOR ALL RECORDS WITH TYPE MAINTENANCE CODE B.
INVESTIGATE NEXT CMA ON LIST
3a
4
IS THERE ANOTHER CMA ON SAME AIRCRAFT SUBSYSTEM WITHIN 2 FLIGHTS?
YES
ENGINEERING ANALYSIS USING 3-M CODES FOR JCN, WHEN DISCOVERED AND MALFUNCTION; AND MAINTENANCE MANUALS
5
8
HAVE ALL CMA ON LIST BEEN CHECKED?
NO
YES
CALCULATE ERROR RATES BY COMPONENT
9



LEGEND

⊘=EITHER PATH

Figure 8. Type II/d Error Measurement

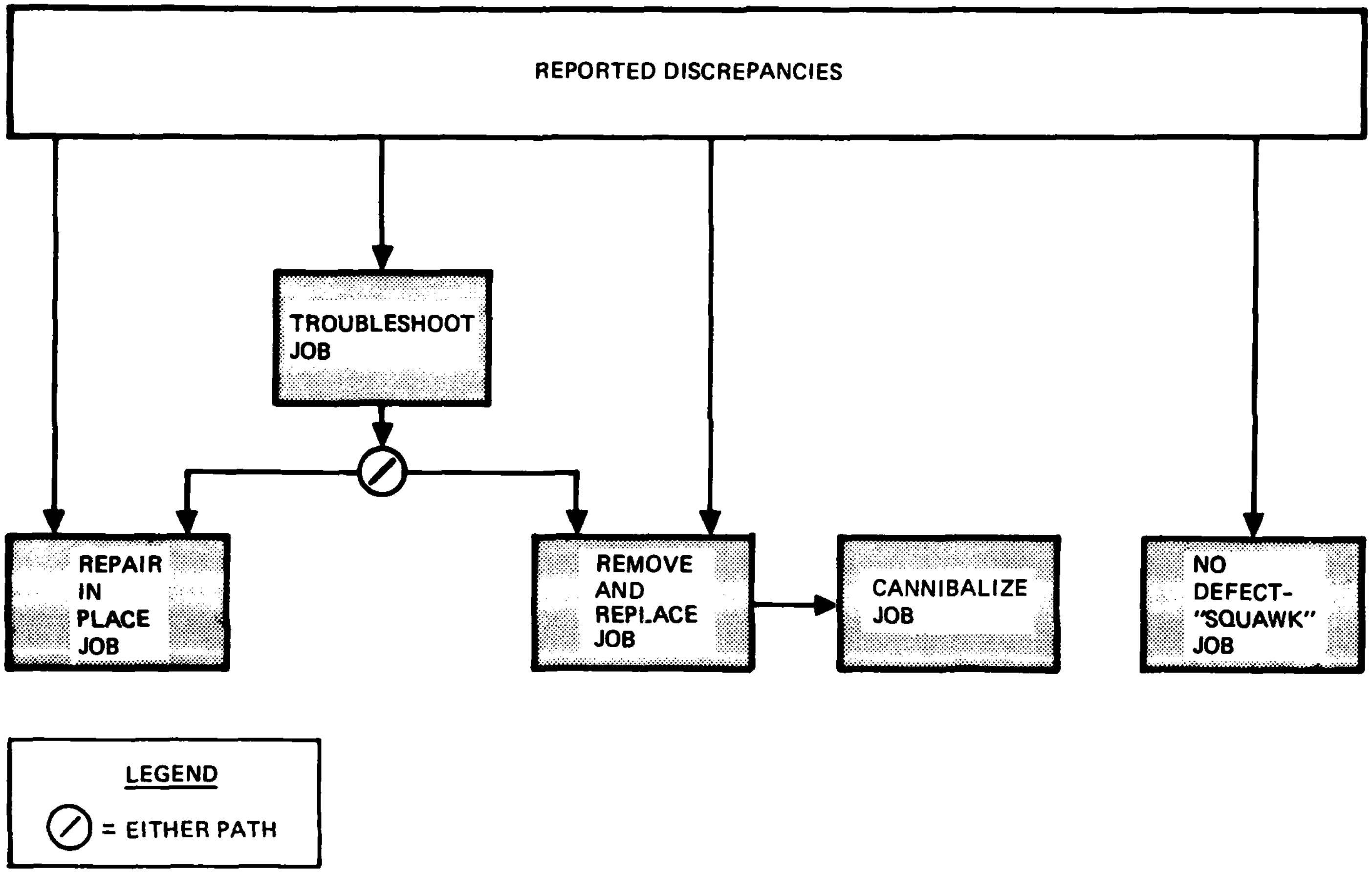


Figure 9. 3-M Statistics Corrective Maintenance Job Generation Overview

Remove/Replace (RR) Job - (RR) Job - the discrepancy is verified and can be repaired by organizational maintenance by replacing with a spare LRU.

Cannibalization Job - results if a spare LRU is not available after a part is removed (RR Job). Cannibalization jobs are only generated following an RR Job and are not included in the model at this time.

Troubleshoot Job - results when the troubleshoot function requires more than a few minutes. When the actual problem is isolated, a RIP or RR Job is generated to correct it. If troubleshooting is accomplished within a time considered "reasonable" by the technician, the troubleshooting time is included with the RIP or RR Job.

The 3-M statistics generate all jobs from reported discrepancies. The AMES Model divides reported discrepancies into three categories.

o False Discrepancies - those discrepancies where no actual defects were present. No Defect Squawks and unjustified removals (Type I error) are "False" Discrepancies.

o Maintenance-Caused Discrepancies - those discrepancies that remain on the aircraft after maintenance to correct the problem has been completed. Undiagnosed failure (Type II) and damage (Type d) errors are caused by faulty maintenance.

o Actual Discrepancies - those of the reported discrepancies that do not fall in the above two categories. Actual component defects requiring report cause these discrepancies.

The AMES Model job generation technique is shown in Figure 10. It is especially important to note that maintenance-caused deficiencies result from other jobs. Reducing these deficiencies by reducing errors, reduces the total number of jobs. The reduced number of jobs, in turn, reduces the number of errors again. Figure 10 represents the true situation more accurately. Even if an aircraft that almost never failed could be built, there would still be discrepancies due to human error.

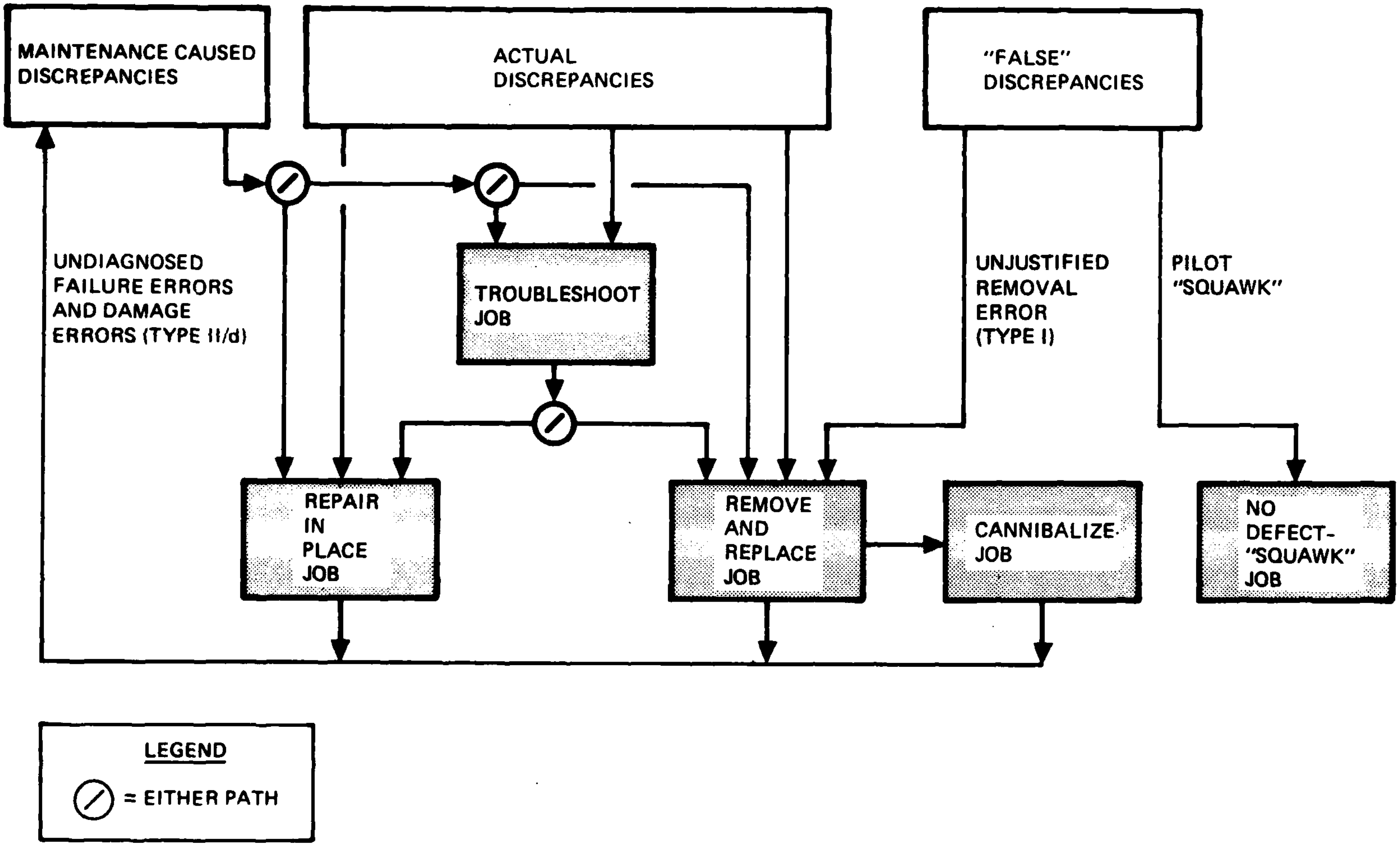


Figure 10. AMES Model Corrective Maintenance Job Generation Overview

SECTION VI

THE AMES MODEL

In light of the previous discussion, the AMES Model can now be described in terms of the general model framework. That is, the AMES Model can be summarized in terms of the following fundamental parts:

- A definition of the objectives of AMES
- An explanation of the scope of the model
- A functional description of its operation
- An outline of the input required by AMES
- An outline of the output produced by AMES

OBJECTIVES

AMES has been developed to study the relationship between maintenance and system performance. More specifically, AMES helps show how the effectiveness of maintenance personnel affects the system performance of an aircraft squadron. To do this, it is necessary first to measure maintenance effectiveness in quantitative terms. This has been accomplished in AMES by treating maintenance effectiveness in terms of performance times and error rates, as described in Section V and Appendix A.

Productivity is defined in terms of aircraft operational readiness and mission completion rate. With productivity so defined, AMES can analyze the sensitivity of productivity to maintenance effectiveness. This is done by varying error rates and performance times (maintenance effectiveness) and observing the resulting effect on aircraft operational readiness and mission completion rate (system performance). Thus, the AMES Model can help to identify those levels of maintenance effectiveness which optimize aircraft operational readiness within feasibility constraints of personnel and other related maintenance costs.

SCOPE

AMES is a model of the maintenance and operation of a carrier-based squadron of naval aircraft. AMES is a dynamic representation of a real system and can be divided into several segments, each of which represents a corresponding segment of the real system. The detail with which a given segment is represented depends upon the interest of that segment to the current objectives of AMES.

Areas Not Currently of Interest to AMES

Those segments of the system which have little relationship to the factors being studied have been simplified. They are represented in only enough detail to complete the model. An aircraft undergoing a mission, for example, is modeled merely by placing the aircraft in a particular set. All details of the mission other than times of takeoff or landing are ignored. This simplication is made because the details of a mission have no effect on the factors being studied by AMES.

Areas of Interest to AMES

Those segments which are directly related to the objectives of AMES are modeled in adequate detail to perform the desired analyses. Some of the more important segments include the aircraft, the components, human performance, planned maintenance, corrective maintenance, component failures, and errors. Exactly how these and other subsystems of AMES are represented is described in detail in Appendix A.

Limitations

Since AMES is a model of an aircraft squadron and not the actual squadron itself, AMES will not behave in exactly the same way as the real aircraft squadron. Since AMES is a simplification, it cannot respond to many of the stimuli that might affect a real aircraft squadron, such as hostile enemy activity or fuel shortages. Some of the peculiarities of a carrier-based naval squadron are built into AMES. To use AMES to model other similar systems, such as a ground-based aircraft squadron, modifications are required. However, AMES has been designed to simplify such modifications.

FUNCTIONAL DESCRIPTION

A detailed functional description of the AMES model can be found in Appendix A. For the purpose of this discussion, the function will be summarized briefly.

AMES can be considered as three basic components and the interactions between them. The components are: a supply of aircraft, a schedule of missions, and a maintenance facility. There are three possible interactions between these three components. Two of these are manifest in the AMES Model: The interaction between missions and aircraft and the interaction between aircraft and maintenance.

The interaction between missions and aircraft is a simple one. Whenever a mission is scheduled and two operationally ready aircraft are available, the mission is flown. Whenever a mission is scheduled and two operationally ready aircraft are not available, the mission is deferred for a period (called the scrub time) or until operationally ready aircraft become available. If the mission is not flown before the end of the scrub time, the mission is cancelled (scrubbed).

The interaction between the aircraft and the maintenance facility involves planned (or preventive) maintenance and corrective maintenance. In one mode, the maintenance facility attempts to perform planned maintenance actions on aircraft which are not on flight duty. These actions are performed as much as possible in accordance with a planned maintenance schedule. In the other mode, the maintenance facility attempts to correct aircraft failures as they occur. Both modes of maintenance operate simultaneously and comprise the interaction between maintenance and aircraft.

The objective underlying the interaction between aircraft and missions is to fly as many of the scheduled missions as possible. The objective underlying the aircraft-maintenance interaction is to continually maintain the highest level of overall squadron operational readiness.

INPUT

The AMES Model is a representation of an actual aircraft squadron. The framework of this representation is based upon three abstract notions: Entities, attributes, and sets. An entity is an item or "thing", such as an aircraft. An attribute is a characteristic of one of the entities, e.g., the number of hours an aircraft has been flown. A set is a collection of entities, such as the set of operationally ready aircraft.

The structure of any system can be described with these basic abstractions. The resulting representation will have sufficient generality to model any particular instance of that system. This generality, however, creates a requirement: the user must describe the particular instance (of the system) that he wishes to study. This is done by supplying a database which "fits" the structure of the system. This database determines the characteristics of an instance of the general system.

AMES Database

As mentioned above, the AMES database must fit the structure of the AMES Model. This structure, or data structure, is described in complete detail in the AMES Source Code, and in slightly lesser detail in the AMES Design Document. The database itself is expected by the AMES Model to follow a certain format. The more important aspects of that format are described in Section V.

Program Control Parameters

In addition to the database just mentioned, the AMES program expects another set of data which consists of parameters that control the operation of the program. These include such parameters as the duration of the run, the frequency of each report, etc.

OUTPUT

The AMES program generates two kinds of output: reports and traces. Both forms are controlled by user input.

Reports

Each report consists of certain information which describes a particular aspect of the current condition of the simulated squadron. The "Status Report", for example, indicates the status of each aircraft at the time of the report. The frequency of each report must be specified by the user as input. A detailed description of the reports may be found in Section IV.

Traces

Traces were originally built into the AMES program as a debugging tool. When an error occurred during the development of AMES, traces facilitated the location or source of the error. Although this function is currently unnecessary, the traces were left in the program for two reasons. First, they can still be used for debugging in case of future developmental work. Secondly, the traces can be used to follow the execution of the program in greater detail. Peculiarities and uncertainties can be more closely examined by "tracing" that part of the run in which they occur. Traces are turned on or off by user input.

SECTION VII

RESULTS

This section describes results of the AMES project. A functional model (AMES) has been produced. We obtained three kinds of results: one from the 3-M data analysis required by AMES, another from application of the model, and the last is the model itself.

RESULTS FROM 3-M ANALYSIS

The model requires quantitative input data, primarily to establish a realistic baseline for future model studies. The results are valuable in the absence of AMES because they give a quantitative picture of present maintenance. The F-14A was chosen to test the model. We present data here that relates either to the entire F-14A aircraft or to one of the five subsystems that require the most maintenance. All of the data is taken from a sampling of six F-14A squadrons. Records for each squadron extend for one year.

Number of Aircraft

Using the 3-M statistics, we can develop a "picture" of the average squadron. It has 12 aircraft. Of these, 57.6 percent (6.92 aircraft) were operationally ready (OR) at any given time. The remaining 42.4 percent (5.08 aircraft) were not operationally ready (NOR). A more detailed breakdown of these figures is shown in Table 7.

Maintenance Manhours Per Flight Hour

For each hour of flight, an F-14A requires 43.2 manhours of organizational level maintenance. This total includes all planned maintenance (PM) and corrective maintenance (CM). Also included are all support actions (SAF) and technical directive compliance (TDC). Table 8 shows the breakdown of hours into those categories.

Errors

Using the error analysis described earlier, one can conservatively determine actual error rates by component. The number of corrective maintenance errors represents 20 percent of the corrective maintenance actions (CMAS).

TABLE 7. AVERAGE SQUADRON OF F-14A AIRCRAFT COMPILED FROM 3-M STATISTICS

AIRCRAFT CONDITION	DETAILED CONDITION CODE	NUMBER OF AIRCRAFT
OR	RMCM - U	.38
	NFE	.39
	NSC	6.20
	TOTAL OR	6.92
NOR	NORM - S	.48
	NORM - U	2.00
	NORS	2.61
	TOTAL NOR	5.08
	TOTAL OR AND NOR	12.00

Note: The total number was chosen to be the nominal squadron size, 12 aircraft.

LEGEND:

OR	Operationally Ready
NOR	Not Operationally Ready
FSC	Full Systems Capable
NFE	Not Fully Equipped
RMCM - U	Reduced Material Condition due to Unscheduled Maintenance
NORM - S	NOR due to Scheduled Maintenance
NORM - U	NOR due to Unscheduled Maintenance

TABLE 8. F-14A ORGANIZATIONAL MAINTENANCE MANHOURS PER FLIGHT HOUR

MAINTENANCE CATEGORY	MANHOURS/FLIGHT HOUR
PLANNED MAINTENANCE (PM)	19.2
CORRECTIVE MAINTENANCE (CM)	16.4
SUPPORT ACTIONS (SAF)	6.4
TECHNICAL DIRECTIVE COMPLIANCE (TDC)	1.2
TOTAL	43.2

For some subsystems, Type I errors are most prevalent; for others, Type II/d errors are most common. Table 9 shows the error rate in percentages for the five subsystems that represent the most work. The figure also shows the percentage of the CMAS where the parts from supply are bad. Table 10 shows the error rates grouped by work center.

The discussion of error rates in a previous section mentioned that the Type I and Type II/d error rates are conservative. The actual error rates are probably considerably higher than those used in the model.

Frequency of Failures

The Mean Time Between Corrective Maintenance Action (MTBCMA) is the average duration of flight between Corrective Maintenance Actions (CMAs). If defects caused by maintenance errors are distinguished from actual hardware defects, we can identify two important items. The traditional MTBCMA is calculated based on the total number of CMAs (not including cannibalization). The Mean Time Between Actual (hardware) Defects (MTBAD) is based on defects where no error has occurred. To determine a MTBAD in the absence of human error we use the total CMAs not resulting from error. Table 11 shows both rates for the five subsystems with the most CMAs. The percentage of CMA and CM manhours represented by the subsystem is also shown in the figures.

Parts Delays

Figure 11 shows the types of CMA. The figure shows percentages for cannibalization parts required and delays. Of all CMAs, 18.3 percent require parts delays greater than 5 days. The average of these delays is 38 days.

RESULTS FROM APPLICATION OF THE MODEL

The model produces two types of results: understanding and quantitative results. As understanding of the model and the maintenance process increases, trust in quantitative results should also increase. In this subsection, two examples of new understanding and one quantitative result will be discussed. These are preliminary results. They are used primarily for illustration.

Planned Maintenance Manhours

In our initial use of the model, work times for PM were chosen from "book times", i.e., specifications. In this case, these values for various PM job segments were taken from Maintenance Requirements Cards (MRC) for the F-14A Aircraft.

TABLE 9. QUALITY OF CORRECTIVE MAINTENANCE -- TOP FIVE SUBSYSTEMS

SUBSYSTEM	WORK CENTER	PERCENT OF RR ACTIONS		PERCENT OF CM ACTIONS*	
		TYPE I	BAD PARTS	TYPE II/d	ALL ERRORS**
AWG-9	Electronics/Weapons Cntl (232)	21	6	6	19.3
TF-30 Engine	Power Plants (110)	1	2	34	28.6
Flight Reference Equip	Electrical/Instr. (220)	22	1	5	11.7
AN/APX-76 & -72	Electronics (210)	13	5	11	18.6
Flight Hydraulic Power System	Airframe -- Hydraulics (120)	0	1.5	8	18.2
All Subsystems	All Work Centers	14.5	1	9.8	13.7

*CM ACTIONS IS THE SUM TS + RR + RIP + CANN

WHERE TS = *Total Troubleshoot Jobs,*
RR = Total Remove and Replace Jobs,
RIP = Total Repair in Place Jobs, and
CANN = Total Cannibalization Jobs

**ALL ERRORS IS THE SUM EI + EIID + BP

WHERE EI = Total Errors of Type I,
EIID = Total Errors of Type II or d,
BP = Total Occurences of Bad Parts

TABLE 10. SUMMARY -- CORRECTIVE MAINTENANCE ERRORS

WORK CENTER	TYPE I*	TYPE II/d**	ALL ERRORS**
Organizational Maintenance Department	14.5	9.8	13.7
Power Plants (110)	5.9	15.9	17.0
Airframe (120)	6.8	16.0	17.3
Corrosion Control (121)	0	6.4	6.4
Aviator Equipment (131)	0	4.1	4.1
Safety Equipment (132)	17.8	11.0	14.9
Electronics (210)	13.0	8.5	12.1
Electrical Instruments (220)	17.7	6.7	10.4
Armaments (230)	5.4	6.6	7.6
Electro-Weapons Control (232)	15.8	7.3	14.7
Troubleshooters (320)	0	12.5	12.5

*Expressed as percent of RR jobs.
**Expressed as percent of all CM actions.

All CM actions is the sum TS + RIP + RR + CANN

where: TS = Total Troubleshoot Jobs,
RIP = Total Repair In Place Jobs,
RR = Total Remove and Replace Jobs, and
CANN = Total Cannibalization Jobs

All Errors is the sum EI + EIID + BP

where: EI = Total Errors of Type I,
EIID = Total Errors of Type II or d, and
BP = Total Occurrences of Bad Parts

TABLE 11. FREQUENCY OF CORRECTIVE MAINTENANCE-TOP FIVE SUBSYSTEMS

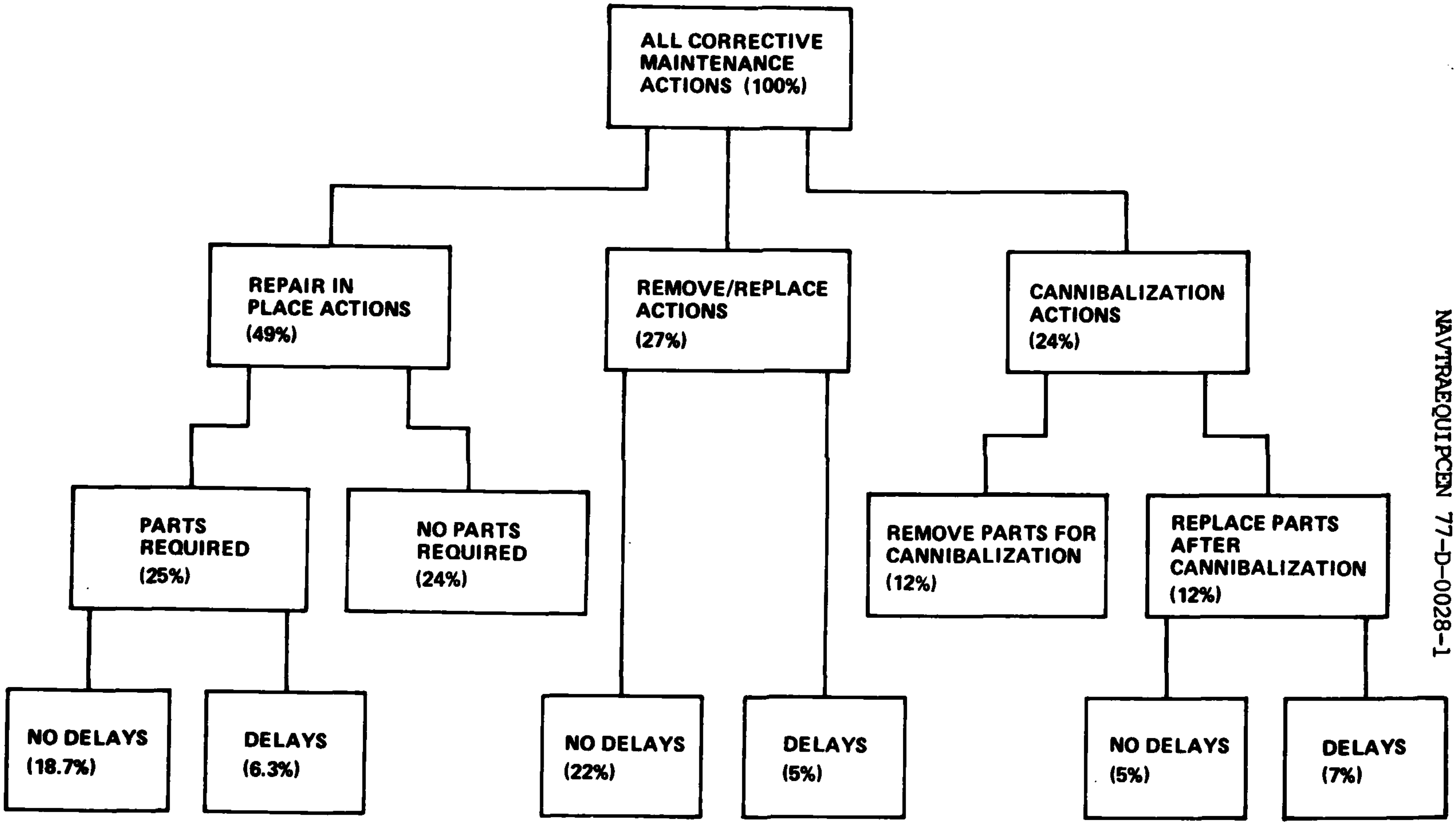
SUBSYSTEM	WORK CENTER	MTBCMA* (Flt hrs.)	% of CM Actions	% of CM Manhours	MTBAD** (Flt hrs.)
AWG-9	Electronics/Weapons Cntl (232)	2.98	10	3	5.74
TF-30 Engine	Power Plants (110)	13.7	3	3	30.1
Flight Reference Equip.	Electrical/Instr. (220)	15.3	2	1	40.3
AN/APX -76 & -72	Electronics (210)	16.2	2	1	26.8
Flight Hydraulic Power Sys.	Airframe - Hydraulics (120)	18.5	2	1	35.8

* MTBCMA - Mean Time Between Corrective Maintenance Actions.

Corrective Maintenance Actions consist of Troubleshoot, Repair in Place, Remove and Replace, Cannibalization Actions and defects caused by human error.

** MTBAD - Mean Time Between Actual Defects.

Actual Defects consist of Troubleshoot, Repair in Place, and Remove and Replace (does not include Cannibalization Actions or errors).



NOTE: 18.3% of all Corrective Maintenance Actions entail a delay for parts greater than five days. These extended delays average 38 days.

Figure 11. Overview of Parts Delays

The number of maintenance manhours suggested by the book times differed substantially from the results of the model run. The values for the 3-M analysis show an average of 19.6 planned maintenance manhours per flight hour. Initial model results yielded about nine PM manhours per flight hour. A sixty percent increase over book times increased the model results to about 18 PM manhours per flight hour. This indicates that book time is substantially below actual time. Further discussion with and observation of maintenance personnel are required to improve the model and discover how realistic the book values are.

Operational Readiness and Missions Completed

In 3-M statistics, Operational Readiness (OR) is traditionally taken as the primary indicator of the quality of system (and therefore maintenance) performance. Initial runs indicate that when a substantial percentage of flights cannot be flown, mission completion is an equally important measure of performance. Considering only the operational readiness parameter could be quite misleading.

A squadron with no missions for a month could have a 100 percent OR status. As missions are flown, failures occur. These failures require maintenance which subtract from the OR status.

When the missions demands are high and error rates are reduced, more missions are completed. The additional flight hours of these additional missions result in more failures. The additional failures could even reduce operational readiness below the base line level (prior to error reduction).

This means that mission completion increases more dramatically than operational readiness when error rates are reduced. We have found this to be true in the initial two year model runs.

Figure 12 shows results from four two-year runs. Each run is indicated by a dot. A line is used to connect the dots. The figure shows that a 90 percent decrease in the error rate causes the percentage of missions completed to increase from 49.8 percent to 57.1 percent. To achieve the increase without a reduction in error rate would require the addition of least one entire aircraft to the squadron. Thus, for the particular parameters of these runs, a 90 percent reductionin error rates is approximately equivalent to adding another aircraft to the squadron.

The model is still very new and has not been thoroughly validated. Thus, the above results should be treated as an indicator only. Both the model and maintenance as a system need to be studied and understood better before specific relationships can be accepted.

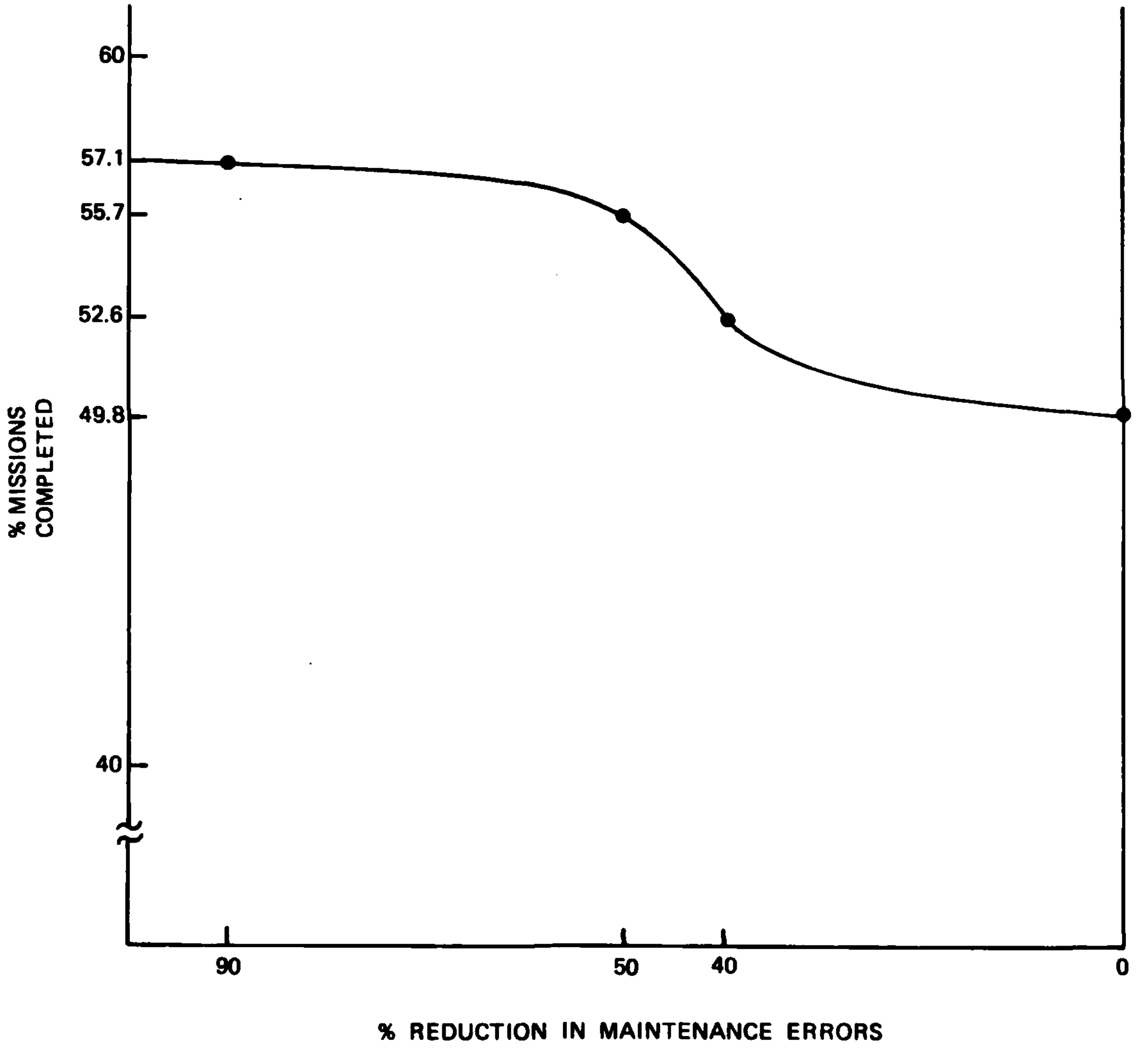


Figure 12. Error Reduction for Each of Four Two-Year Simulations

THE MODEL ITSELF

The model itself is a result. At the completion of this study, only the first step has been made toward a better understanding of the interaction of human performance with the maintenance process. The model is at present a strong, flexible model that simulates maintenance. It has been designed and executed so that it is easy to understand. In the next step of modifying the model to increase the verisimilitude of the simulation, we will learn a great deal more about maintenance.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

The AMES project was intended as a step toward establishing a quantitative relationship between the effectiveness of maintenance and the operational readiness/mission completion of aircraft served by maintenance personnel. The quantitative relationship should indicate the tremendous importance of people-related efforts alongside of hardware development.

In undertaking AMES, we have two long range goals for the application of the AMES results:

- To provide a tool enabling R&D managers to assign higher priorities to people-related efforts in maintenance research.
- To provide a basis for training new maintenance managers to understand maintenance as a system.

Our immediate objective on the road to these two goals can be stated as follows:

- To create a prototype functional simulation model for studying aircraft maintenance effectiveness.

The manner in which these goals and this objective have been satisfied or advanced is discussed in the first part of this section. In the second part, recommendations are presented. The third part consists of a closing statement.

CONCLUSIONS

The accomplishments of the project are described under the following headings:

- AMES - A Prototype Functional Simulation Model for Aircraft Maintenance Effectiveness
- AMES - A Tool for R&D Managers
- AMES - A Basis for Training Maintenance Managers

AMES - A Prototype Functional Simulation Model for Aircraft Maintenance Effectiveness

The flying and maintenance of aircraft comprise a system of extreme complexity. Because of the complicated way in which the many elements of the system interact, the changes in system performance of one element are difficult to predict. For instance, it is difficult to predict quantitatively how the number of missions completed might change when maintenance error rates are reduced. A functional simulation model overcomes these difficulties.

A functional simulation model duplicates the functions of the flying and maintenance process. Each of the individual functional elements, such as flights or corrective maintenance, must be described quantitatively. The interactions between elements proceed in a causal manner as they do for actual aircraft. The use of a computer to accomplish the simulation allows several years of simulated aircraft flying and maintenance to occur in seconds. By counting how often the aircraft flies or how many hours an aircraft is operationally ready during the simulation, one can discover the system performance. In effect, our computer model is a small, rapidly evolving copy of an aircraft flight and maintenance system. The functional model should respond to changes in resource allocation, error rate, or other elements in a manner similar to a real squadron.

The Aircraft Maintenance Effectiveness Simulation (AMES) Model has been designed and constructed to include the following features:

- Human maintenance performance
- Human maintenance error rates
- Manpower levels
- Flights and failures
- Corrective maintenance (except cannibalization)
- Turnaround and daily flight inspections
- Planned maintenance (except corrosion control and technical directive compliance)
- Parts and facilities delays

The model has been programmed in a language similar to English so that maintenance personnel can be used to help improve the model's agreement with an actual squadron. To duplicate the proper response of the elements, we must use statistical information from actual squadrons. Various data -- such as performance time to complete maintenance, flight time between aircraft component failures, and rate of human errors -- must be used with the model to provide a quantitative baseline of performance for each of the functional elements. Some of the baseline data, such as preventive maintenance schedules, are available from aircraft documents. Some, like the rate at which discrepancies are discovered in an aircraft component, are available from Naval 3-M data. Other data, like the maintenance error rates, were derived from 3-M data by our own analysis techniques.

AMES has undergone extensive testing during all phases of construction and at completion. The testing has employed baseline data from actual squadrons, as well as data chosen to exercise all features of the model.

Squadron performance using AMES (with baseline data for the F-14A aircraft) has been represented for periods of up to two years of simulated time. Fluctuation of results from these AMES computer runs indicates that reducing error rates by 90 percent can increase the mission completion rate by 15 percent. (Error rate reduction of 90 percent by using proper training work aids is possible. These results, determined by our analysis, are for an error rate of 15 percent - one error each six corrective maintenance actions.)

AMES -A Tool for R&D Managers

A long-range goal is to provide R&D managers with a tool enabling them to assign higher priorities to people-related efforts in maintenance research. As an aircraft (or any weapon system) is designed, R&D managers must make the important decisions determining design trade-offs. For instance, should the landing gear be constructed of steel (which is cheaper) or titanium (which is lighter but more expensive)? These decisions are based on cost effectiveness. These managers attempt to produce the most aircraft possible for the least money. For these decisions they require quantitative data.

At the present time R&D managers do not include maintenance effectiveness in their set of trade-offs. They do not believe the effects of human error or poor performance are important enough to include in their consideration. To show them the importance of maintenance and to allow them to include maintenance in cost effectivness requires quantitative data relating such maintenance performance to system performance. System performance can be related to cost.

The initial and tentative AMES results given above show that reducing error rate by 90 percent is equivalent to increasing performance by 15 percent. This increase corresponds to between one and two additional aircraft per squadron of 12 aircraft. At a cost of $21 million per aircraft, this represents a $400 million saving on the 300 aircraft purchased so far. Such indications show the importance of considering errors as well as time-to-perform when studying the human factors of maintenance.

At a future stage it is hoped that an improvement of the AMES Model will allow R&D designers to include human performance variables in design analysis. Optimizing the present system may produce good aircraft, but aircraft that cannot be repaired cannot fly. With a descendent of AMES, cost effectiveness can include all aspects of system performance, including people-related considerations.

AMES - A Basis for Training Maintenance Managers

The second long-range goal is to provide a basis for training new maintenance managers to understand maintenance as a system.

The maintenance manager has the job of assigning the men and equipment required to maintain aircraft. Such a job is very important, especially considering the huge cost of maintenance errors. For the F-14A we have found that an aircraft is not available for flight 44 percent of the time.

Maintenance managers have little formal training to help them understand maintenance as a system. Much of the time, a maintenance manager has received training in only one area. Perhaps the best way to train a manager of maintenance operations would be to give him a great deal of training on the job. The training would be enhanced by allowing him to try different strategies to begin to understand how changes in resource allocation produce changes in system performance. Such training requires much time and a squadron of aircraft. This is an unacceptably expensive training technique.

There are two ways that AMES can provide a basis for training maintenance managers: as a development tool for formulating new maintenance strategies and as a training tool in the form of a maintenance simulator.

The developmental purpose of AMES is to acquire a true understanding of how maintenance works. The studies that lead to a better understanding will produce new strategies for optimal utilization of maintenance resources.

The training purpose of AMES is to teach maintenance managers to improve effectiveness. Simulators are gaining acceptance in maintenance training because of their comparative cheapness. A simplified version of the AMES Model is much less expensive than using a squadron for training. Also, the results of several months of maintenance using a particular resource allocation plan could be seen almost immediately.

RECOMMENDATIONS

In pursuit of a quantitative understanding of maintenance as a system, six specific recommendations are advanced. They are arranged in the order in which they should be carried out.

1. Continued study and improvement of the AMES Model. The human factors community has always needed a maintenance system to study. The enormous cost of aircraft has prevented a systematic study of the maintenance system. The AMES Model provides such an inexpensive tool. AMES must be improved and studied with help from actual maintenance personnel to assure that AMES will more closely duplicate actual maintenance procedures.

2. Systematic sensitivity studies. The maintenance system is tremendously complicated. Changes in failure rates, human performance, and mission schedule all interact to change aircraft availability. By systematically manipulating only a single variable at a time, interactions and trade-offs can be studied and understood.

3. Study of error rate reduction on an actual subsystem. Studies should be undertaken to determine if a 90 percent reduction in error rate for a single subsystem is feasible. Such results can be extended to all systems using the model to determine if such an error reduction is cost effective.

4. Train maintenance managers using AMES. It is not feasible to tie up an entire squadron to train those who will make decisions on maintenance. AMES is an exact analog of simulation used for training pilots or maintenance personnel. A simplified model of AMES could be used interactively to teach maintenance managers their trade.

5. Set specifications for human performance relative to system performance. Human performance in maintenance can be specified in terms of error rate and performance time. The AMES Model can be used to relate these specifications to system performance.

6. Include human maintenance performance considerations in hardware design. Now cost effectiveness of hardware design trade-offs can be investigated during design. The AMES Model provides the possibility of including the human factors of maintenance into design decision.

CLOSING STATEMENT

Modern analytical techniques are now used for all phases of hardware design. The people-related factors of maintenance have had almost no analysis as they relate to system performance variables of the aircraft. AMES is an initial step toward indicating the importance of these considerations and discovering strategies toward improving both human performance and system performance.

APPENDIX A

THE MODEL

The Ames Model is best described in the way it was developed — from the "top down". In top-down design, the program is described (and implemented) in general levels first, and then into levels of increasing detail.

The Ames Model is written in the language Simscript II.5. One of the primary advantages of this language is its readability by those not expert in computer work. The terms in the following explanation are, for the most part, those actually used in the program. The program itself reads very much like English. The understanding, gained at the general levels in the following explanation, may be applied directly to an understanding of the more detailed levels of the program itself.

The model simulates the events and activities of aircraft and maintenance personnel as time passes. It is important to realize that the times in the simulation are not equivalent to real time. For example, three months of simulated time for a squadron require only a few minutes of actual time to be simulated by the computer. For the purposes of the following discussions, all times are simulated times.

The model may be divided into five levels of implementation. Each succeeding level is more complicated than its predecessor. At each succeeding level more detail is added. Some parts of the program may be changed substantially from level to level; some parts not at all. The five levels of implementation are as follows:

I Flying the Aircraft
II The Failure of Components
III Corrective Maintenance: Repairing Failures
IV Planned Maintenance, Including Flight Inspections
V Priority Repair for Immediate Mission Assignment

Each of the levels is described with a figure. These diagrams attempt to show how the program is constructed at each level. The diagrams actually follow the structure of the program quite closely. The following conventions are observed:

1. Circles represent groups of aircraft, herein termed "sets".

2. Boxes represent procedures that act on the aircraft, either moving them from set to set or working on the aircraft within a set.

3. All aircraft must be in one and only one of the sets, except for a brief time when a procedure moves them from one set to another.

4. The duty scheduler procedure does much of the moving of the aircraft from one set to another.

5. All movement of aircraft is governed by an externally imposed schedule of missions. Every effort is made to fly as many missions as possible.

6. The diagrams are designed to show movement and action with respect to the aircraft. Other considerations, like temporal relationships, may be neglected for the sake of clarity.

7. A much more detailed document, written in an English-like design language, has been constructed to describe tne model in much greater detail. Due to its length it has not been included in the report. However, it is available to facilitate future improvement of the model.

LEVEL I - FLYING THE AIRCRAFT

In the most general sense, the purpose of aircraft is to fly missions. Each mission is composed of one or more sorties. In Figure A-1, basic purpose is shown. The diagram depicts aircraft operation if no aircraft component ever failed.

Aircraft with all systems operational are stored in the FSC (Full Systems Capable) POOL. As the simulation begins, all aircraft are in the FSC POOL. Each mission has a scheduled start time, a duration, and a scrub time. The scrub time is the delay allowed the aircraft before the mission is cancelled.

Before the missions of a given day are flown, the number of aircraft required to carry out the missions is determined. The desired number of aircraft are moved from the FSC POOL to the TA WORKSHOP (turnaround inspection area). Those aircraft with the fewest accumulated flight hours are selected first. Here they are subject to inspection before the first flight, after the last flight and between flights. At Level I of the implementation, however, there are no inspections -- just a place to do them.

Since the aircraft have no failures, no planned maintenance (PM), and no inspection, all aircraft are certified for flight on passing out of the TA WORKSHOP. The aircraft certified for flight are put in the FLIGHT CERTIFIED AIRCRAFT POOL. They remain certified until an aircraft is actually scheduled to fly or until aircraft are no longer required.

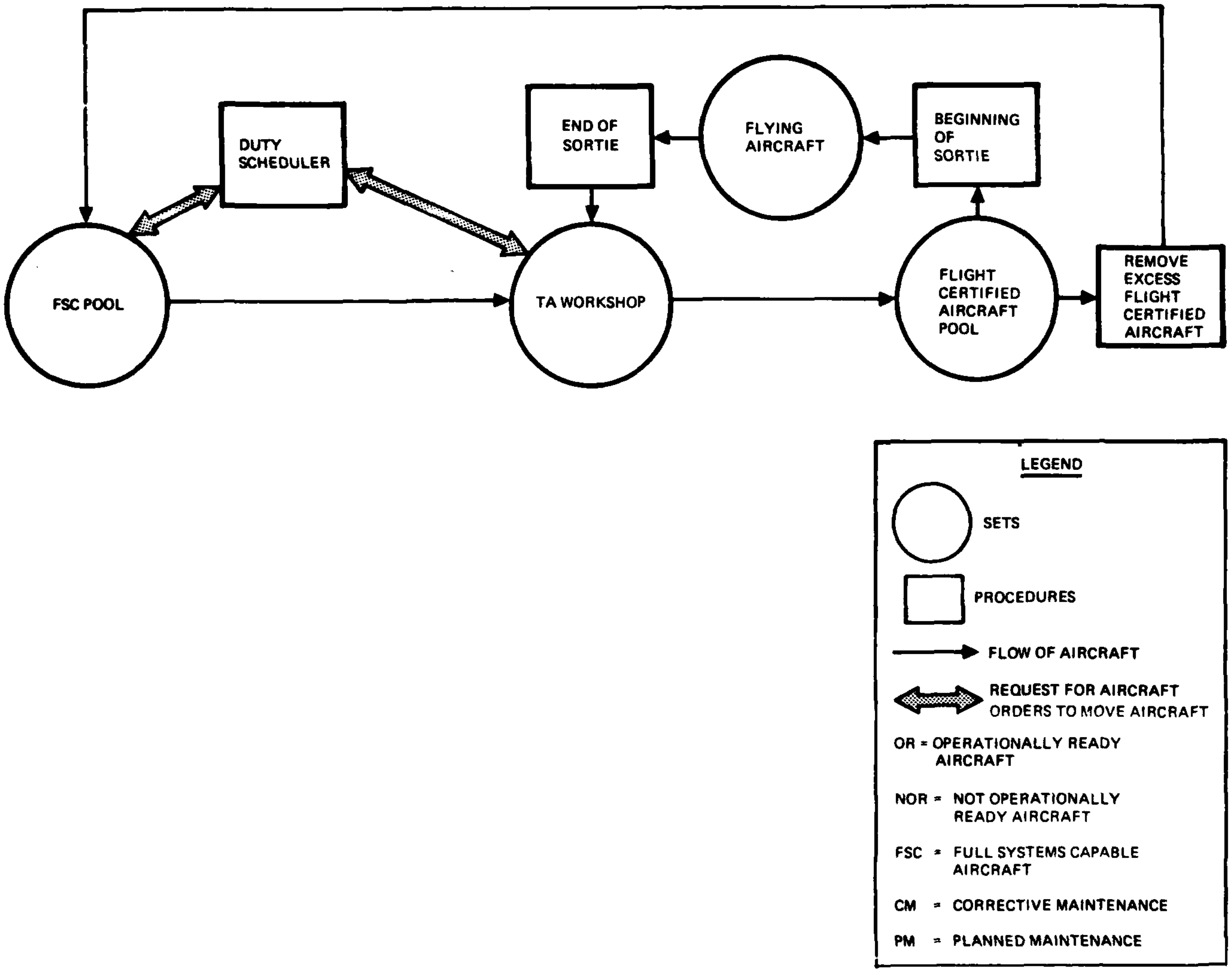


Figure A-1. Level I – Flying the Aircraft

When the time for a scheduled mission occurs, BEGINNING OF SORTIE removes the aircraft from FLIGHT CERITIFIED AIRCRAFT POOL. Those aircraft with the lowest number of flight hours are selected first. If they are available, aircraft are launched at the scheduled start time. If aircraft become available after the scheduled start time but before the scrub time has passed, they are launched immediately. If aircraft have not become available before the end of scrub time, the mission is cancelled. After takeoff, the aircraft is placed into the set of FLYING AIRCRAFT. At the launch, BEGINNING OF SORTIE also schedules an END OF SORTIE to complete the mission after the scheduled duration.

When the duration of the SORTIE is completed, the END OF SORTIE occurs. END OF SORTIE advances the flight time statistics of the aircraft. The landing of the aircraft, as well as removing the aircraft from FLYING AIRCRAFT, occurs at END OF SORTIE. Finally, END OF SORTIE replaces the aircraft in TA WORKSHOP for the turnaround inspection required after the flight.

As the missions of the day are flown, the computer keeps count of how many missions remain. If ever there are more aircraft in the set of FLIGHT CERTIFIED AIRCRAFT POOL than are required for all of the remaining missions of the day, the excess aircraft are removed by REMOVE EXCESS FLIGHT CERTIFIED AIRCRAFT. The removed aircraft are placed in the FSC POOL. The aircraft are removed from FLIGHT CERTIFIED AIRCRAFT POOL based on the total number of flight hours: those aircraft with the most flight hours are removed first.

LEVEL II - THE FAILURE OF COMPONENTS

The simple picture, diagrammed in Figure A-1, describes aircraft operations in the absence of failures. Level II of the model includes component failures. The aircraft picture is enlarged to include components. For the purposes of this level of the model, the aircraft is a flying set of components with flight statistics. From the data analysis, we know the Mean Time Between Failures (MTBF) for each of the subsystems of the aircraft. AMES is designed so that although specific component failures occur randomly for a given subsystem, the average time between failures from the model run will approximate the actual MTBF.

Each of the simulated aircraft then contains a list of all components. For each component the list includes the following information:

- Whether the component is good, defective or removed.
- The criticality of the failure (whether the next failure renders the aircraft NOR).
- The specific number of flight hours until the next failure for a particular component.

The diagram of Figure A-1 may be extended to include these modifications. Figure A-2 shows the diagram including component failures. This second level of detail includes all items of the previous level, but to accommodate the component failures, the following modifications have been added.

1. TA WORKSHOP - a turnaround to check for defective components.

2. DUTY SCHEDULER - the decision whether a particular aircraft may be scheduled for flight.

3. OR MAINTENANCE POOL - the set of OR aircraft to be repaired.

4. NOR MAINTENANCE POOL - the set of NOR aircraft to be repaired.

5. INITIATE CM (Corrective Maintenance) to remove aircraft that fail to pass inspection to the NOR MAINTENANCE POOL.

Before the simulation begins, the flight time until the next failure for each component of each aircraft is determined from actual flight failure statistics, as is the criticality of the failure. At this stage of implementation, repair jobs are completed instantaneously.

The simulation begins again with mission requirements for aircraft. The DUTY SCHEDULER attempts to find enough aircraft to fly the mission. Aircraft are selected for flight in the following order of preference.

1. Aircraft with all components good (FSC POOL).

2. Operationally Ready aircraft that require maintenance but are not already flying (these are found in OR MAINTENANCE POOL).

3. Those aircraft that have failures that render them not operationally ready (NOR) are kept in NOR POOL. These aircraft may not be flown until all serious defects are corrected.

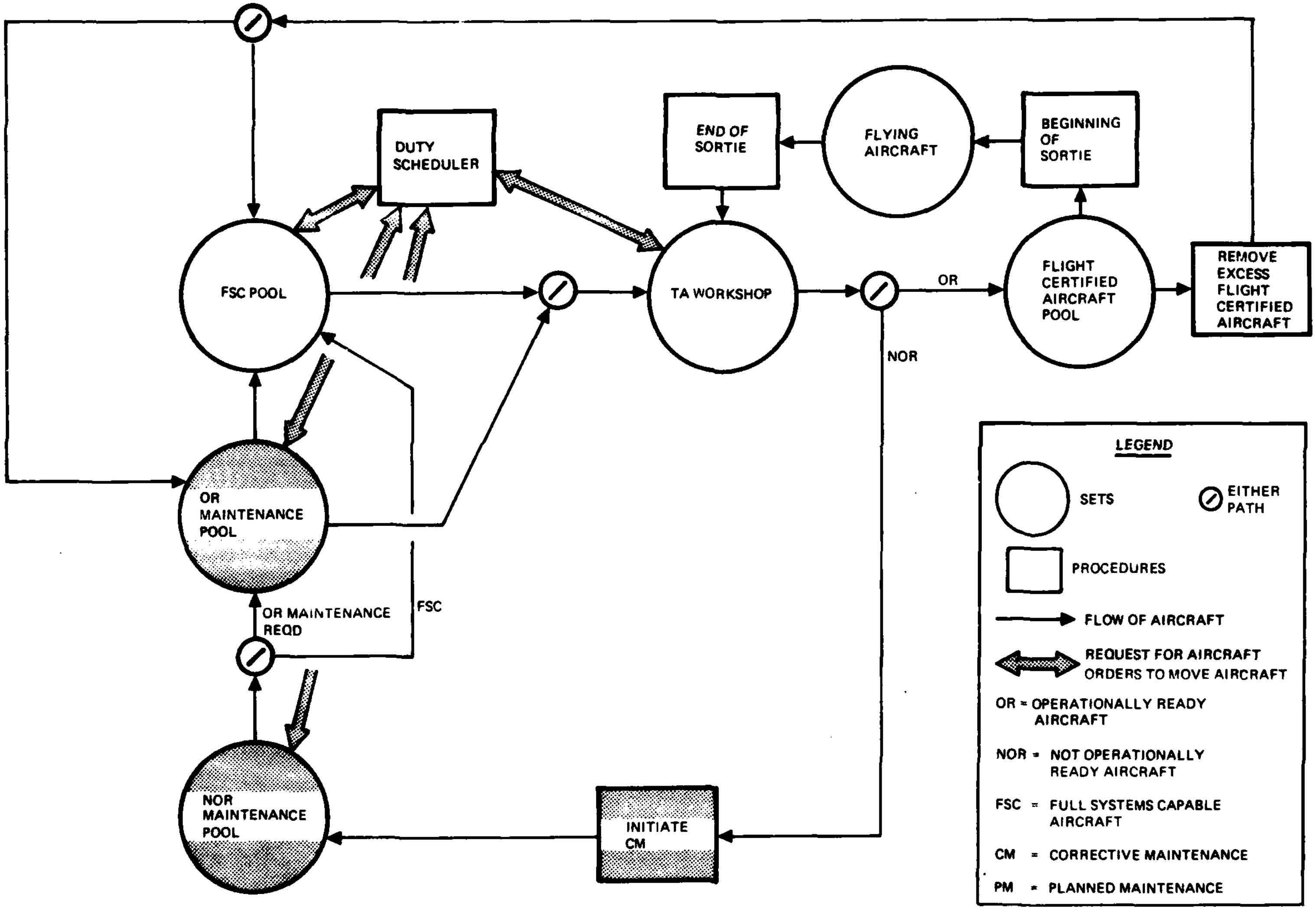


Figure A-2. Level II - The Failure of Components

The aircraft designated for flight by the DUTY SCHEDULER are moved into the TA WORKSHOP to undergo the turnaround inspection. If more aircraft are required than can be found, the Duty Scheduler waits until repair is completed on an NOR aircraft. When the repair has been completed, the aircraft becomes OR and is moved to OR MAINTENANCE POOL from the NOR MAINTENANCE POOL. Should enough aircraft to fly a mission not be available at the time of the scheduled takeoff, the mission is deferred in BEGINNING OF SORTIE. Normally two aircraft are required for a mission. If the aircraft are still unavailable after the scrub time, the mission is cancelled.

The inspections consist of checking each component of a particular aircraft to see if it has failed since the last inspection. Aircraft with components that fail but do not render the aircraft NOR may continue to fly. A single NOR component failure results in the aircraft being classified NOR. No further flights for this aircraft may occur until its NOR components are corrected. Components on aircraft that are still OR but continue to fly may fail again and become NOR.

LEVEL III - CORRECTIVE MAINTENANCE: REPAIRING FAILURES

The third level actually repairs the aircraft. At this level, we must include the following:

- Different Types of Repair Jobs
- Personnel
- Details of the Various Jobs
- Errors

Since the purpose of AMES is to relate the system performance to various characteristics, the third level contains many of the important details. Each of the above topics will be treated in some detail.

Different Types of Repair Jobs

The basic structure shown in Figure A-2 has been expanded to include practically all of corrective maintenance (CM) in Figure A-3. The third level implements the details of the CM JOBS. The following are the 5 types of CM JOBS:

REPAIR-IN-PLACE (RIP) JOB - the defective component can be repaired in place on the aircraft. Parts may be needed.

REMOVE/REPLACE (RR) JOB - the defective component is removed and replaced with another. RR JOBS may lead to cannibalizing other aircraft to speed repair.

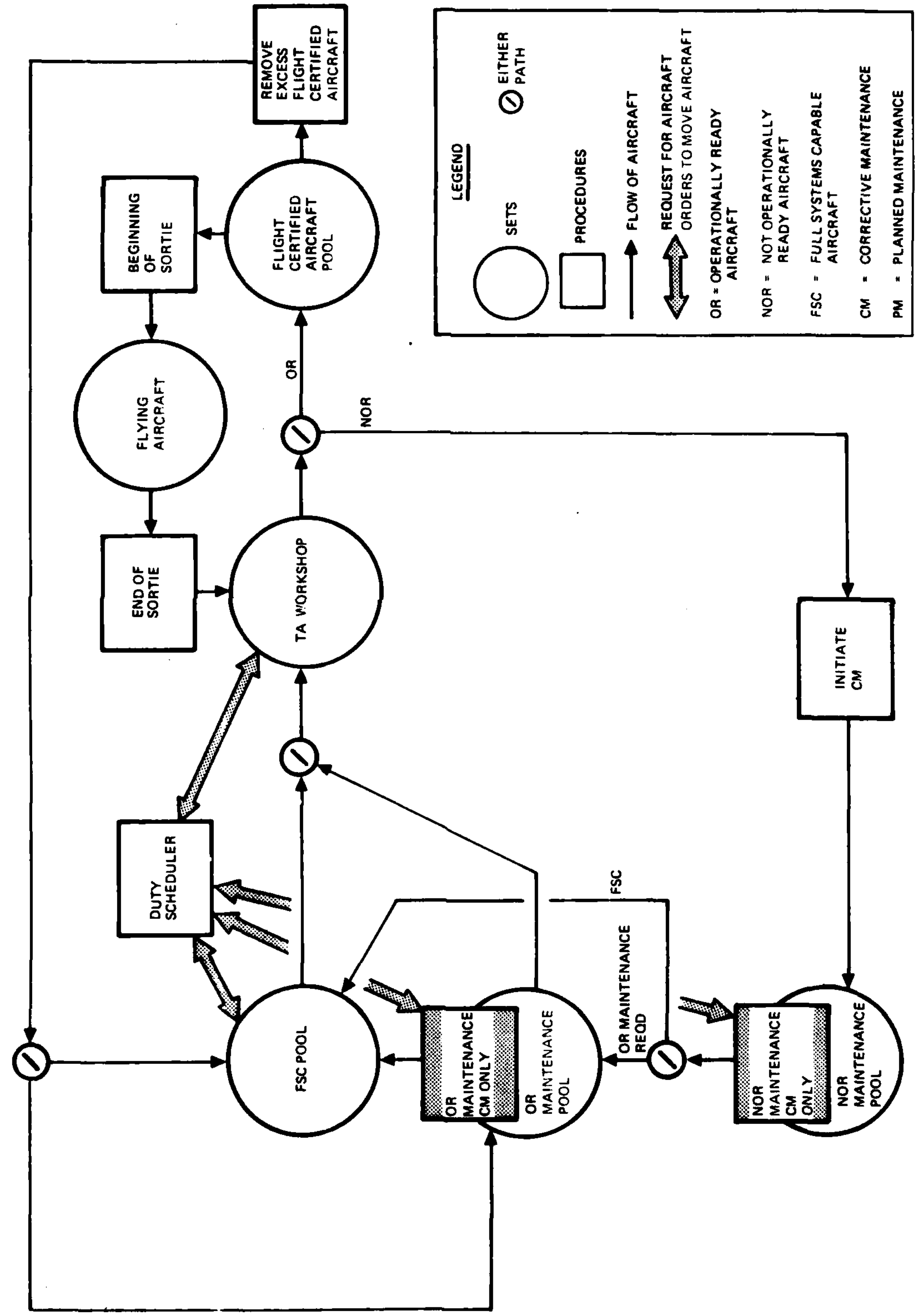


Figure A-3. Level III - Corrective Maintenance : Repairing Failures

TROUBLESHOOTING (TS) JOB - If the troubleshooting time extends beyond the normal 5 to 10 minutes, the troubleshooting action is considered to be a separate job. Following TS JOB an RR or RIP JOB is generated to repair the component.

NO DEFECT (ND) JOB - the troubleshooting job fails to detect the failure reported by the flight crew (squawk).

CANNIBALIZATION (C) JOB - the parts required for an RR JOB have long delays. The good part is removed from a NOR aircraft to hasten repair. When the part finally does arrive, it is replaced into the NOR aircraft that was cannibalized. Cannibalization has been designed but not yet included in the model.

The CM jobs, with the exception of cannibalization, are shown schematically in Figures A-4, A-5, A-6 and A-7. All of these jobs occur when the aircraft are in the OR MAINTENANCE POOL or the NOR MAINTENANCE POOL. The principal distinguishing features are the following:

REPAIR-IN-PLACE (RIP) JOB (Figure A-4). The job begins when an aircraft is placed in the OR MAINTENANCE POOL or the NOR MAINTENANCE POOL after a component failure has been detected. People are required briefly to determine if facilities are available and/or parts are required. If either is required, the program waits until both are available. The time of the wait is determined statistically. This will be explained later.

Once parts and facilities are available, the job commences as soon as the proper complement of people is available. The duration of the work is also determined statistically. If a Collateral Duty Inspector (CDI) has been working on the job, no inspection is required. Otherwise a CDI inspection is required.

At the completion of the job, it is determined (based on probabilities provided as input) whether an undiagnosed failure (Type II) or damage (Type d) error has been made. If an error occurred, the component remains failed but the job is completed. The failed component will be found by inspection at a later time. At the time of discovery, a new job is generated. If a Type II error does not occur, the component is reset to good.

REMOVE/REPLACE (RR) JOB (Figure A-5). The RR job is very similar to the RIP job with the following exceptions:

1. Facilities are required before it can be determined if a part delay will be required.

2. Cannibalization can occur to speed delivery. At this time, cannibalization is not included. Future improvements in the model will correct the simplification.

TROUBLESHOOTING (TS) JOB (Figure A-6). These jobs require facilities only. Parts are not required. After the facilities are available and people are found, work commences. At the conclusion of the TS job, an RR or RIP job is generated. Errors and CDI inspection do not occur during this job.

NO DEFECT (ND) JOB (Figure A-7). Following a flight crew squawk, troubleshooting begins but no defect is found. This job is equivalent to a TS Job where no defect is found.

Personnel

The model includes 3 skill levels of personnel:

Collateral Duty Inspectors (CDIs)
Senior Technicians (SENIORS)
Junior Technicians (JUNIORS)

They are arranged in work centers in each of several shifts. Initially, for each shift, a specified complement of men is assigned to a work center. Depending on the subsystem that fails, personnel from the appropriate work center are selected to repair the failure. Each corrective maintenance (CM) job requires at least 1 CDI or SENIOR. If no CDI's worked on the job, an additional CDI inspection following completion of the repair is required. Subject to the above conditions, JUNIORS are preferentially chosen to work on a job.

People are assigned preferentially to work on jobs with the shortest estimated time to repair. At the conclusion of the job, the people are returned to the work center for reassignment. At the completion of the shift, all jobs are stopped, all personnel are returned to the work center. The workers from the next shift are then assigned, based on the same criteria.

Occasionally, an OR aircraft is required when none are available except those currently undergoing maintenance. In such cases, the DUTY SCHEDULER firsts selects the OR aircraft with the fewest jobs to be completed, then discontinues all jobs on the selected aircraft and moves the aircraft into the TA WORKSHOP. When this occurs, the personnel (who had been performing maintenance on the selected aircraft) are returned to their respective work centers.

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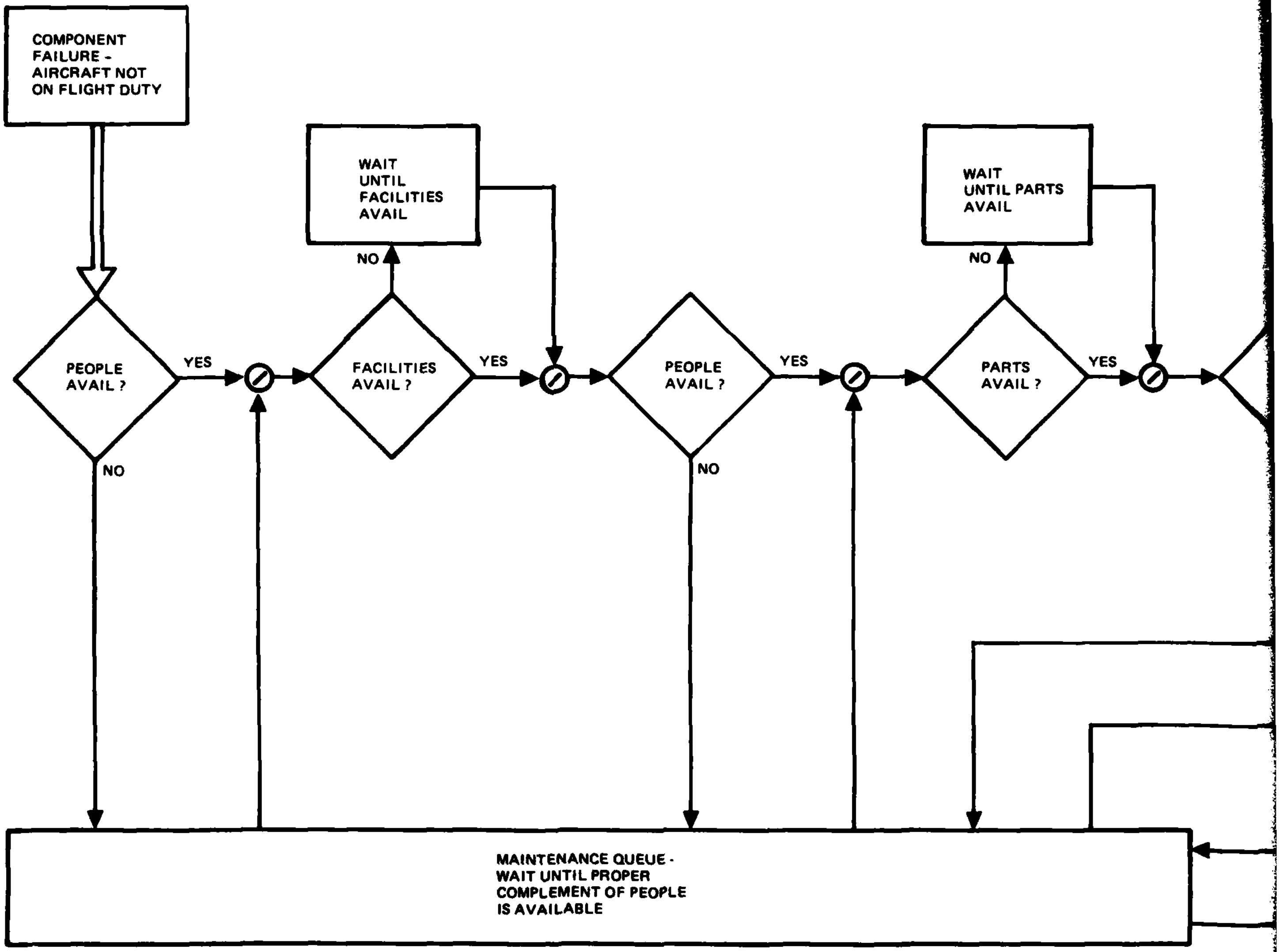

COMPONENT FAILURE - AIRCRAFT NOT ON FLIGHT DUTY
PEOPLE AVAIL ?
YES
NO
WAIT UNTIL FACILITIES AVAIL
NO
FACILITIES AVAIL ?
YES
PEOPLE AVAIL ?
YES
NO
WAIT UNTIL PARTS AVAIL
NO
PARTS AVAIL ?
YES
MAINTENANCE QUEUE - WAIT UNTIL PROPER COMPLEMENT OF PEOPLE IS AVAILABLE

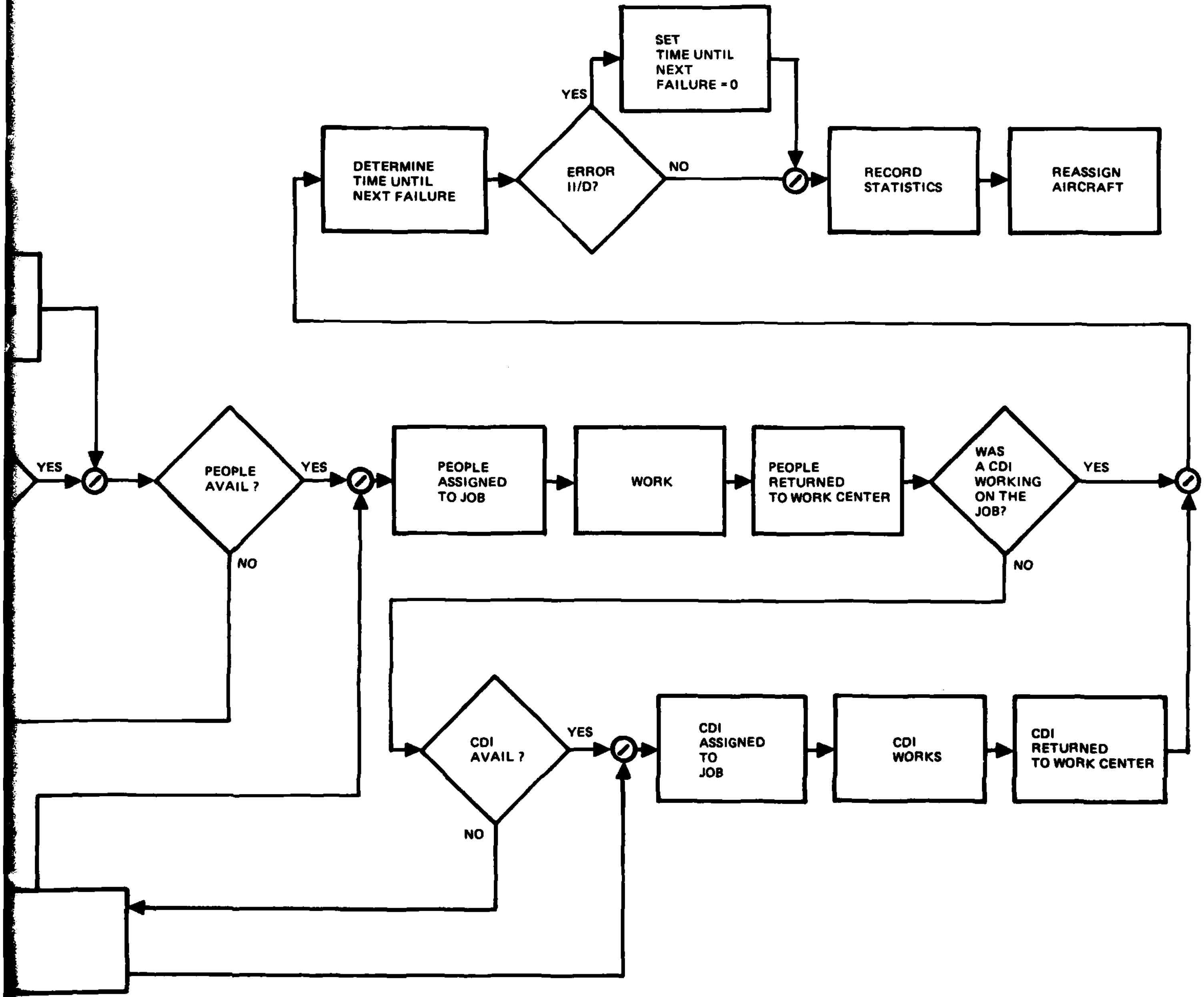
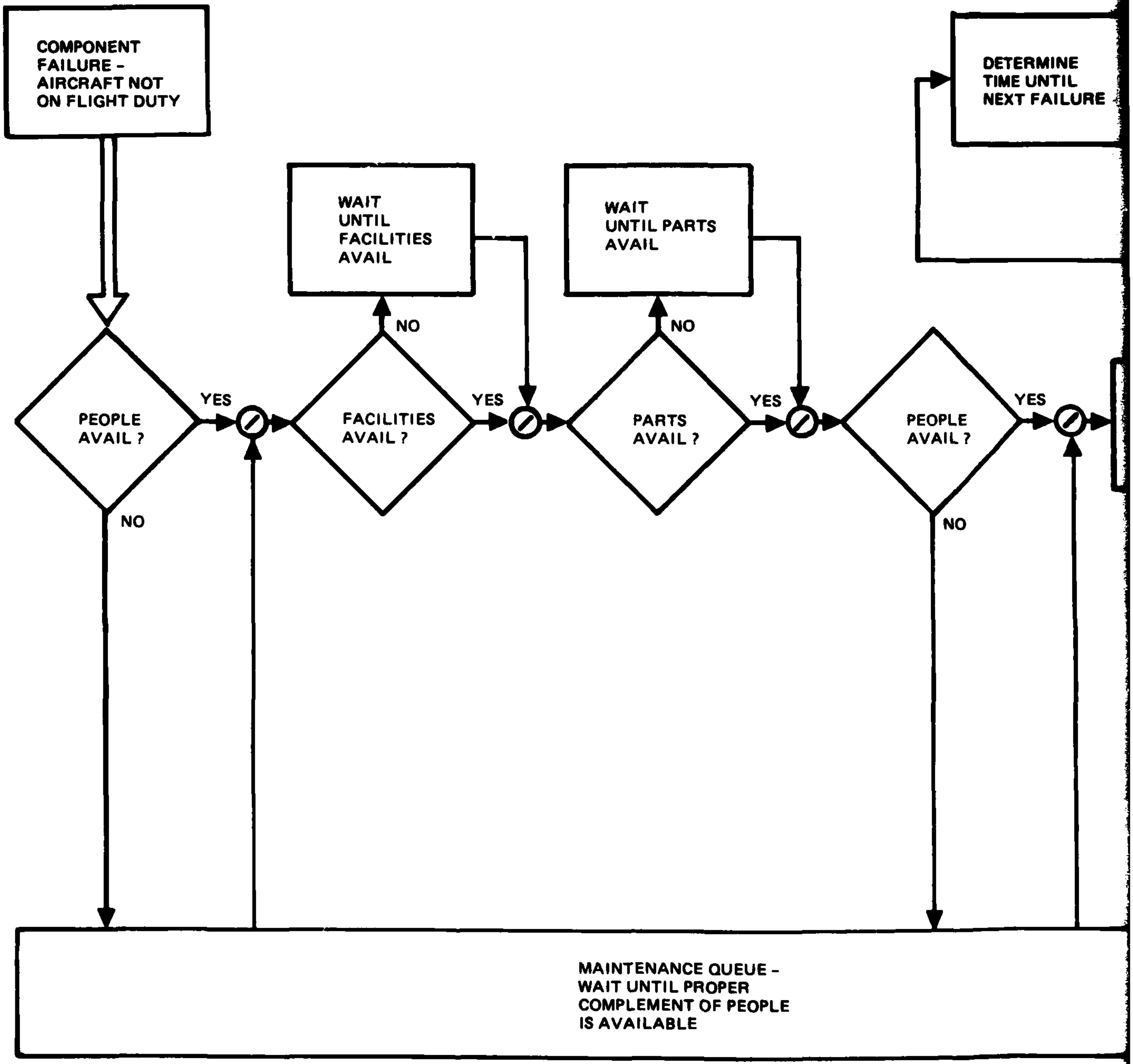


Figure A-4. Repair-In-Place (RIP) Jobs


COMPONENT FAILURE - AIRCRAFT NOT ON FLIGHT DUTY
PEOPLE AVAIL ?
YES
NO
WAIT UNTIL FACILITIES AVAIL
FACILITIES AVAIL ?
YES
NO
WAIT UNTIL PARTS AVAIL
PARTS AVAIL ?
YES
NO
PEOPLE AVAIL ?
YES
NO
DETERMINE TIME UNTIL NEXT FAILURE
MAINTENANCE QUEUE - WAIT UNTIL PROPER COMPLEMENT OF PEOPLE IS AVAILABLE

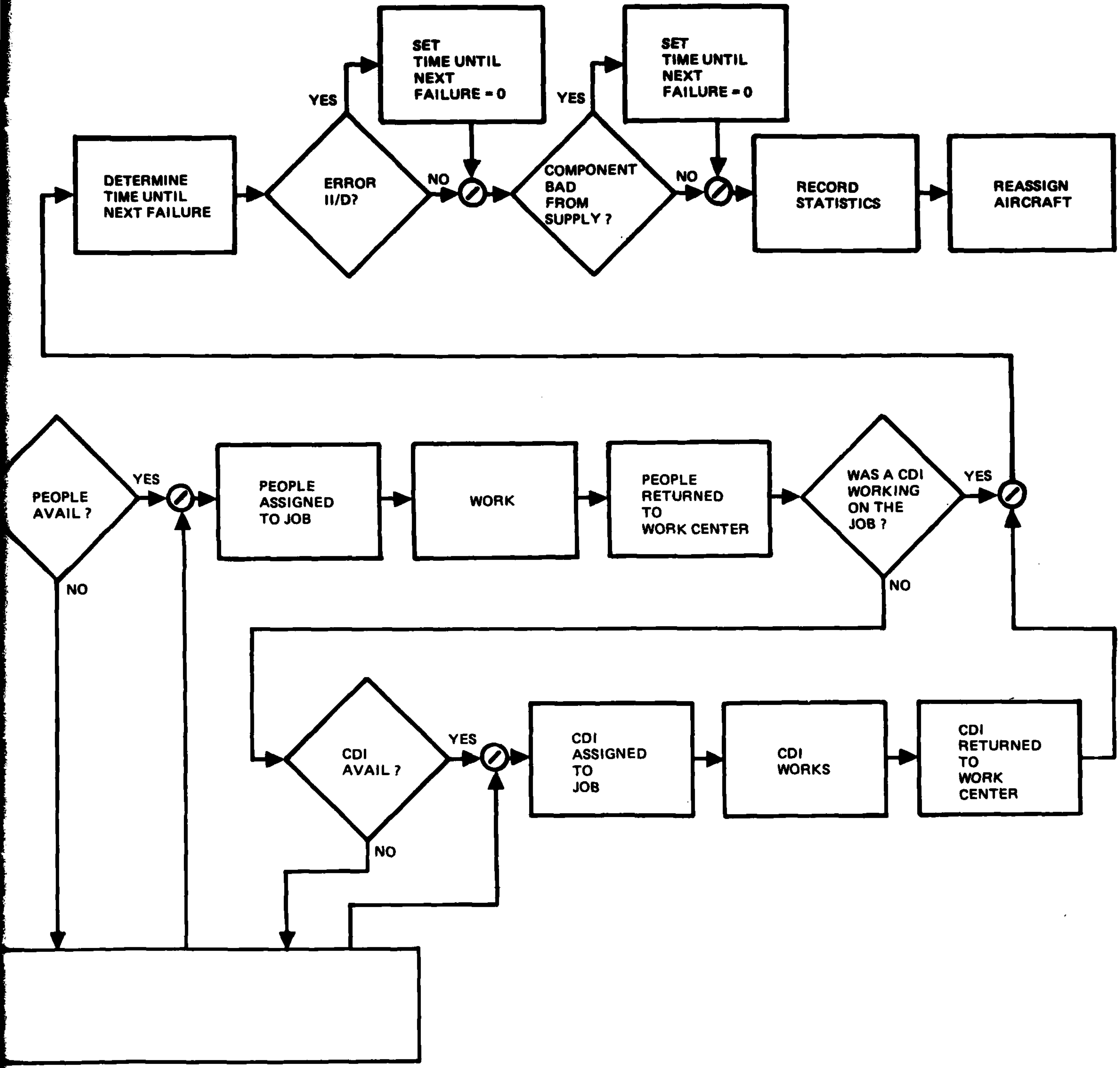
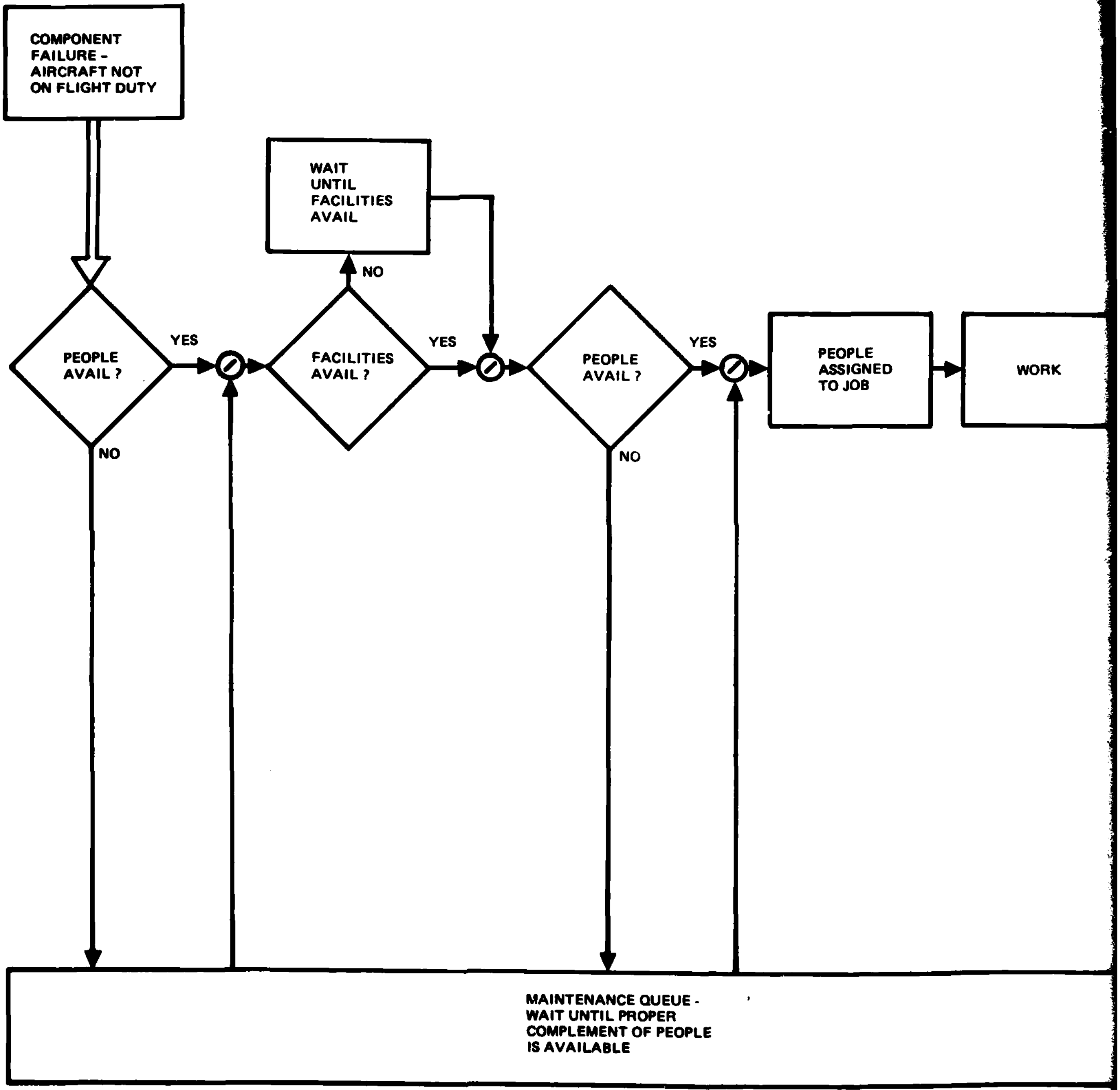


Figure A-5. Remove/Replace (RR) Jobs


COMPONENT FAILURE - AIRCRAFT NOT ON FLIGHT DUTY
PEOPLE AVAIL ?
YES
NO
WAIT UNTIL FACILITIES AVAIL
NO
FACILITIES AVAIL ?
YES
PEOPLE AVAIL ?
YES
NO
PEOPLE ASSIGNED TO JOB
WORK
MAINTENANCE QUEUE - WAIT UNTIL PROPER COMPLEMENT OF PEOPLE IS AVAILABLE

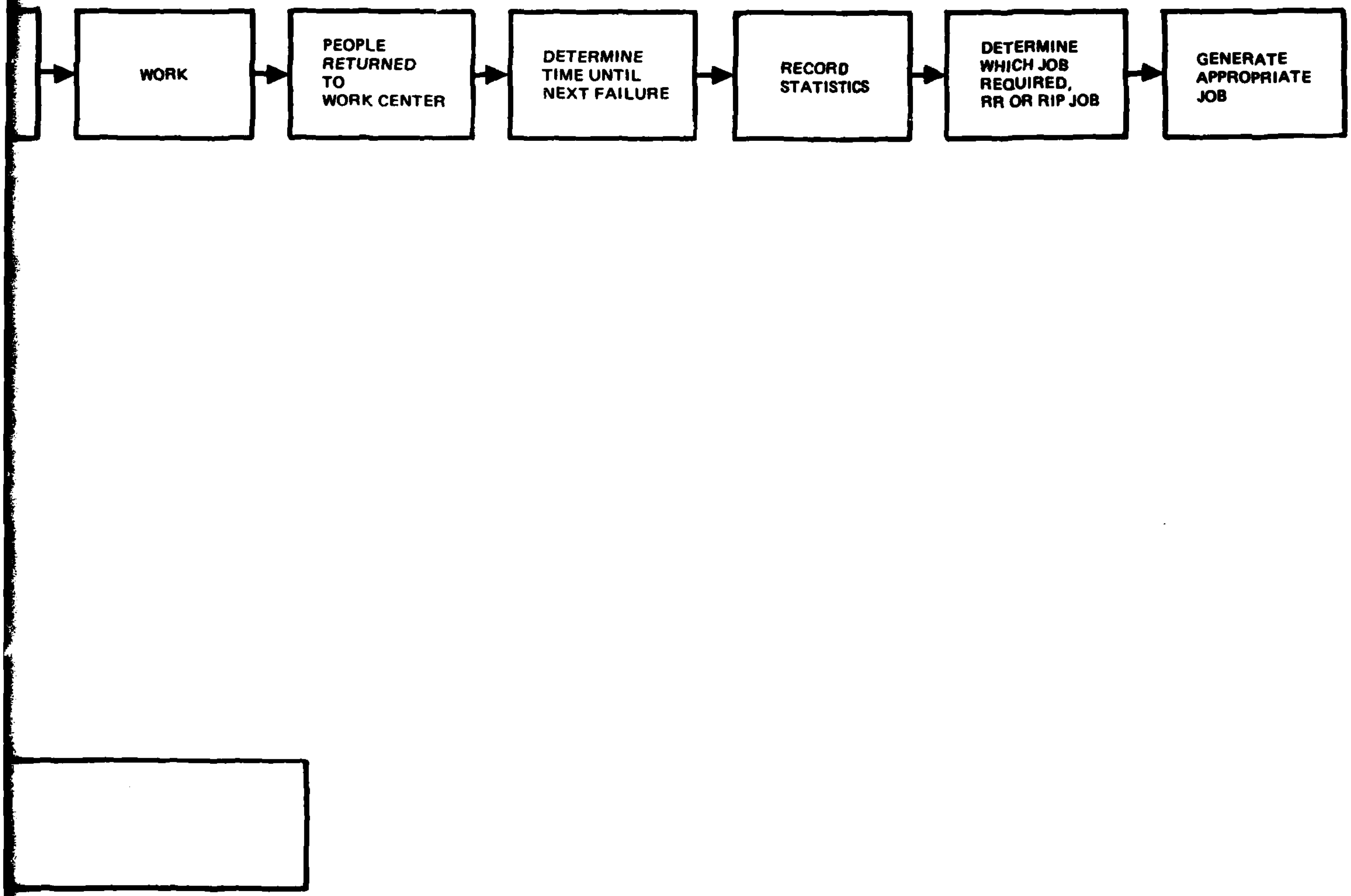
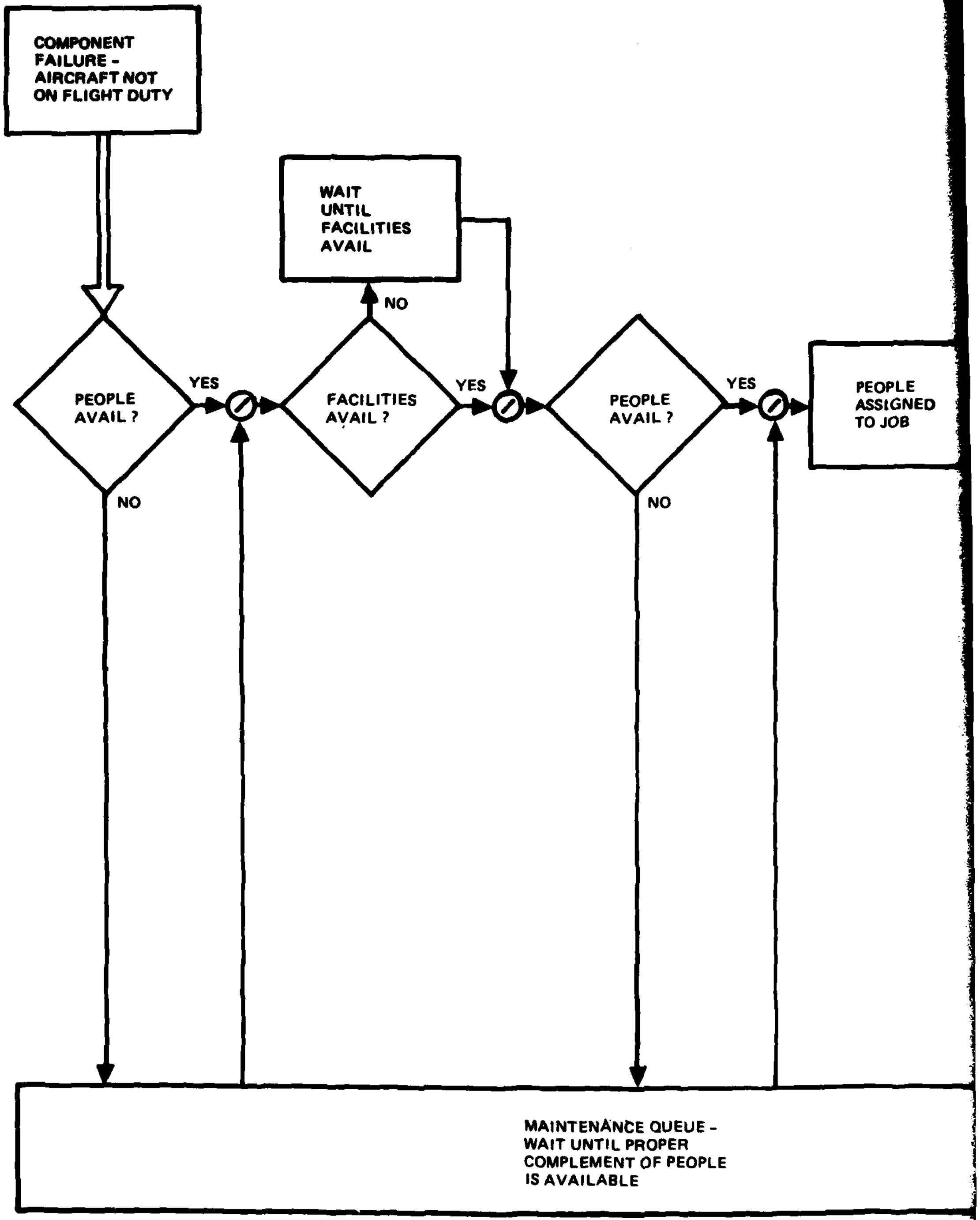


Figure A-6. Troubleshooting (TS) Jobs


COMPONENT FAILURE - AIRCRAFT NOT ON FLIGHT DUTY
PEOPLE AVAIL ?
YES
NO
WAIT UNTIL FACILITIES AVAIL
NO
FACILITIES AVAIL ?
YES
PEOPLE AVAIL ?
YES
NO
PEOPLE ASSIGNED TO JOB
MAINTENANCE QUEUE - WAIT UNTIL PROPER COMPLEMENT OF PEOPLE IS AVAILABLE

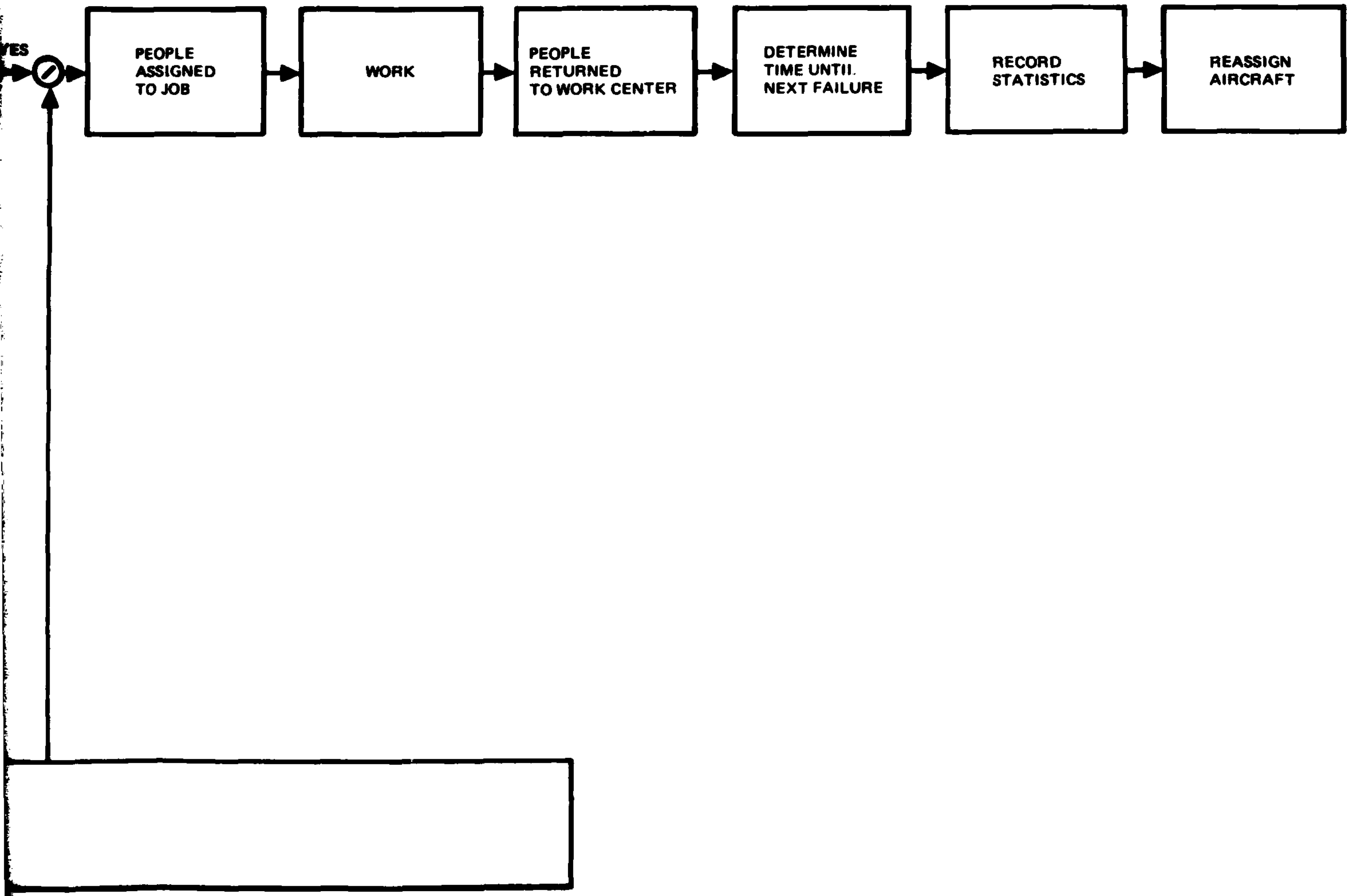


Figure A-7. No Defect (ND) Jobs

Much of the information relevant to human performance is derived from statistical analysis of the actual data. This information includes elapsed maintenance time (EMT) and the number of men required. For a given job, the EMT and number of men are determined by a random draw from the statistical data.

Details of the Various Jobs

There are only slight variations in details among the CM jobs, as shown in Figures A-4 through A-7. Because of basic similarities among the jobs, the Repair-In-Place (RIP) job will be described.

Once a component failure is detected, the job to complete the repair is generated. The job cannot begin until several conditions are met. First, the aircraft must not be on flight duty, i.e., must be in either the OR MAINTENANCE POOL or the NOR MAINTENANCE POOL. Once an aircraft is placed in the appropriate maintenance pool, all repair jobs for that aircraft are awaiting personnel. As soon as people of the proper skill level become available at the work center that repairs the defective component, the job begins. The personnel are required only for a brief time to determine which facilities are required. Should the facilities not be available, the job must wait until they become available.

When facilities are available, personnel are again required to determine the parts required. If the parts are unavailable, the job can continue only when the parts become available. At this stage of development, both facilities and parts delay are determined statistically by component from distributions derived from the 3-M data. Determining parts delays is simpler than determining facilities delays, but less correctly approximates reality. (Should actual quantitative and more correct measures of facilities and parts delays be desired later, they can be included in the model.) All facilities and parts required to complete the job are now present.

As people again become available, they are assigned to work on the job. The time required to complete the job — the elapsed maintenance time (EMT) — is selected at random from a statistical distribution from the actual 3-M data. After work, the job is completed, and the personnel are returned to the work center. If all personnel working the job are JUNIORS and SENIORS, an additional CDI inspection is required. A small percentage of the EMT will have been left over for the inspection. When the CDI is available, he is assigned to the job to complete the inspection, and is then released.

The job is now completed. The flight time until the next failure (FTNF) is selected from an observed distribution. The error check which follows next is described later in this report. Following the error check, all statistics of the job (EMT, manhours, parts delays, and failed components) are recorded.

The other types of jobs contain substantially the same elements. The troubleshooting job, after it is complete, generates an additional RR or RIP job to do the repair actually discovered in troubleshooting.

As soon as a failure is detected, a job to repair the component is generated. The decision as to which of the types of jobs is required is determined from 3-M statistics by component.

After all statistics have been recorded, the aircraft is returned to the proper pool: OR MAINTENANCE, NOR MAINTENANCE, or FSC. It has been noted that maintenance can be interrupted on OR aircraft at any time if an aircraft is needed for flight. At the conclusion of the required flights (when the aircraft is returned to one of the maintenance pools) the jobs may continue when facilities, parts, or people become available.

Errors

One of the important aspects of the AMES Model is its consideration of human errors. The model includes the following types of errors:

- Undetected failure errors
- Damage errors
- Parts bad from supply
- Unjustified removal errors
- No defect errors

The manner in which each error is incorporated in the model is now described. Since at this time undetected failure (Type II) errors and damage (Type d) errors are difficult to separate in the 3-M statistics, they are considered collectively (Type II/d).

The manifestation of both undetected failure and damage errors is that a particular component on an aircraft is thought to be good when it is, actually faulty. The errors are discovered at the completion of all but troubleshooting jobs. (Following a troubleshooting job, the component still has not been repaired.) When such errors occur, the status of the component is "defective". The failure will be discovered later.

Parts bad from supply are handled in a similar way. If a part is defective when it is placed into an aircraft, it will be detected subsequently.

Unjustified removal (Type I) errors cause removal of good components. They only occur in RR jobs. To handle this error, additional RR jobs are generated statistically.

No defect errors are handled similarly to unjustified removal errors, except extra ND jobs are generated.

LEVEL IV - PLANNED MAINTENANCE, INCLUDING FLIGHT INSPECTIONS

The fourth level adds planned maintenance (PM) (see Figure A-8). This level can be divided into the following sections:

- Planned Maintenance Overview
- PM Scheduling
- Turnaround and Daily Inspections
- PM Jobs

Planned Maintenance Overview

Since each type of PM is performed frequently, there are relatively few problems like facility delays, parts delays, or human errors. PM has been included in a simple way because it does account for a significant fraction of the maintenance manhours. Occasionally, aircraft availability is also limited because of overdue PM. For these reasons, the form of PM is different from CM.

Planned maintenance, as implemented in AMES, is divided into special inspections, phased inspections, daily inspections, turnaround inspections, conditional inspections, and corrosion control. Planned replacement and compliance with technical directives are not included in the model at this time.

All of the above types included in the model have requirements based on three denominations: calendar time, flight hours, and number of flights. Special inspection can be denominated in any of the three. Phased inspection is only denominated in flight hours. Daily inspection is only denominated in calendar time.

PM Scheduling

Each of the PM and inspection requirements must be repeated at specified intervals of calendar time, flight hours, or flights. The specified intervals will be called the nominal intervals. To facilitate all other maintenance, the requirements may be accomplished at any time within a required tolerance of the nominal interval.

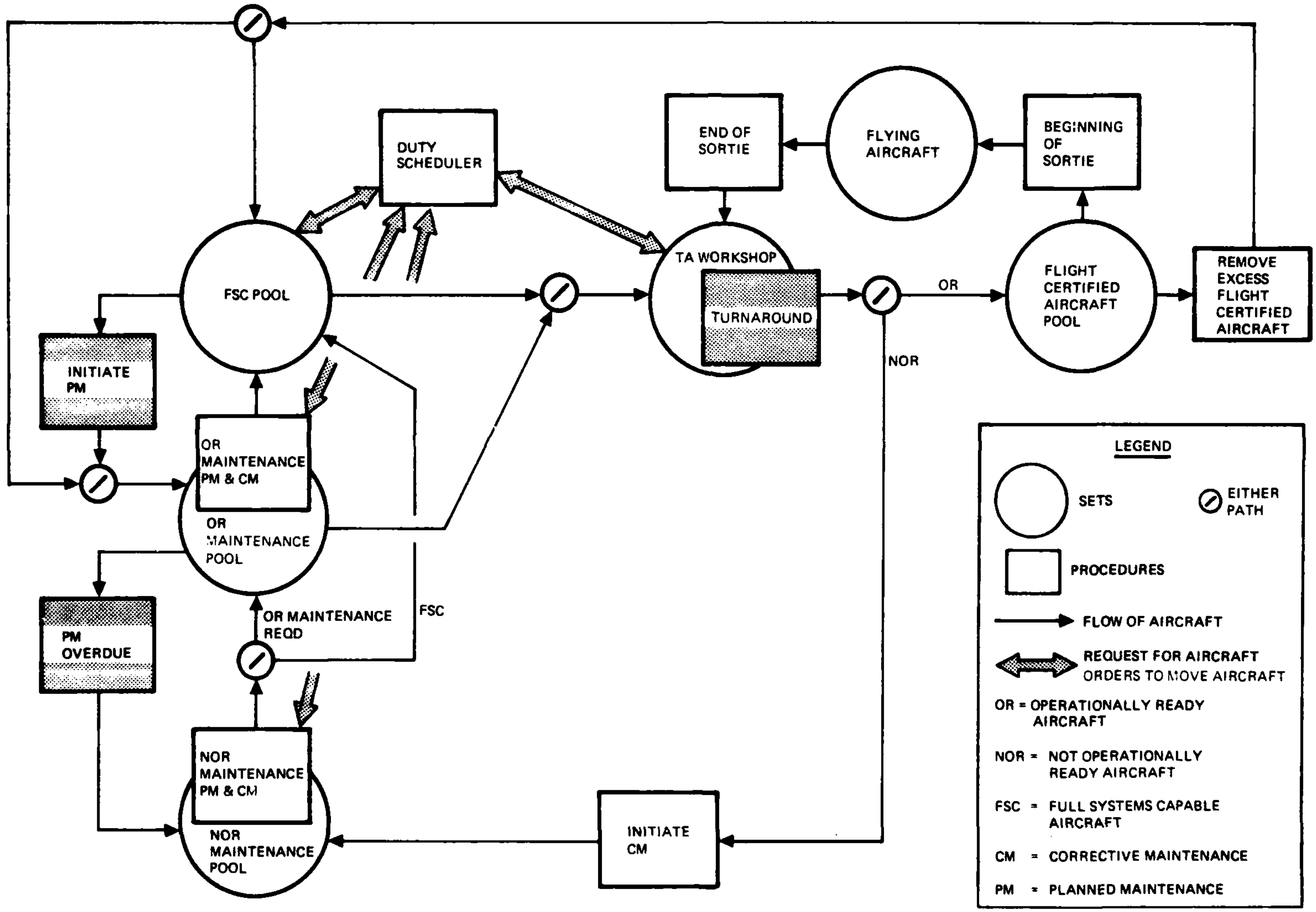


Figure A-8. Level IV - Planned Maintenance, Including Flight Inspections

For example, a PM requirement every 500 hours (the nominal value) can be performed within a tolerance of 10%. The requirement is within the allowable limits if it begins after at least 450 flight hours and is completed before 550 flight hours. If the aircraft accumulates in excess of 550 hours since the last performance of the specified maintenance, it becomes NOR and may not fly until the maintenance is completed. The tolerances are shown explicitly as follows:

- For requirements denominated in calendar time, the requirements must be completed within 3 days of the nominal value to be within the acceptable range.

- For requirements denominated in flight hours or flights, the acceptable tolerance is 10% of the nominal value.

The program must make every effort to assure that people are available to accomplish planned maintenance when it is required. A system was designed to help the AMES Model effectively allocate maintenance personnel to perform planned maintenance within acceptable tolerances. The interval when a planned maintenance requirement may be accomplished within tolerance has been divided into three equal intervals. Each of the three intervals is treated as a different stage of priority. To these, a fourth stage of priority is added when the requirement becomes overdue. The four stages of priority are as follows:

1. Early - first interval - personnel will be assigned, if available, if the aircraft is in the OR MAINTENANCE POOL or the NOR MAINTENANCE POOL. The early stage is the first one third of the tolerated interval.

2. Nominal - second interval - personnel may be assigned, but only if the aircraft is not required for flight and the maintenance personnel required are available.

3. Critical - third interval - personnel will be assigned unless no personnel are available. Unless the aircraft is required for flight, the aircraft will be placed where maintenance may begin (OR MAINTENANCE POOL or NOR MAINTENANCE POOL).

4. NOR - past the tolerated limits - the aircraft is no longer suitable for flight until the PM is completed. The aircaft will be placed in the NOR MAINTENANCE POOL if it is not there already. Personnel will be assigned as soon as they become available with preference given only to inspection or maintenance required for flight.

Turnaround and Daily Inspections

The turnaround and daily inspections have not been included until this level. Turnaround and daily inspections are treated here separately because they are PM requirements that depend on both flight and calendar requirements.

Turnaround inspection is required before the first flight of the day, between flights, and following the last flight. It is not required when the aircraft is not flying. Turnaround inspection is scheduled automatically every time the aircraft is put into the TA WORKSHOP. Turnaround inspection is valid for 24 hours.

The daily inspection is required before flight. It is valid for 24 hours if the aircraft is to fly, unless the aircraft undergoes CM. If the aircraft does not fly, the daily inspection is required every 72 hours. At the conclusion of each daily inspection, a new daily inspection is scheduled for 72 hours hence. Each time the aircraft enters the TA WORKSHOP from the FSC POOL or the OR MAINTENANCE POOL, it is determined if the aircraft requires a daily inspection to fly. If required, the daily inspection is done in the TA WORKSHOP.

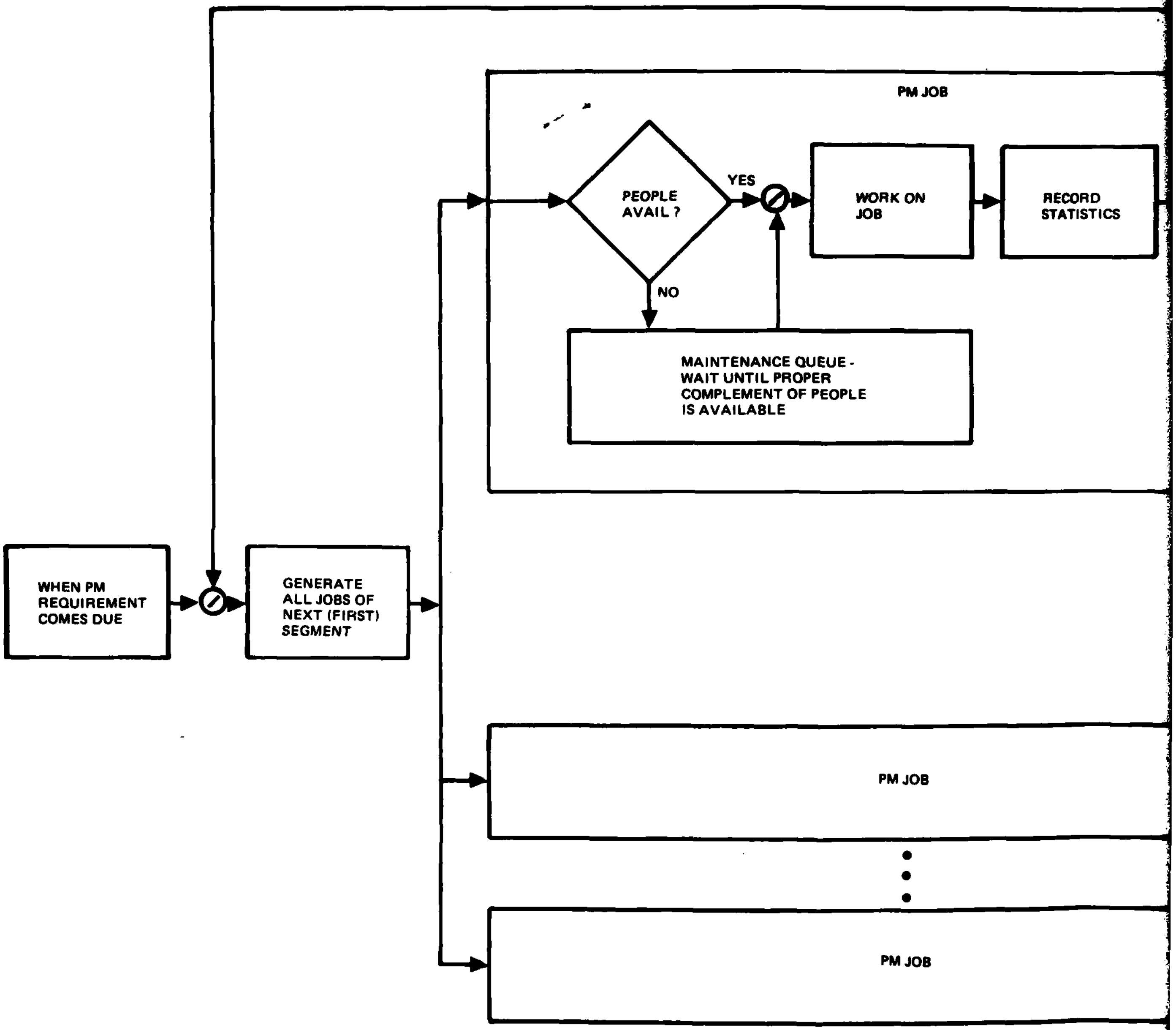
Since both turnaround and daily inspections are flight related, they have the highest priority.

PM Requirements

The structure of PM requirements differs from that of CM jobs. Each PM requirement consists of a set of segments. Each segment may include work at several work centers. That part of the work of a segment at a given work center is called (by the model) a PM work center job (or simply PM job). Each segment may have several PM jobs. Each of these jobs has a fixed time. Figure A-9 shows schematically how a PM requirement is completed.

Each of the PM jobs is like a CM job, but much simpler. As shown in the insert of Figure A-9, all that is required is to wait for people. When people are available, the work commences. At completion, the people are released and statistics are recorded.

When all of the PM jobs in the segment are completed, the next segment is begun. After all of the segments of the PM requirement are finished, the next PM requirement is scheduled and the aircraft is reassigned.


WHEN PM REQUIREMENT COMES DUE
GENERATE ALL JOBS OF NEXT (FIRST) SEGMENT
PM JOB
PEOPLE AVAIL ?
YES
NO
WORK ON JOB
RECORD STATISTICS
MAINTENANCE QUEUE - WAIT UNTIL PROPER COMPLEMENT OF PEOPLE IS AVAILABLE
PM JOB
PM JOB

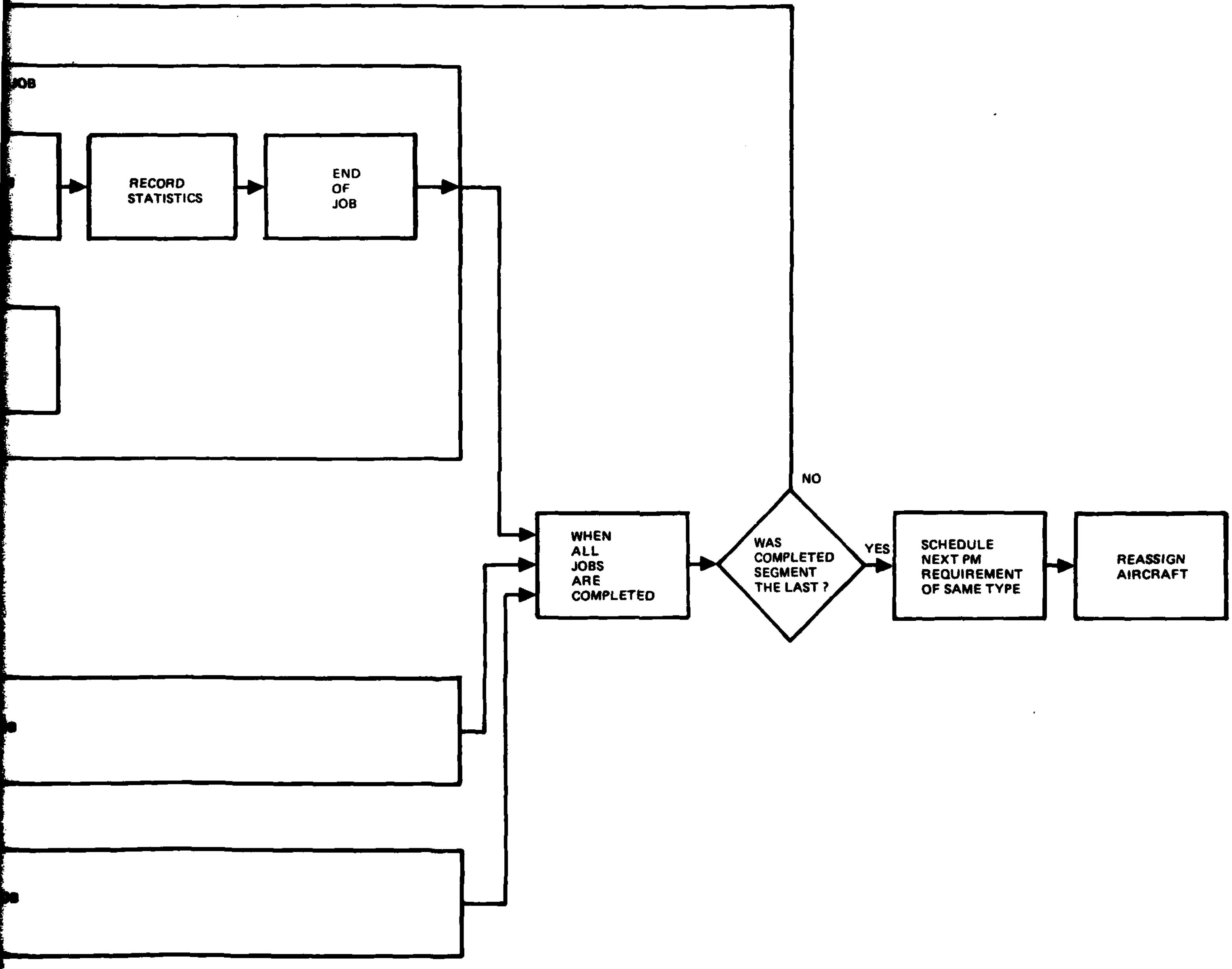


Figure A-9. Planned Maintenance (PM) Requirements

All PM jobs, except phased maintenance, may be interrupted. Phased maintenance may not be interrupted until a requirement is completed.

LEVEL V - PRIORITY REPAIR FOR IMMEDIATE MISSION ASSIGNMENT

Since the primary purpose of the aircraft is to fly missions, every effort must be made to procure an aircraft before a mission is scrubbed. As shown in Figure A-10, when the aircraft is needed, the DUTY SCHEDULER first looks for aircraft in this order: in the FSC POOL, in the OR MAINTENANCE POOL not actually undergoing maintenance, and finally in the OR MANTENANCE POOL actually being worked on. When an OR aircraft is found, maintenance is discontinued immediately; the aircraft is transferred to the TA WORKSHOP for flight preparation.

If the aircraft is NOR, the components or PM requirements causing the aircraft NOR status must be repaired before flight is possible. Facilitating of the repair can be accomplished by making sure that people are available. Since assignment of people is based on a priority system, raising the priority and reassigning people expedites the job.

This priority repair can occur in two situations:

1. NOR failure is discovered, in turnaround inspection, that requires less than 4 hours to repair (based on parts, facilities, and anticipated time to repair). The repair is accomplished using personnel from a special work center on the flight deck (in the TA WORKSHOP).

2. An aircraft is required, none are available in the OR MAINTENANCE POOL, and there is a NOR aircraft that can be repaired in less than 4 hours.

In both of these cases, the aircraft is placed in the PRIORITY MAINTENANCE POOL with a high priority exceeded only by priorities for turnaround and daily inspections. Priority repair is not permitted on aircraft with overdue PM requirements.

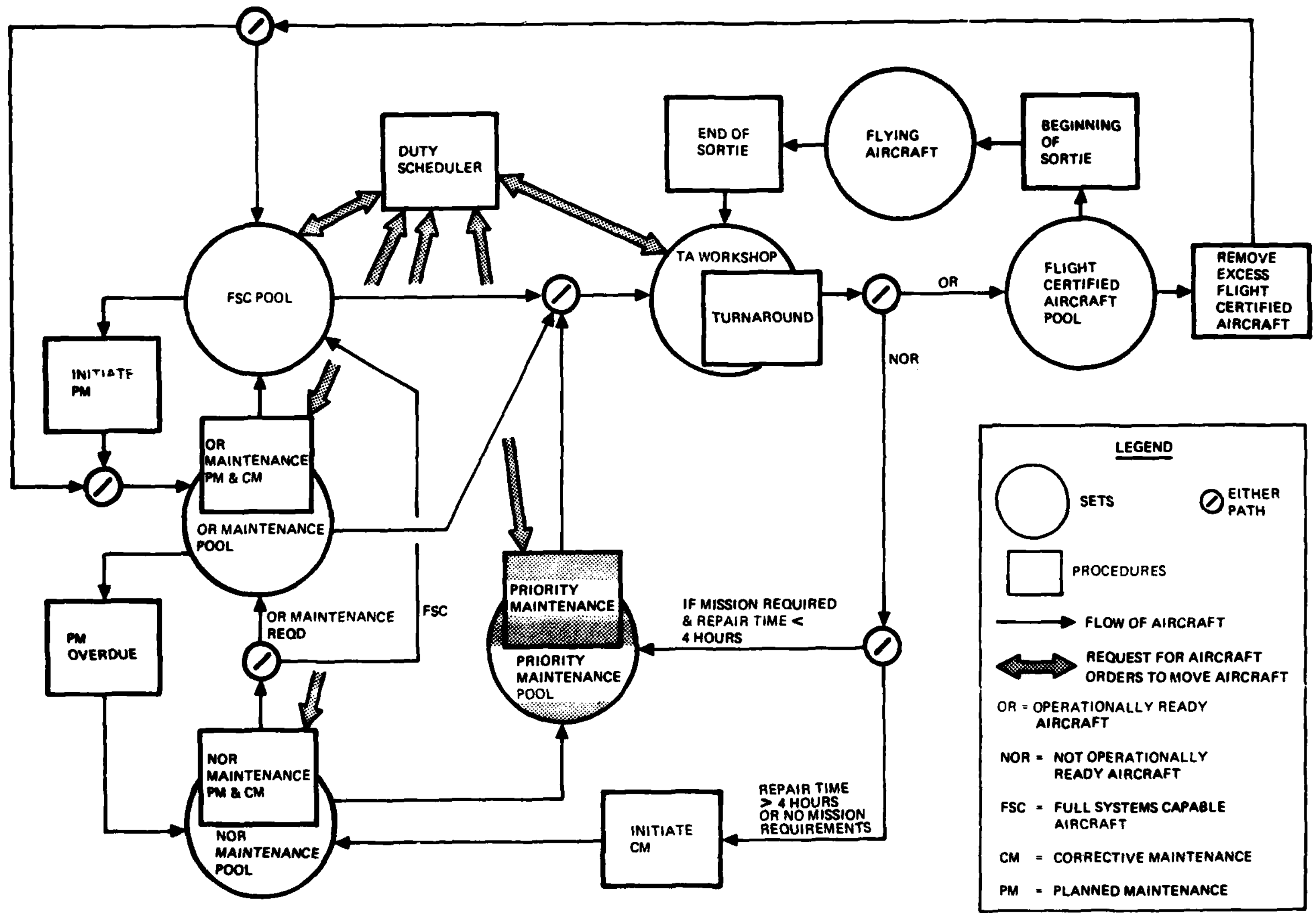


Figure A-10. Level V - Priority Repair for Immediate Mission Assignment

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