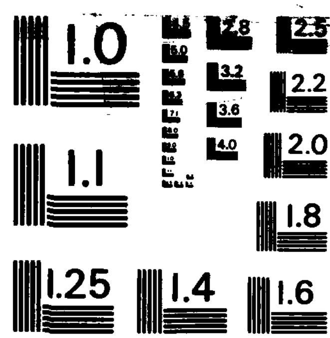
AD-A141 175 B-1B AVIONICS/AUTOMATIC TEST EQUIPMENT: MAINTENANCE QUEUEING ANALYSIS(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING 1/2

UNCLASSIFIED L M ROARK DEC 83 AFIT/GOR/OS/83D-11 F/G 15/5 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFIT/GOR/OS/83D-11

B-1B AVIONICS/AUTOMATIC TEST EQUIPMENT: MAINTENANCE QUEUEING ANALYSIS

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Operations Research

Lance M. Roark, B.S.

Captain, USAF

December 1983

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

ADA 141 175

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFIT/GOR/OS/83D-11	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: School of Engineering; 6b. OFFICE SYMBOL (If applicable): AFIT/ENS	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code): Air Force Institute of Technology, Wright-Patterson AFB, Ohio 45433	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT NO.
11. TITLE (Include Security Classification): See Box 19	

12. PERSONAL AUTHOR(S): Lance M. Roark, B.S., Capt, USAF

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
MS Thesis	FROM ______ TO ______	1983 December	125

16. SUPPLEMENTARY NOTATION

Approved for public release: IAW AFR 190-17.
LYNN E. WOLAVER 7 May 84
Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB OH 45433

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Queueing Theory, Simulation, Avionics Maintenance, Station Loading
12	2		
15	5		

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

Title: B-1B AVIONICS/ATE MAINTENANCE QUEUEING ANALYSIS

Thesis Advisor: James Bexfield, Lt Col, USAF

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Ken Feldman, Maj, USAF	513-429-1543	AFIT/ENS

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

The purpose of this research effort was to develop a technique to determine B-1B automatic test equipment (ATE) station quantities required to support the B-1B avionics components at base level. As part of this effort, both simulation and analytical solutions were developed. A detailed and complex simulation model was developed in the Q-GERT simulation language. In addition, an analytical model was developed based on the theory of open queueing networks and other queueing techniques. However, the analytical model required many crude and simplifying assumptions, and the analytical results were not entirely satisfactory. The Q-GERT simulation model was selected as the best choice for the remainder of the research effort.

Two techniques were developed to determine test station quantities based on the model output. The first technique was to buy sufficient test stations to achieve a four day maximum base repair cycle time for the avionics components. The second technique was to conduct a cost-benefit analysis by comparing the costs of additional test stations (and the benefits of shorter repair cycle times) to the benefits of fewer test stations (and the costs of longer repair cycle times). Considerable sensitivity analysis was performed with the simulation model, and the research effort concludes with a range of management options for consideration by the B-1B System Program Office.

AFIT/GOR/OS/83D-11

B-1B AVIONICS/AUTOMATIC TEST EQUIPMENT:

MAINTENANCE QUEUEING ANALYSIS

THESIS

Lance M. Roark
Captain, USAF

AFIT/GOR/OS/83D-11

Approved for public release; distribution unlimited

B-1B Avionics/Automatic Test Equipment:

Maintenance Queueing Analysis

I. Background and Problem Statement

Background

Modern USAF aircraft have complex avionics components which require frequent unscheduled maintenance. As part of their maintenance concept, USAF aircraft are delivered to their bases with complex and expensive automatic test equipment (ATE). Avionics components, called line replaceable units (LRUs), are removed from the aircraft when a malfunction is detected and are taken to a nearby repair shop where the ATE is located. Maintenance technicians then use the ATE for fault detection, isolation, and ultimately repair of the avionics LRU. The ATE consists of specialized test stations. Each test station is devoted to a different grouping of the avionics LRUs. For example, one test station might be used for the repair of radio frequency (RF) LRUs, while another test station might be used for the repair of digital computer LRUs. Since there are many aircraft at each base, and since each aircraft has many complex LRUs, there may be numerous LRUs sent to the repair

Preface

This research effort is a queueing analysis of B-1B avionics maintenance. In this analysis, the queueing "customers" are the avionics components of the B-1B, and the queueing "servers" are automatic test equipment stations. To solve this queueing situation, both analytical and simulation techniques were considered. In looking at any queueing situation, I believe it is very worthwhile to try both simulation and analytical techniques, and to keep an open mind about which technique is best until both are developed.

I am in obligation to my thesis advisor, Lt Col Jim Bexfield, for his guidance and expertise in queueing theory. My thesis reader, Maj Ken Feldman, provided helpful advice from a real-world management point of view. I would also like to thank Lt Col Dick Diehl and Lt Col Tom Clark for getting me started on this project. Finally, I would like to thank the many people at the B-1B System Program Office and at Headquarters Strategic Air Command who helped me keep the project going.

Lance M. Roark

Table of Contents

List of Figures

List of Tables

Abstract

The purpose of this research effort was to develop a technique to determine B-1B automatic test equipment (ATE) station quantities required to support the B-1B avionics components at base level. As part of this effort, both simulation and analytical solutions were developed. A detailed and complex simulation model was developed in the Q-GERT simulation language. In addition, an analytical model was developed based on the theory of open queueing networks and other queueing techniques. However, the analytical model required many crude and simplifying assumptions, and the analytical results were not entirely satisfactory. The Q-GERT simulation model was selected as the best choice for the remainder of the research effort.

Two techniques were developed to determine test station quantities based on the model output. The first technique was to buy sufficient test stations to achieve a four day maximum base repair cycle time for the avionics components. The second technique was to conduct a cost-benefit analysis by comparing the costs of additional test stations (and the benefits of shorter repair cycle times) to the benefits of fewer test stations (and the costs of longer repair cycle

times). Considerable sensitivity analysis was peformed the simulation model, and the research effort concludes a range of management options for consideration by the B System Program Office.

shop each day. This may generate a significant workload on each of the test stations.

The workload of avionics on ATE test stations is of particular interest to the B-1B System Program Office (SPO). The ATE which will be deployed with the B-1B bomber consists of four specialized test station types which will be used to support over 100 avionics LRUs. Unless the B-1B SPO has the ability to quantify and predict this workload, the SPO will be uncertain as to the best quantity of test stations of each type to procure for each B-1B base. Not buying sufficient test stations would degrade B-1B avionics readiness; buying too many test stations would be needlessly expensive. A technique to estimate the avionics workload on the ATE would not only be useful for decision-making about the best quantity of test stations to procure, but could also be used to justify ATE funding requirements. Due to the tremendous lead times involved in the procurement process, such decision-making must take place very early in the life of the B-1B program.

Statement of Problem

The B-1B SPO needs a technique, and ultimately a model, which can be used to analyze ATE test station requirements. The B-1B SPO will continually update its information, and therefore needs its own model and user's manual. This model would be used to examine the tradeoffs of cost versus avionics readiness. This model would also be useful for "what if" trade studies (for example, impact of different operational or maintenance concepts).

Objective of the Research

The overall objective of the research effort was to provide the B-1B SPO with a computerized model which provides the capability to assess the avionics maintenance workload on ATE test stations. Further, the research effort needed to develop criteria and procedures for selecting the best quantities of stations once the workload had been measured. This was accomplished by the sequential attainment of the following subobjectives:

1. It was essential to develop a detailed and accurate description (model) of B-1B avionics maintenance. As part of this description, it was necessary to consider all possible factors that could have a bearing on the avionics maintenance workload on ATE test stations. This description was obtained from a review of various B-1B logistics and maintenance planning documents and also from personal interviews with personnel from the B-1B SPO and HQ SAC. This conceptual description of avionics maintenance was to become the framework of all subsequent model development.

2. Since the research effort involved a practical application, it was necessary to obtain, collect, and review relevant data needed for the model development. B-1B operational data (such as number of aircraft per base, flying hours per aircraft per month, etc.) were obtained from the B-1B SPO. Reliability and maintainability estimates for each avionics LRU were obtained from the B-1B associate contractors. In addition, operational reliability and maintainability data were collected from actual experience with the F-16 fighter and the B-52 Offensive Avionics System (OAS) update. The data were examined by goodness-of-fit tests and other techniques to determine the most realistic probability distributions which were eventually incorporated during the model development.

3. A very detailed and complex simulation model of B-1B avionics maintenance was developed. This model was developed in the Q-GERT simulation language. The model simulates the flow of avionics LRUs from LRU failure to LRU repair (and return to base supply). Once the model was developed, the next step was to design the simulation experiment. As part of this experimental design, variance reduction techniques were used. The model was also used for sensitivity analysis since much of the data inputs were preliminary contractor estimates.

4. A second model, based on queueing theory, was developed. The analytical model was based on the theory of queueing networks and other advanced techniques. The analytical model, not surprisingly, requires many more simplifying assumptions than does the simulation model. The queueing theory approach includes writing the balance equations and then solving these equations by a numerical technique. The research effort also examined the tradeoffs between simulation and analytical techniques for this particular application and concluded that the simulation model was best suited for the B-1B SPO.

5. The research effort also included two tradeoff studies on avionics maintenance. First, it was necessary to conduct a cost-benefit analysis on procurement of additional test stations versus procurement of additional LRU spares. This was part of the effort in determining the best quantities of stations to procure. Second, the impact of a hypothetical B-1B deployment for a major conventional war was considered.

Literature Search and Review

Since this proposed thesis research involved a queueing analysis of B-1B avionics, the focus of the literature search has been on the mathematical techniques of queueing theory. In queueing theory, "customers" stand in line (called a queue) awaiting service by some type of service facility. The time between arrivals of the customer and also the time to serve a customer are usually described by some probability distribution. In this thesis effort, the customers represent avionics LRUs, and the act of service represents maintenance of a LRU on the ATE test station. Queueing theory will be used to determine the minimum number of test stations (by type) which can accommodate the maintenance workload at each base.

With any queueing system, the system must be designed so that the mean system capacity to process customers can handle the average workload of customers. If this is not the case, a "traffic jam" or bottleneck will result and the queue site will grow indefinitely. But even if the mean system capacity can handle the average workload, a "traffic jam" can still occur because the actual volume of workload fluctuates (in a statistical sense). Because of these fluctuations, the queue size may become too big or the time a customer spends in the queueing system may be unacceptably high (1:1). The main purpose of queueing analysis is to precisely measure the queue size and the time a customer spends in the system.

Queueing theory, in its most ambitious form, can be used to analyze a queueing network or system. A queueing network is often represented as a set of queues, and the network may process many different types or classes of customers. The individual queues are usually described in terms of numbers of servers, queueing (scheduling) disciplines, and probability distributions for the service and arrival times at each of the queues. Some queueing networks can be represented as Markov processes. A Markov process represents a system as a generally discrete set of disjoint states. In the case of queueing theory, the state of the system or network is usually the number of customers awaiting service at each of the queues. The set of states and the transitions between the states define a set of linear equations. By adding an equation which states that the state probabilities must add to one, it is possible, at least in principle, to derive the equilibrium probability of each state (2:25). However, more complicated situations cannot be solved in practice, and it is necessary to resort to computer simulation to obtain any results for the queueing analysis.

If the state probabilities can be obtained, it is usually desirable to condense this information into performance measures of the queueing system. These performance measures can then be used to assess the adequacy of the queueing system. In the case of simulation models, the performance measures are typically estimated directly. In any event, the most common measures of performance for a queueing system are the average number of customers in the system, the average number of customers waiting in queue, the average amount of time a customer spends in the system, and finally the average amount of time a customer waits in queue (3:261). In some cases, it is possible to compute these performance measurements directly without explicitly computing the system state probabilities.

The most common queueing model is a single server exponential model. "Single server" means that there is only one server to process customers; customers stand in line before this server and wait for their turn to be served. "Exponential" means that both the time between customer arrivals and the time to service each customer have exponential probability distributions. This is a relatively simple and popular model, and it can be found in many texts such as Ross. Ross has described the mathematics of the state probabilities and the system performance measurements in full detail (3:264-267).

There are many extensions to the single server exponential model. Ross has developed the solution to the case where the queue for the single server has a finite capacity (3:270-272). Cooper presents the case where the arrival of customers follows a "quasi-random process". In such a process, the requests for service are generated by a finite number of sources where each source follows an exponential distribution (4:102-116). This contrasts with the simple single server exponential model described earlier, because in the simple model the customers arrive from an infinitely large population of sources. Finally, Kleinrock describes the most general exponential model. It allows for the queueing system to have more than one server, a finite capacity queue, and a finite population of sources (5:108-110). Almost all other exponential models are special or limiting cases of this general model.

Cooper also develops a model which allows for different types of customers. The customers still arrive and are served according to an exponential distribution, but the different types of customers are allowed to have different mean service times. The equations of state probabilities cannot be solved directly for such a model, but they can be approximated by a finite state space and solved iteratively by a numerical technique such as Gauss-Seidel iteration (4:123,158-165).

There are also many applications where the service time is not exponential, but can be approximated by a sum or weighted average of exponential distributions. In mathematical terms, the service time has an Erlang or a hyperexponential probability distribution. Such an approximation is valid for many situations since the analyst can control the variance of the model service time relative to the mean of the model service time by the selection of an appropriate sum or weighted average. Cooper develops a solution to such a model; the solution is called the method of phases (4:171-175). This technique allows the transformation of a general service time model into essentially an exponential service time model. In this technique, the states represent not the number of customers in the system, but rather the number of exponential phases yet to be completed in the system. This technique may also be applied to cases where the time between customer arrivals is not exponential.

It is possible to analyze multiple queue systems called networks in which a customer requires service at more than one queueing station. Customers enter the system at various points, queue for service, and then proceed to some other point in the network to receive additional service. Kleinrock shows that if each queue has exponential service times, and if the time between arrivals (from outside the network) at each queue is also exponential, and if the customers move from one queue to another according to a specified probability distribution, then each queue can be separately analyzed and solved by the simple exponential model (5:147-161). A special case of this is the closed network, which has a fixed and finite number of customers. Customers circulate throughout the system but never leave it, and no new customers may enter the system (6:14-15).

If the analysis of the network can be broken down to analysis of the individual queues, the solution of the network is relatively inexpensive. However, there are many applications which cannot be solved by this technique since they do not meet the restrictive assumptions. Sauer and Chandy discuss many of these applications which include simultaneous resource possession, priority queue disciplines (where the customers are not served first-in, first-out), and other variations of the queueing network. Sauer and Chandy discuss techniques which can be used to obtain numerical approximations to these applications (2:26-30).

An even more general model has been developed by Basket, et al, which allows for many different classes of customers in the network. The model also allows for several different service disciplines, and for a broad class of service time distributions. The model was developed to describe a computer system as a network of processors and a collection of customers (jobs and tasks). Different service centers may have different queueing disciplines. Different customers may have different routes through the network; customers may also change from one class to another when changing service centers. The solution calculates the marginal distribution of the number of customers at each queue (7:248-260). Cox, as an AFIT thesis, has written a FORTRAN computer program which solves the model of Basket, et al. His computer program uses special algorithms which are computationally efficient for large networks (8:3-3,3-26).

Traditionally, the most common technique used to model avionics maintenance is computer simulation. Clark and Allen have developed a Q-GERT simulation program which is a model of F-111 avionics and automatic test equipment maintenance. The model considers not only the failures and repairs of avionics LRUs, but also the failures and repairs of the ATE itself. The model also considers the impact of scarce resources such as maintenance technicians or spare parts (12:394-397). The F-16 prime contractor, General Dynamics, has also developed a simulation model of the avionics maintenance workload on ATE. The General Dynamics model, called the Station Loading Model, is a FORTRAN computer program which uses Monte Carlo (random number) techniques to simulate the arrivals and repair of avionics LRUs. The model is very detailed in the modeling of the maintenance of the LRUs and has separate inputs for set up, ATE warm up, primary test time, and other maintenance task times. General Dynamics has also written a Station Loading Model User's Manual which explains the inputs, logic, and outputs of the model (13).

Three AFIT/LS students (Bryson, Husby, and Webb) in 1982 wrote a joint thesis on a simulation model of F-16 avionics maintenance. The F-16 research effort was similar in purpose to the current B-1B research effort, and similarly involved the development of a Q-GERT simulation model. This previous research effort was of particular interest since the F-16 ATE is very similar to the B-1B ATE. The two ATE programs have a high degree of hardware commonality since they are both manufactured by the same vendor. There were four serious deficiencies in the F-16 thesis effort. First, the authors chose to model only one station type, and only one "representative" LRU. However, in reality, the actual workload on a test station is the cumulative impact of many LRUs. Second, the authors only modeled the peacetime maintenance of F-16 avionics, and failed to consider the F-16 wartime surge requirement (and associated deployments and increase in flying hours). Third, the model ignored the impacts of ATE test station failures and maintenance, the impacts of maintenance technician manning constraints, or the impacts of occasional spare part shortages. Fourth, the authors recognized the need to examine the tradeoffs between the costs of longer waiting times (and the benefits of buying fewer test stations) and the benefits of shorter waiting times (and the costs of buying more test stations). However, they failed to develop a technique to measure or quantify this tradeoff (14).

Simulation has many advantages for the modeling of avionics maintenance. It allows for tremendous flexibility in the development of models. A simulation model can be structured to reflect maintenance shift changes and the impact of scarce resources. In addition, many different probability distributions may be used in a simulation model. However, Cooper points out many disadvantages to a simulation approach. First, there is always some uncertainty as to when equilibrium (steady state) is reached. Second, simulation introduces a sampling error since the model results are based on only a finite number of events. Finally, an error is introduced by the random number generator. Cooper concludes that simulation should only be used when mathematical analysis is not feasible.

Queueing theory is a useful analytical technique which can be used to study many situations involving customers (avionics LRUs) waiting for service (maintenance). The actual queueing model developed in this research effort involved the combination of three techniques. Specifically, the solution technique to be described later uses Kleinrock's discussion of queueing networks, Cooper's discussion of the method of phases approximation, and Cooper's numerical approach for problems with classes of customers with different mean service times. However, the actual analytical queueing model still required many simplifying assumptions, and the results obtained were not entirely satisfactory. The simulation model could accomodate a more realistic (and complex) approach. The simulation model developed for this research effort used many features taken liberally from the Clark and Allen model and the General Dynamics Station Loading Model.

II. B-1B Avionics Maintenance

B-1B Program Description

The B-1B is a new multi-role bomber which will eventually replace the B-52 as the penetrating bomber element of the strategic TRIAD. The B-1B also has collateral missions as a conventional bomber or as a cru missile launch platform. The B-1B could potentially be for naval and theatre conventional warfare, or for theat nuclear warfare. Current plans call for the production deployment of a force of 100 B-1B aircraft assigned to f main operating bases (MOBs). Delivery of 26 aircraft to #1 will start in June 1985, delivery of 16 aircraft to M #2 will start in September 1986, delivery of 32 aircraft MOB #3 will start in January 1987, and delivery of 16 aircraft to MOB #4 will start in October 1987. Each B-1 squadron consists of 16 Primary Aircraft Authorizations (PAA). MOB #1 also has an additonal 10 aircraft for a Combat Crew Training Squadron (CCTS). MOB #3 will be th base for two squadrons. It should be noted that the PAA total assigned to the MOBs consists only of 90 aircraft; this allows for a reserve of 10 aircraft to allow for aircraft attrition or airframe maintenance at a depot (16:II-1).

The B-1B has an integrated avionics system totaling over 424 installed line replaceable units (LRUs) of which there are approximately 212 repairable LRUs. Tentatively, 109 LRUs have been designated for base level repair on the B-1B automatic test equipment (ATE). Other repairable LRUs are designated for base level repair on other support equipment or for depot level repair. The B-1B avionics consist of offensive avionics, defensive avionics, and miscellaneous avionics associated with other systems. The B-1B offensive avionics uses updated B-52 Offensive Avionics System (OAS) equipment as well as a terrain following radar and a new inertial navigation system. The B-1B defensive avionics consists of a complex electronic countermeasures (ECM) system known as the ALQ-161. A smart jamming enhancement and a tail warning function have also been included on the B-1B. Another important avionics system is the Central Integrated Test System (CITS). CITS is an automated system that performs fault isolation and verification of system performance in real time. It provides information both to the crew during flight and on the ground for maintenance debriefing and troubleshooting. It is on the CITS data, for the most part, that the organzational level maintenance actions are based (16:I-1).

Organizational Level Maintenance

Organizational level maintenance consists of those tasks normally performed on-aircraft (on the flight line) by SAC maintenance technicians. For the avionics LRUs, this maintenance consists of debriefing, fault isolation, removal and replacement of the failed LRU, and clean-up tasks such as documentation (16:II-2). The crew debriefing is at the end of each flight. Typically, the B-1B air crew communicates discrepancies to the maintenance team chief on the ground while the aircraft is returning to base. The maintenance chief then calls the appropriate maintenance personnel to the crew debriefing room. When the crew arrives, each crew member is matched with his maintenance counterpart to discuss the malfunctions and to agree on the description of the discrepancy which will then be written in various maintenance documents. Maintenance will then be performed to remedy each discrepancy (17). For avionics LRUs, it is usually first necessary for the maintenance technicians to isolate the cause of the discrepancy to a single LRU. For example, a reported radar system discrepancy may be found to be due to a failed radar antenna. The CITS information will be used by the technicians for the fault isolation. Whenever the CITS information is ambiguous or incomplete, the maintenance technicians would have to engage in manual troubleshooting to find the failed LRUs. Once the fault is found, the maintenance technicians remove the failed LRU from the aircraft and replace it with a good LRU (obtained from base supply) of the same type. The technicians then perform a system verification to ensure that the discrepancy has been resolved. Once the technicians complete the maintenance, they then fill out all maintenance documentation and also take the failed LRU to a production control point of the Avionics Maintenance Squadron (AMS) at intermediate level.

Organizational level maintenance is performed by maintenance technicians from the Organizational Maintenance Squadron (OMS). The OMS technicians not only remove and replace LRUs, but also service the aircraft and conduct various pre-flight and post-flight inspections. Each aircraft has a dedicated maintenance team headed by a team chief (usually a Master Sergeant). The OMS technicians are not avionics specialists, and have no intermediate level duties. For this reason, they might occassionally call for special assistance from the AMS technicians if required (21).

Intermediate Level Maintenance

The intermediate level shops, which are located at base level, house the specialist activities that maintain and support the aircraft systems. One of the most important organizations at intermediate level is the AMS, which is responsible for the repair of the failed avionics LRUs. The repair of LRUs designated for maintenance on the B-1B ATE is an AMS responsibility, although the AMS has other duties as well.

The scheduling of avionics LRU repair is accomplished approximately on a first-come, first-serve basis. However, there might be an adjustment to allow for a higher priority for LRUs with a low spare asset posture. Once scheduled, an AMS technician repairs the LRU on the ATE test station of the appropriate type. In most cases, the technician is able to successfully repair the LRU at intermediate level; such a maintenance action is designated as Repairable This Station (RTS). For an RTS maintenance action, the repair takes place in a complicated sequence of events. First, the technician must set up the LRU on the ATE test station. The LRU is physically connected to the station via an interface test adapter (ITA). The technician then runs a performance test until the fault in the LRU is found. The fault is usually in one of the printed circuit boards of the LRU. The printed circuit boards are known as shop replaceable units (SRUs). Once the bad SRU is identified, the technician goes to supply to get a good replacement SRU. A small number of high failure rate SRUs are kept in a forward supply point; other SRUs are obtained from base supply. In any event, the technician removes the bad SRU from the LRU and replaces it with the good SRU. The technician then runs one complete performance test to verify the success of the repair. The repaired LRU is then removed from the station and taken to base supply. The technician also fills out all required maintenance documentation. Repairs may not always be this simple, however. The performance test may not always be able to fault isolate to a single SRU. Rather, the test might only fault isolate to a group of SRUs, or may indicate ambiguous results. In such a case, the technician resorts to manual troubleshooting to precisely locate the fault. Another complication is that not all maintenance actions lead to actual repairs. One possibility is that the LRU has failed in a way which is beyond the capability of the AMS to repair. For example, if the failure has occurred in a chassis of the LRU, and not a removeable SRU, the LRU would then be sent to depot for repair. Such a maintenance action is called Not Repairable This Station (NRTS). The LRU is then sent to depot (for greater facilities and higher skill level technicians) for repair. Another possibility is that the AMS technician cannot find any problem with the LRU. This might occur if the LRU was unnecessarily removed, or if there is some incompatibility between the CITS and the ATE. This type of mainteance action is called Retest Okay (RTOK). The LRU is taken to base supply without any repair being required.

AMS technicians that repair LRUs on ATE can come from one of four branches. Each AMS technician has an Air Force Specialty Code (AFSC) which describes his particular specialty. There is a dedicated AFSC for offensive avionics LRUs, for defensive avionics LRUs, for communication and navigation LRUs, and for automatic flight control and instrument LRUs. There is no cross-utilization of personnel between branches.

ATE Maintenance

Not only do LRUs fail and require maintenance, but so do the ATE test stations themselves. The test stations, being automatic test equipment, are complex electronic devices. When a station fails, a technician must be called to repair the station. The technician actually uses the station itself as part of the repair process. The technician must first isolate the station fault to a test replaceable unit (TRU). A TRU is the station equivalent of an LRU. The technician must then further isolate the fault to a bad SRU; the technician removes and replaces the failed SRU in a manner similar to LRU repair. Station maintenance is accomplished by technicians from the Precision Measurement Equipment Laboratory (PMEL) branch of the AMS.

III. Data Collection and Gathering

B-1B ATE Source Selection

The B-1B prime contractor, Rockwell International, selected the B-1B ATE vendor by a competitive source selection. This was a source selection conducted by Rockwell and not by the Air Force. As part of the source selection process, Rockwell International required each competing potential vendor to prepare a station loading analysis (which is logistics terminology for an avionics/ATE queueing analysis). To allow each vendor the opportunity to perform such an analysis, Rockwell provided each vendor with detailed reliability and maintainability data on all of the avionics LRUs designated for repair on the ATE. This data, with two exceptions that will be explained later, became the baseline for the analysis conducted in the next two sections. This reliability and maintainability data, which was included in the Rockwell Request for Proposal (RFP), is included in the computer listing included in Appendix A. An example of this data is shown in Table I.

Table I. Sample Reliability/Maintainability Data

WUC	NOMENCLATURE	ASSOC	QTY A/C	AR RATE	RETEST % OK
58AAA	Avionics Processor	BM	8	6.671	25

TP	TS	TD	TR
124.0	20.0	16.0	26.0

The term WUC refers to a five character work unit code designation for each LRU. This particular LRU is called an avionics processor. The LRU is provided by Boeing, one of the three B-1B associate avionics contractors. There are eight avionics processors installed on every B-1B aircraft. The term AR RATE refers to the arrival rate of this particular LRU into the AMS. The arrival rates included in the Rockwell RFP were estimated by the associate contractors before March of 1983. These values were superseded by more recent contractor estimates that were available during this research effort, as explained in the next subsection. The term RETEST % OK means for this LRU that 25% of the maintenance actions will be RTOKs. The term TP refers to performance test time. The avionics processor requires 124 minutes to run one complete performance test. This is the second term in the original RFP which has been adjusted. Rockwell International estimated the LRU performance test times for a hypothetical, generic ATE design. Rockwell estimates presumably reflect the level of contemporary ATE technology. Immediately after contract award, however, the winning ATE vendor (General Dynamics Electronics) suggested that their ATE design, due to expanded ATE computer capabilities, could achieve a dramatic 60% reduction in the LRU performance test times. This means, for example, that GDE estimates that the avionics processor performance test time would only be 49.6 minutes. The GDE estimates were adopted as the baseline for this research effort. The impact of this reduction is described in the discussion on sensitivity analysis included in Section VI. The term TS is the set-up time, also in minutes, required to initially set-up the LRU on the ATE test station. The term TD refers to the time in minutes for the technician to tear-down the LRU from the ATE after the maintenance action is completed. Finally, the term TR refers to the time to repair the LRU (remove and replace an SRU) also in minutes.

In the Rockwell instructions provided in the RFP, the furnished maintainability data were expected to be used to compute the mean task times for both LRU RTS actions and LRU RTOK actions. These means would be computed as follows:

$$\text{(MEAN REPAIR TIME, RTS)} = TS + (0.5)TP + TR + TP + TD \quad (1)$$

$$\text{(MEAN TASK TIME, RTOK)} = TS + TP + TD \quad (2)$$

Note that the time for fault isolation is assumed, on the average, to be one half the time of one complete performance test. In other words, the time of fault isolation is assumed to be distributed uniformly over the first performance test. Interviews with SAC maintenance and logistics personnel (21) revealed many deficiencies in the Rockwell approach. First, it failed to account for the travel time to obtain an SRU spare for a repair (the technician who obtains the SRU spare is the same individual accomplishing the repair). Second, the mean repair time assumes that the fault isolation is always successful, and does not allow for the possibility of extended troubleshooting. Third, the equation for the mean task time of a RTOK maintenance action excludes the possibility of a second performance test. In practice, however, the technician may feel the need for a second performance test if he feels that the first test was not completely correct and unambiguous. Fourth, and finally, the Rockwell equations do not consider the possibility of a NRTS maintenance action. Refinements to these equations are proposed in the next subsection.

Reliability and Maintainability Estimates

LRU reliability estimates from each of the B-1B associate avionics contractors are regularly furnished to the B-1B SPO. The most recent estimates (as of August 1983) formed the baseline for this research effort. Reliability in a logistics sense (as opposed to an engineering sense) is measured in Mean Time Between Demand (MTBD). Demand refers to a demand on supply (which occurs when an LRU is removed from the aircraft for corrective maintenance). This includes not only true (inherent) failures, but also includes induced failures and RTOKs. The time in MTBD is measured in aircraft flying hours (and not LRU operating hours). The estimates, by LRU, are included in the computer listing included in Appendix A. In addition to the contractor estimates, MTBD estimates were also obtained from HQ SAC maintenance and logistics personnel (21). The SAC estimates were typically, but not always, significantly more pessimistic than the contractor estimates. The SAC estimates were based on the current experience of like LRUs on the B-52, FB-111, and other systems.

LRU maintainability estimates were obtained from the Rockwell International ATE RFP as explained in the last subsection. However, the lower (more optimistic) GDE performance test times were used as the baseline of this research effort. In addition, the algorithms to compute the mean task times were modified as follows:

$$\text{(MEAN REPAIR TIME, RTS)} = TS + (0.5)TP + (.75)TR + (.25)(2)TR + TP + TD \quad (3)$$

$$\text{(MEAN TASK TIME, RTOK)} = TS + TP + (0.3)TP + TD \quad (4)$$

$$\text{(MEAN TASK TIME, NRTS)} = TS + (0.5)TP + TD \quad (5)$$

These modifications were developed based on discussions with HQ SAC maintenance and logistics personnel (21). For the LRU repairs, the fault isolation to a single SRU by the performance test is assumed to be successful only 75% of the time. For the other 25%, the repair times are doubled to account for manual fault isolation. For the LRU RTOKs, it is assumed that a second performance test is run 30% of the time. The actual percentage would depend on the degree of confidence that the technician has in the ATE software (performance test). A third mean task time has been added for NRTS maintenance actions. It is assumed that the technician can successfully fault isolate, but that no repair at base level is possible. Therefore, the LRU is removed from the station to be sent to a depot for repair.

In addition to the calculation of the above mean task time estimates, the models of the next two sections also include an allowance for time to obtain a SRU spare. This only applies to repairs (RTS actions), and not to RTOK or NRTS actions. The travel time to the forward supply point is estimated at 15 minutes round trip, and the time to obtain a SRU spare from base supply is estimated at one hour. It is also estimated that a SRU spare will be available on the forward supply point 25% of the time, and will be available at base supply the remaining 75% (21).

B-1B Operational Data

As described earlier, the building block of the B-1B fleet is the 16 PAA squadron. A typical weekly flying schedule for a 16 PAA squadron was obtained from HQ SAC personnel (15). In any given week, only 8 aircraft will actually fly daily training missions. The other 8 aircraft will have alert obligations or will be undergoing scheduled (phase) inspections. The 8 aircraft that will fly missions will typically fly a total of 21 sorties in a week, leading to 107 flight hours in a week. A significant aspect of the flying schedule is that the sorties are not spread evenly during the days of the week. Typically, 3 sorties will be flown on Monday, 6 sorties on Tuesday and Wednesday, 4 sorties on Thursday, and 2 sorties will be flown on Friday. In addition, for any day of the week, the sorties are not spread evenly over the day. Sorties will typically be launched in the morning or in the late evening. What this means, from the point of view of a modeling strategy, is that the arrival rate of the avionics LRUs will not be constant over the maintenance day or during different days of the week.

In addition to B-1B flying hour data, information was also obtained (21) on maintenance technician manning levels. These values represent maintenance manpower authorizations, and are shown in Table II. Values are shown for the 16 squadron and the 10 PAA CCTS.

Table II. Maintenance Manpower Authorizations

Category	(Actual Authorizations) 16 PAA	(CCTS) 10 PAA	(Assumed Di Labor/Shi 16 PAA	(C 10
Organizational Maintenance Squadron (OMS)	128	78	38	
Communication Navigation Branch, AMS	22	10	7	
Auto Flight Control/ Instrument Branch, AMS	14	6	4	
Offensive Avionics Branch, AMS	55	18	16	
Defensive Avionics Branch, AMS	35	14	10	
Precision Measurement Equipment Laboratory Branch, AMS	18	0	5	

These manpower authorizations represent total slots available to each squadron. As a first approximation, t maintenance policy will call for two 8-hour shifts of maintenance per work day (Monday through Friday). Manpo authorizations will then be divided evenly between the t shifts. As a better approximation, the technicians may perform maintenance during the "graveyard" shift on an occasional basis as workload requirements dictate. In addition, a certain number of OMS technicians would have be available during the "graveyard" shift to launch and service aircraft. For modeling purposes, the authorizations were divided evenly between the two shifts. Moreover, only 60% of the technicians were assumed to be available for direct labor. The other 40% would account for illness, leave, or duties outside the scope of this research effort.

Goodness-of-Fit Analysis

The baseline inputs used in this research effort were reliability and maintainability estimates obtained from the B-1B associate contractors. However, the estimates represent mean values, and do not specify the distributional nature of the reliability and maintainability random variables. To select the best distributional assumptions for subsequent model development, operational data was obtained from the F-16 program and the B-52 OAS program for goodness-of-fit analysis.

The first factor considered was avionics reliability. Reliability in this context means Mean Time Between Demand (MTBD) and not the usual MTBF. It would be highly desirable to perform goodness-of-fit tests on the LRU inter-arrival times to obtain the best distributional approximation. However, actual operational maintenance data is not collected in this manner. Maintenance technicians record the time of the removal of the avionics LRU from the aircraft; it is not possible to reconstruct the actual inter-arrival times of the LRU failures. For this reason, it was only possible to test if the LRU arrival process could be approximated by a Poisson process. Another issue in testing the distribution of the LRU arrivals is the measure of time. Time could either be measured in flying hours or in calendar time. These two approaches would not be equivalent since the flying hours per base per month will not be perfectly constant; the variation in the flying hours would add to the variability of the LRU arrival process. Rather than derive a distribution for the flying hours and derive a distribution for the arrival process (in flying hours), it was simpler to fit a distribution to the LRU arrival process measured in calendar time. In the models discussed in the next two sections, flying hours per base per month are treated as a fixed constant and not as a random variable. The variability in the flying hours is reflected in the distribution of the arrival process. In any event, the key question was if the LRU arrival process could be approximated by a Poisson process.

Operational maintenance data on 19 major F-16 avionics LRUs were obtained from the F-16 SPO Centralized Data System (CDS). All of these 19 LRUs are repaired on the F-16 ATE. These LRUs were examined on an aggregate basis, and also two LRUs were examined on an individual basis. A chi-square goodness-of-fit was used to test the null hypothesis that the LRU arrival process was a Poisson process. Failing to reject the null hypothesis does not prove that the LRU arrival process is truly Poisson; it merely suggests that it should be a reasonable approximation. In examining the F-16 reliability figures, two concerns become quickly evident. First, in general, the F-16 avionics reliability had significantly improved over time since the initial F-16 deployment. To overcome this concern, the data used in the chi-square goodness-of-fit test reflected only the last six months of F-16 experience, thereby capturing a mature, steady-state situation. It should be pointed out, therefore, that the models described in the next two sections should only be used to estimate the workload during mature, steady-state experience. Second, the F-16 reliability varied considerably from one base to another. This is in part due to configuration differences, and in part due to differences in the quality of maintenance documentation. To estimate the variability at a single base, the data used in the test was generated by a single base, Nellis Air Force Base. For the data for a mature six month period from a single F-16 base, it was concluded that the Poisson process would be a reasonable approximation to the LRU arrival process. This was true for the arrivals of the two individual LRUs tested, and it was true for the aggregate arrivals of the 19 LRUs considered. Another point that needs to be mentioned is that the time interval selected (for each data point in the test) was one week. This would then, of course, smooth over any possible differences between days of the week or different times of the day. The statistical results are presented in Table III.

Table III. Results of Chi-Square Goodness-of-Fit Tests
Null Hypothesis: LRU Arrival Process is Poisson Process
(Measured on a Weekly Basis)

Test	Chi-Square Statistic	Degrees of Freedom	Significance
F-16 Inertial Navigation Unit	2.32	3	>.250
F-16 Low Power RF Unit	1.63	3	>.250
F-16 Major Avionics LRUs	2.56	4	>.250

The second factor considered was avionics repair time (or other task time) at intermediate level. Again, operational data was obtained from the F-16 program. For reasons discussed earlier, the data was obtained for a mature six month period from a single base. It was not possible to get separate data on set-up times, test times, repair times, or tear-down times; maintenance documentation is not that detailed. It was only possible to get task times for the overall maintenance action. It was possible, however, to separately analyze repairs, RTOKs, and NRTS actions. As will be seen, the mean and variance are quite different for different types of maintenance actions.

The task time was first collected for a single F-16 LRU (the low power RF unit). 52 observations were obtained for repairs (RTS actions), and 19 observations were obtained for RTOKs. There were only 3 NRTS actions during the six month period which is not sufficient to do a meaningful test. For the repairs and the RTOKs, the following distributions were tested for the possible distribution of the maintenance task times: exponential, Erlang, and lognormal. An Erlang was used instead of a (general) gamma because an Erlang is easier to simulate, and because an Erlang distribution can be used in the method of phases technique of analytical queueing theory. It would have been necessary to resort to a (general) gamma only if all Erlang distributions were poor approximations. The results for the RTS maintenance actions are shown in Table IV.

Table IV. Results of Chi-Square Goodness-of-Fit Tests
Null Hypothesis: LRU Maintenance Task Times Have Specified Distribution
(Case for RTS Maintenance Actions)

Specified Distribution	Chi-Square Statistic	Degrees of Freedom	Significance
Exponential	21.10	7	<.005
Erlang (k=2)	4.40	6	>.250
Erlang (k=3)	4.68	6	>.250
Lognormal	11.21	6	<.100

For an Erlang distribution, the ratio of the mean to the standard deviation is known to be the reciprocal of the square root of the k parameter. By taking the sample mean divided by the sample standard deviation, it was possible to obtain a point estimate of that k parameter. The test was run with k=2 and k=3 since 2 and 3 were the closest integer values to that point estimate of 2.6.

Similar results were obtained for the RTOK maintenance actions. The Erlang (this time with k=5) was judged to be a reasonable approximation. This time, the lognormal was also a reasonable approximation. Of course, with only 19 data points, it is difficult to establish a meaningful and powerful test.

At this point two assumptions were made. First, the Erlang distribution, with the right k value, could be used to approximate the maintenance task times. Second, since there was not sufficient data to perform tests on the NRTS maintenance actions, it was assumed that the distribution of a NRTS action would be the same as for a RTOK action. The next step was to look at a second F-16 LRU (the inertial navigation unit) and also a B-52 OAS LRU (the signal data converter). The purpose was to make point estimates of the coefficient of variation (the mean divided by the standard deviation) to see if there were any patterns in k-values. This data is presented in Table V.

Table V. Estimates of Coefficient of Variation

	Estimate	k-value
F-16 Low Power RF Unit		
– Repair	.622	2.6
– RTOK	.436	5.3
F-16 Inert Nav Unit		
– Repair	.745	1.8
– RTOK	.473	4.5
B-52 Signal Data Converter		
– Repair	.585	2.9
– RTOK	.531	3.5

The B-52 OAS data was not large enough, unfortunately, to conduct a meaningful goodness-of-fit test. There were only 7 repairs and only 17 RTOK actions. It should also be noted that the actual k-value of an Erlang distribution must, of course, be an integer. At this point in the research effort, it was assumed that the RTS actions could be approximated by an Erlang distribution with a k-value of 2, and that RTOK and NRTS actions could be approximated by an Erlang distribution with k=5.

IV. Simulation Model

Model Overview

A detailed Q-GERT simulation program was developed which can be used to measure the workload of avionics maintenance on intermediate level automatic test equipment (ATE). The model simulates the flow of avionics line replaceable units (LRUs) from LRU failure to LRU repair and return to base supply. This flow is shown in Figure 1. The model also simulates the failures and maintenance of the ATE test stations themselves.

The model begins with a simulation of avionics LRUs which fail on B-1B aircraft while in flight. Sorties are assumed to be launched early in the morning and at night, so the arrival rate of avionics LRUs is not constant throughout the day. The arrival rate is also different for different days of the week due to different flying schedules. As an LRU fails, the model assigns various attributes (characteristics) to that LRU which describes its subsequent repair. These attributes include the test station type requirement, the intermediate level technician requirement, the type of maintenance action required, and the hours that will be required for the LRU repair.

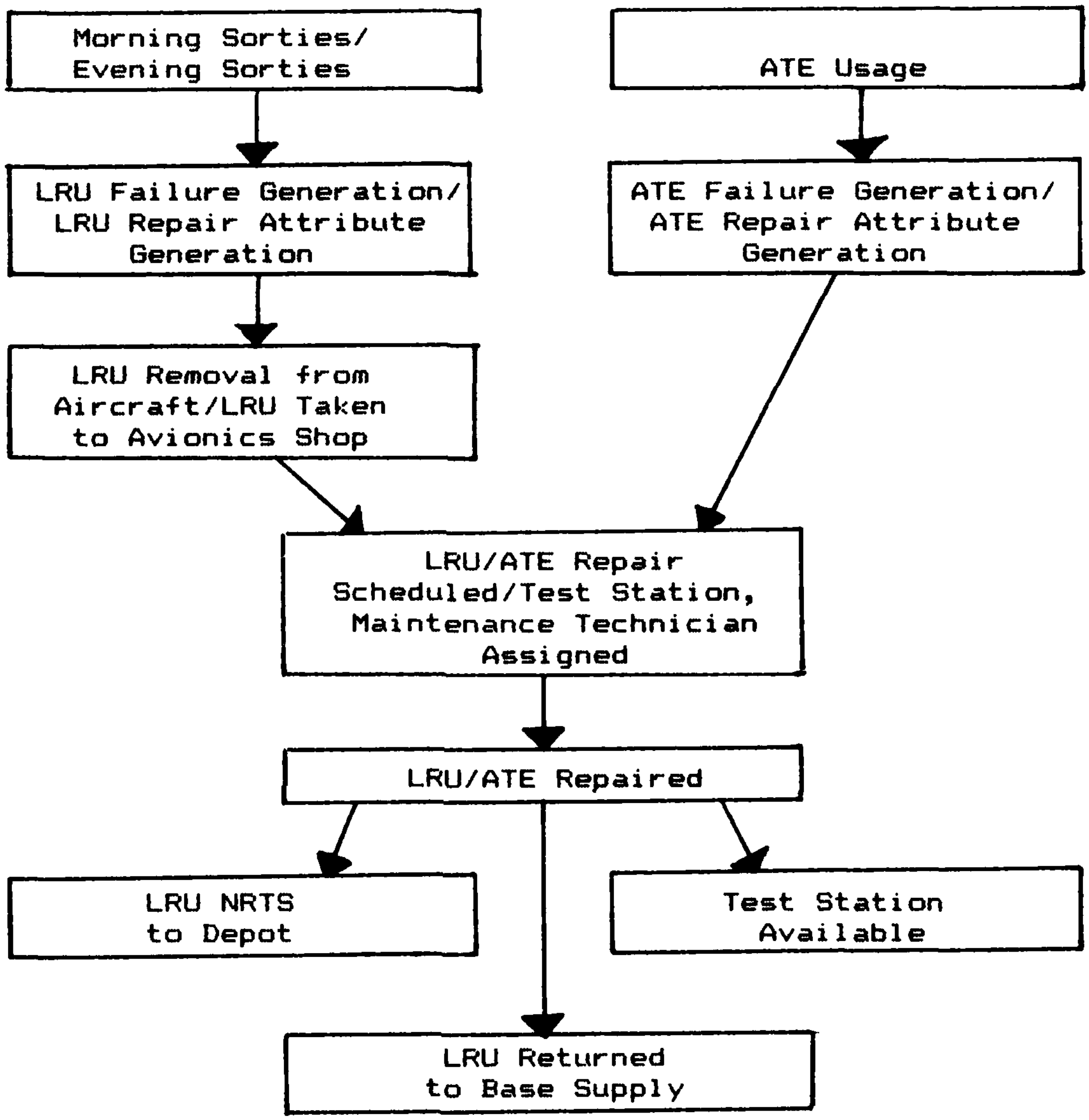


Figure 1. Flow of Avionics LRU/ATE Repair

Once an avionics LRU fails, it requires maintenance from the Organizational Maintenance Squadron (OMS) technicians. This maintenance consists of debriefing, removal of the failed LRU from the aircract, and transportation of the LRU to the avionics shop. The model treats OMS technicians as constrained resources, and therefore failed LRUs must wait (or queue) for an available technician until maintenance may be performed.

Once at the avionics shop, the LRUs queue for intermediate level maintenance at the Avionics Maintenance Squadron (AMS). The LRUs require both a technician and a test station before maintenance can commence. Each of the station types and each of the AMS technician types are treated as constrained resources in the model.

Not only do avionics LRUs fail and require maintenance, but the ATE test stations themselves fail and require repair. The model generates ATE failures, and for each failure, assigns attributes which describe the subsequent repair. The model assumes that ATE repair takes precedence over LRU repair since an ATE test station must be in good working order in order to be used during the LRU repair.

The key outputs of the model are resource utilization and LRU base repair cycle time. Resource utilization for all station types and all technician types is included. The base repair cycle time is the time from LRU failure until return (of the LRU) to base supply. It is this second output feature that will be used to determine test station requirements. The Q-GERT network diagram and the computer listing for the model are both included in Appendix A.

Detailed Model Description

The model generates avionics LRU failures according to the B-1B flying hour profile at each base. LRU failures are generated as a Poisson process for a four hour period twice each day. B-1B aircraft are assumed to be launched in the morning from 0800 until 1200, and in the late evening from 2000 until 2400. The B-1B sortie duration is assumed to last 5.0 hours, so the avionics LRU failures are generated from 1100 until 1500 and from 0100 until 0500 for each day. Nodal modification is used to start and stop the Poisson process for each four hour period. The model also keeps track of days of the week since the flying hour profile (and therefore LRU arrival rate) is different for different days of the week.

In order to generate LRU failures according to a Poisson process, it is necessary to simulate exponential interarrival times over a fixed period (in this case, from 1100 until 1500 and from 0100 until 0500). This is accomplished in the model by a FORTRAN user function, where the numerical value assigned to the user function is the exponential interarrival times between successive LRU failures. The FORTRAN user function also defines attribute values for each LRU failure which are used in the later portion of the model. Detailed task listings of the FORTRAN initialization subroutine and the user function are shown in Figure 2 and Figure 3. The initialization subroutine simply defines all variables which are needed in the user function. Variable information is transmitted to the user function through use of FORTRAN COMMON statements. The FORTRAN user function then computes the mean interarrival time of avionics LRU failures for the correct day of the week and the correct time of day. The actual LRU failure interarrival time is then simulated according to an exponential distribution. The user function then uses several more random number draws to determine the characteristics of the LRU maintenance which will take place later in the model. These characteristics are stored as attributes of the failed LRU.

Once the avionics LRUs have failed, they require maintenance at organizational level (i.e., at the flight line). This maintenance is performed by two OMS technicians. The avionics LRUs must wait in queue until technicians are available. The maintenance consists of three distinct tasks performed in series. First, the maintenance crew must attend a debriefing (with the aircrew) which takes a constant time of 1.0 hour. Second, the

Subroutine UI

1. Initialize variables by data statements

2. Add LRU arrival rates to obtain aggregate avionics Mean Time Between Demand (MTBD in flying hours)

3. Compute LRU arrival rate as percentage of aggregate avionics arrival rate (reciprocal of MTBD)

4. Add test station failure rates to obtain aggregate ATE Mean Time Between Maintenance (in operating hours)

5. Compute test station failure rate as percentage of aggregate ATE failure rate

Figure 2. FORTRAN Subroutine UI

Function UF

1. Get day of the week

2. Convert aggregate avionics MTBD from flying hours tc real time
   - Depends on day of the week
   - Depends on time of day (day or night)

3. Simulate uniform (0,1)
   - Convert to exponential time between LRU failures

4. Simulate uniform (0,1)
   - Compare uniform number to LRU failure rate percentages to determine which LRU has failed

5. Get data on failed LRU and place attribute values ir transaction
   - Attribute for test station requirement
   - Attribute for technician (AFSC) requirement
   - Attribute for LRU maintenance (to distinguish frc ATE maintenance)

6. Simulate uniform (0,1)
   - Compare uniform number to LRU RTS, RTOK and NRTS percentages to determine type of maintenance acti

7. If maintenance action is RTS (repair):
   - Assign maintenance action attribute for RTS
   - Compute mean repair time
   - Simulate two uniform (0,1)
   - Convert to Erlang repair time with k=2
   - Divide repair time into two attributes
     -- Attribute for setup and fault isolation time
     -- Attribute for time to remove and replace SRU teardown LRU
   - Simulate uniform (0,1)
     -- Compare uniform number to SRU spare part availability percentage to determine SRU availability for repair
     -- Set attribute for SRU spare availability

Figure 3. FORTRAN User Function UF

8. If maintenance action is RTOK:
   - Assign maintenance action attribute for RTOK
   - Compute mean task time for RTOK
   - Simulate five uniform (0,1)
   - Convert to Erlang task time with k=5
   - Divide task time into two attributes
     -- Attribute for setup and test time
     -- Attribute for second test (if required) and teardown time
   - Set attribute for SRU spare part availability (SRU spare not needed for RTOK)

9. If maintenance action is NRTS:
   - Assign maintenance action attribute for NRTS
   - Compute mean task time for NRTS
   - Simulate five uniform (0,1)
   - Convert to Erlang task time with k=5
   - Divide task time into two attributes
     -- Attribute for setup and fault isolation time
     -- Attribute for teardown time
   - Set attribute for SRU spare part availability (SRU spare not needed for NRTS)

Figure 3. FORTRAN User function UF (Continued)

technicians actually remove the failed LRU from the aircraft; the removal time is simulated as an Erlang distribution with a mean of two hours and a k-value of four. The removal time was assumed to be Erlang. The mean and k-value were estimated from B-52 OAS data. Finally, the maintenance technicians take the failed LRU to the avionics shop. This is assumed to take a constant time of 30 minutes. The technicians are then free to perform organization level maintenance on other LRUs.

Not only do the avionics LRUs fail and require maintenance, but so do the ATE test stations. This is accomplished in the model by a FORTRAN user subroutine which determines the ATE failure interarrival times and assigns attributes to each ATE failure. The user subroutine is very similar to the user function. A detailed task listing of the FORTRAN user subroutine is shown in Figure 4.

Once the failed LRUs (or in an abstract sense, the failed ATE test stations) arrive at the shop, they must wait in queue until resources are available so that the intermediate level (avionics shop) maintenance can be performed. First, the failed LRU (or station) must wait until a station of the right type is available. The model allows for four station types with a user input quantity of stations of each type. The four types of stations for the B-1B are the Digital station, the Digital Analog Video station, the Radio Frequency station, and the Radar

Subroutine US

1. Simulate uniform (0,1)
   - Convert to exponential time between ATE failures

2. Simulate uniform (0,1)
   - Compare uniform number to ATE failure rate percentage to determine which station type has failed

3. Place attribute values for station repair transaction
   - Attribute for station type
   - Attribute for technician (PMEL) requirement
   - Attribute for ATE maintenance (to distinguish from LRU maintenance)
   - Attribute for type of maintenance action (station repair is only RTS)

4. Simulate two uniform (0,1)
   - Convert to Erlang repair time with k=2
   - Divide repair times into two attributes
     -- Attribute for setup and fault isolation time
     -- Attribute for time to remove and replace SRU

5. Simulate one uniform (0,1)
   - Compare uniform number to SRU spare part avilability percentage to determine SRU availability for repair
   - Set attribute for SRU spare part availability

Figure 4. FORTRAN User Subroutine US

Electronic Warfare station. The FORTRAN user function determines by a random number the actual LRU that failed. Each LRU has a known station type requirement and that station type requirement is set as an attribute value by the user function. The LRU is then routed to the correct station queue by conditional branching. Similar branching occurs for station maintenance. Second, the LRU (or station) must also wait until a technician of the right type is available. The model allows for the five AMS maintenance technician types described in Section II. This includes the four types for LRU maintenance, and also the PMEL technician type for ATE station maintenance. The quantity of maintenance technicians (direct labor per shift) was shown in Table II in Section III. The FORTRAN user function determines by a random number the actual LRU that failed. Each LRU has a known technician type requirement and that technician type requirement is set as an attribute value by the user function. The LRU is then routed to the correct technician queue by conditional branching. All station maintenance is routed to the PMEL technician queue. For example, if the failed LRU is from the B-1B ECM system, then the failed LRU will require (say) a Radar/EW test station and a defensive avionics technician.

Once both (station and technician) resources are available, the technician performs the first part of the maintenance action. For ATE maintenance and for LRU repair, this includes the time for setup and fault isolation. For LRU RTOK actions, this includes the time to set up and run one performance test. For LRU NRTS actions, this includes the setup and fault isolation time. For all cases, the time to accomplish the first part of the maintenance action is simulated by the FORTRAN user function (or subroutine) and stored as an attribute.

For LRU and station repairs, a SRU spare is required before any further maintenance may continue on the LRU or station. In the FORTRAN user function or subroutine, there is a 90% chance that the correct replacement SRU spare will be available at base level. If the spare part is not available for an LRU repair, the LRU is taken off of the test station and placed in awaiting parts (AWAP) status. The station and technician resources are then freed to do other work. If the spare part is not available for station maintenance, then only the technician resource is freed to do other maintenance. The station stays in down-for-parts status until the correct spare part can be ordered and shipped. For both LRUs and stations, the order and ship time for SRU spares is assumed to be a constant 8 days. On the other hand, if the correct spare part is available at base level, then the technician obtains the SRU spare and proceeds with the maintenance. The time to obtain the SRU spare is determined by probabilistic branching. There is a 25% chance that the SRU spare will be available at the forward supply point. This is assumed to take a constant time of 15 minutes. There is a 75% chance that the SRU spare will be obtained from base supply. This is assumed to take a constant time of one hour. Of course, for LRU NRTS and RTOK actions, no SRU spare is required, and there is a separate branch in the model for these cases.

The maintenance technician then peforms the second part of the maintenance action. For station and LRU repair, this includes the time to remove and replace the failed SRU and the time for teardown. For LRU RTOK actions, this includes the time for a second performance test and the time for teardown. There is a 30% chance that a second performance test will be required. For NRTS actions, this includes the time to teardown the LRU only since no repair is possible. For all cases, the time to accomplish the second part of the maintenance action is simulated by the FORTRAN user function (or subroutine) and stored as an attribute. Once the second part of the maintenance is complete, the station and technician are then freed to do other work. After maintenance is complete, LRUs are then taken to base supply.

Numerous statistic nodes have been included in the model to measure the performance of the maintenance queueing system. Interval statistics measure the base repair cycle time which is the time from LRU failure to return to base supply. Statistics are collected separately for each station type (for example, the Digital station). LRU maintenance statistics are also kept separate from ATE maintenance statistics. The LRU NRTS actions are also removed from the statistics since no repair was actually accomplished; the model figure of merit is base repair cycle time.

Finally, the model keeps track of all changes associated with the shift changes. Maintenance technicians and stations are available from 0800 until 2400 each working day (i.e., two maintenance shifts per day). Resource alter nodes are used to control the beginning and end of each shift. Since Q-GERT alter nodes are nonpreemptive, however, this means that a maintenance task must be completed before the technician is allowed to go home. This is why the maintenance time was divided into two parts. It is possible to have a technician complete the first part of a maintenance action, go home at the end of a shift, and complete the second part of the maintenance action the following day. Dividing the maintenance time into two parts therefore minimizes the actual amount of "overtime" which occurs in the simulation model. Actual experience with the model indicates that the amount of "overtime" varies from zero to two hours per day (both shifts combined) depending on the station workload. This is considered reasonable and realistic since the SAC maintenance policy does allow for occasional "graveyard" maintenance to respond to maintenance workload requirements. The resource alter nodes also model scheduled maintenance on the ATE test stations. The stations are assumed to require a daily confidence test at the beginning of the first maintenance shift. This is assumed to take a constant time of 15 minutes for each station.

Design of Simulation Experiment

The purpose of the simulation experiment is to determine if varying test station quantities can influence LRU base repair cycle time. Therefore, base repair cycle time is the dependent variable of interest, and test station quantity is the factor to be varied. Treatments considered will be quantities of one, two, or three test stations (of each station type) at each base. To reduce variance in the simulation experiment, the method of common random numbers is used. This means that, for each block, the base repair cycle time is measured against the three treatments with the same number of LRU failures, the same type of maintenance actions, and the same LRU repair times. This, of course, requires blocking to be used in the experimental design since the observations within a block are now related. In this experimental design, there are three treatments and ten blocks. This experiment has 18 degrees of freedom in the error term. A crude rule of thumb is that the degrees of freedom for the error term should be at least 10 (22:164). This experiment was conducted a total of 12 times (one for each of four station types and one for each of three aircraft quantities). A sample of the simulation output (for the 16 aircraft base) is shown in Table VI.

For each of the 12 experiments, the factor of test station quantity was found to have a statistically significant influence (with α= 0.5) on LRU base repair cycle time. Since the variance for different treatments was clearly not constant (see Table VI), the (normal based) ANOVA was not appropriate to analyze the experimental results. For this reason, the experimental results were analyzed using Friedman's test, which is the nonparametric equivalent of one way ANOVA with blocking (complete randomized block design). Multiple pairwise comparisons in each of the 12 experiments were also almost always statistically significant. In fact, 32 out of 36 pairwise comparisons were found to be statistically significant. The detailed data on the experimental design is included in Appendix B.

Statistical significance, however, may not be the critical issue in determining test station quantities. These quantities should be selected to minimize the overall cost of avionics support. This cost should include both the cost of service (cost of test stations) and the cost of waiting (cost of avionics LRU spares). Test station

Table VI. Base Repair Cycle Time (in hours)

Block	Radar EW 1	Radar EW 2	Radar EW 3	Radio Freq 1	Radio Freq 2	Radio Freq 3
1	70.8	23.3	22.7	52.1	31.1	23.6
2	40.5	29.8	25.6	57.3	25.2	22.2
3	50.5	31.0	24.1	89.1	28.0	26.1
4	36.8	26.2	20.3	34.3	28.0	27.3
5	126.7	28.3	23.9	48.9	28.7	24.4
6	147.5	28.1	22.8	70.8	36.2	25.9
7	41.2	26.7	27.2	56.7	26.9	23.2
8	138.3	25.8	25.5	155.6	30.6	27.4
9	89.3	25.0	23.0	50.5	25.7	28.8
10	62.2	23.7	24.1	76.6	26.9	29.8
(Avg)	80.4	26.8	23.9	69.2	28.7	25.9
(Std Dev)	42.7	2.5	1.9	34.1	3.2	2.5

Block	Dig An Video 1	Dig An Video 2	Dig An Video 3	Digital 1	Digital 2	Digital 3
1	69.3	24.3	23.3	63.3	25.8	19.8
2	45.8	23.3	22.9	25.7	31.6	22.2
3	55.5	24.9	20.6	35.9	22.5	24.3
4	56.7	24.6	23.9	24.3	24.6	20.4
5	50.5	26.7	22.5	34.2	25.6	21.9
6	49.0	31.5	21.5	22.5	24.7	26.5
7	30.5	21.6	18.9	25.7	22.4	24.1
8	31.8	21.7	22.5	51.7	22.3	21.7
9	52.0	22.1	22.1	35.4	23.2	28.0
10	76.8	28.5	21.4	31.8	26.9	24.3
(Avg)	51.8	24.9	22.0	35.1	25.0	23.3
(Std Dev)	14.4	3.2	1.4	13.1	2.8	2.6

16 Aircraft/Base
Baseline Estimate
1, 2, and 3 Test Stations

quantities should be selected to achieve the optimum balance between cost of service and cost of waiting and achieve the lowest overall cost. This tradeoff will be analyzed in Section VI.

Test for Transient Conditions

Any simulation experiment must be concerned with the effect of transient conditions. In the case of a queueing model, if the queues are initially empty, it may take a certain period of time for the queue length to grow to its steady state size. The simulation experiment described earlier used simulation periods of 6240 hours, corresponding to six months of avionics maintenance. To test if this period was sufficiently long to achieve steady state conditions, the experiment was run again for a simulation period of 12480 hours for all four station types with five replications each. The Wilcoxon Signed Ranks Test was used to test if there was any statistically significant difference in the average base repair cycle time between the two simulation periods. A nonparametric test was again selected since variance was not constant for different test station utilizations. For any $\alpha < 0.10$, there is no statistically significant difference in base repair cycle time between the two simulation periods. The conclusion reached is that te simulation period of 6240 hours is sufficent to achieve steady state results.

Sensitivity Analysis

Considerable sensitivity analysis was conducted on the various model inputs. This is essential since the baseline analysis was based on preliminary contractor estimates. Major elements investigated include LRU reliability, LRU test times, ATE reliability, ATE repair times, and other factors currently used in the model. It appears that the test station quantities may vary considerably with only modest and quite credible changes to most of the major elements. For this reason, it is too early in the B-1B program to precisely determine ATE test station quantities. Rather, it is only possible to determine a reasonable range of quantities. The range of station quantities is presented in Section VI.

Verification and Validation

Verification means ensuring that the model behaves exactly as it is intended. To assist in the verification process, the simulation model is the synthesis of 5 smaller models which were developed earlier. Each of these smaller models corresponds to a major portion of the final simulation model. Specifically, a smaller model was developed for (1) B-1B flying hour profile and LRU failure generation, (2) resource allocation (both test stations and technicians), (3) ATE failure generation, (4) detailed test and repair procedures, and (5) FORTRAN user functions and subroutines used in the model. Each of these smaller models was programmed with very detailed output and each was sufficiently simple to allow manual verification.

Validation is a process to ensure that the model realistically portrays the real world. The most important element of the continual process of validation was the coordination of all major ground rules and assumptions with personnel from HQ SAC that have had actual experience with avionics maintenance in the B-52 and FB-111 programs. These individuals provided a significant amount of feedback and constructive criticism. In addition, an effort is now being conducted to run this model on the B-52 OAS and its ATE. Model output will then be compared to the actual operational experience.

V. Analytical Queueing Model

Background

One of the most important theorems of queueing net theory is known as Jackson's result; the theorem applie a so-called open network of queues. An open network is multiple queue system in which a customer typically req service at more than one queueing station. It is assum that customers enter the network at one of the queueing stations, queue for service, and then depart the networ else proceed to another queueing station in the network additional service. It is also assumed that each queue station has s parallel servers with exponential service times. It is also assumed that the time between arriva (from customers outside the network) at each queueing station is exponential. Finally, it is assumed that customers at a given queueing station either depart the network or move to another queueing station according t specified probability distribution which is not state dependent. Jackson's result states that for such a net the state probabilities and performance measures for ea queueing station may be obtained by applying the simple exponential (M/M/s) model to each queueing station separately (5:146-161).

A second powerful technique is known as the methods of phases. This technique applies to service times (or interrarival times) which are Erlang or hyperexponential. In many cases, it is still possible to obtain a closed-form expression for the state probabilities by transform methods. The solution technique is to redefine the state space; the state of the system does not refer to the number of customers in the system but rather to the number of exponential phases yet to be completed in the system. The key to the solution is to express the Erlang distribution as the sum of exponential distributions, or to express the hyperexponential distribution as the weighted average of exponential distributions. In either case, it is then possible to construct classical exponential rate diagrams for the queueing system. A closed-form expression may then often be obtained by use of transforms (4:171-175).

A third technique of queueing theory involves multiple classes of customers with different mean service times. It is still required that the customers arrive and are served according to an exponential distribution. The state space for this type of problem is a set of vectors; each entry in the vector represents the number of customers of each class. Depending on the situation, there may not be a closed-form expression for the state probabilities. It is possible, however, to write the balance equations for the state space as a linear system of equations and unknowns. The unknowns are the state probabilities for the system. The solution technique is to approximate the state space by a finite number of elements. For most queueing situations, the steady-state number of customers in the system falls within a finite range with a probability close to one. For example, it might be a reasonable approximation to postulate that the steady-state number of customers in the system never exceeds a certain number. For the finite case, there is always one dependent equation in the set of balance equations. The solution technique is to remove one of the equations and then add an equation which states that the probabilities over the state space sum to one. The final step is to solve the finite system of equations and unknowns by a numerical technique such as Gauss-Seidel iteration (4:123,158-165). By using a simple formula for expected value, it is then possible to find L, the expected number in the system, for each class. Little's formula may then be used to find the expected waiting time, W, for each customer class (3:261-262).

The actual technique developed in this research effort is a synthesis of the three queueing techniques discussed earlier. The LRUs that require maintenance compose the first class of customers; the ATE stations that require maintenance compose the second class of customers. The repair time at intermediate level is treated as Erlang and the method of phases is used. The transition from organizational maintenance to intermediate level maintenance is treated as a network of queues.

Model Description

The analytical queueing model treats B-1B avionics maintenance as a queueing network; this network is shown in Figure 5. The avionics LRUs are assumed to arrive to the organizational maintenance squadron queue according to a (homogeneous) Poisson process. The servers for this queue represent pairs of OMS maintenance technicians. Since there are 38 OMS maintenance technicians per shift, there are 19 pairs of technicians and thus 19 servers. The LRU removal time is assumed to be exponential with a mean of 3.5 hours. After passing through the OMS queue, the LRUs then pass on to the test station queues in one of two ways. One way is for the LRUs to go into awaiting parts (AWAP) status, which is treated as an infinite server queue where the service time represents the order and ship time for the SRU spare. The purpose of the branch is to make sure that the waiting time for SRU spares is included in the base repair cycle time. The other way is for the LRUs to proceed directly to the test stations. This corresponds to the case, which happens for 90% of the repairs and for all RTOKs and NRTS actions, where it is not necessary to order a SRU spare

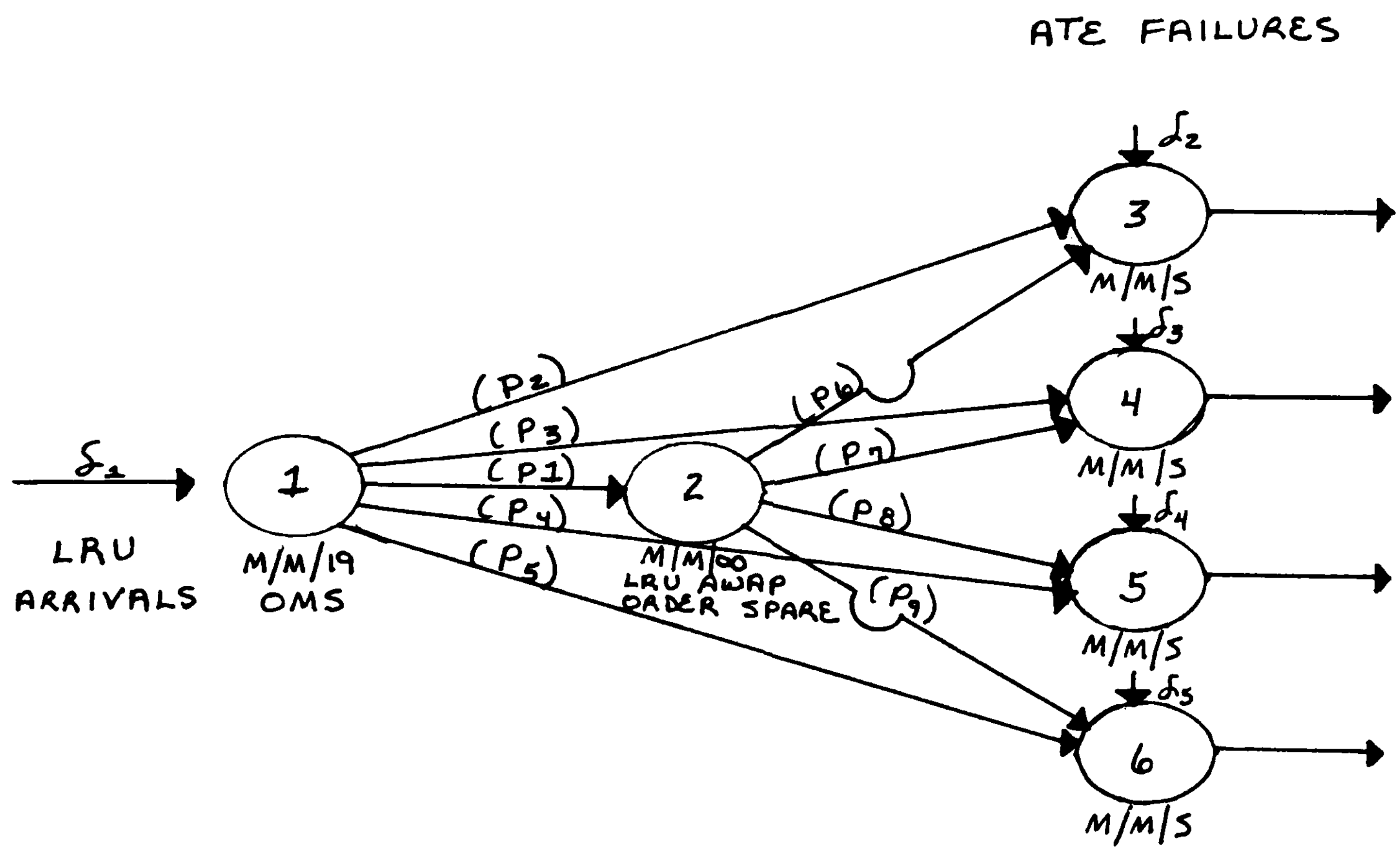


Figure 5. B-1B Avionics Maintenance as Open Queueing Network

from depot level. In either case, LRUs arrive to each of the test stations according to a Poisson process. In addition, ATE failures arrive to the test station queues, also according to a Poisson process. The LRU failures and the ATE failures are treated as two classes of customers. The ATE failures require an exponential service time with a mean of one hour, but the LRU failures require an Erlang (with k=2) service time with a mean which is computed by the model. The model assumes that all LRUs have the same mean repair time; this, of course, is only a crude approximation. In fact, each LRU may have a different mean repair (service) time. The model calculates the LRU mean repair time as a (reliability) weighted average of all mean LRU repair times. Each of the mean LRU repair times, in turn, is a weighted average of the RTS, RTOK and NRTS mean repair times. The detailed task flow for the analytical queueing model is shown in Figure 6.

Solution Techniques

The organizational maintenance and awaiting parts queues are both simple exponential (M/M/s) queues. Simple closed form expressions for the state probabilities and the waiting time for the M/M/s queue are found in Ross (3:264-267); the model has a FORTRAN subroutine which uses

PROGRAM QUEUE4

1. Get data from subroutine BLOCK DATA through FORTRAN COMMON statement

2. Add LRU failure rates to obtain aggregate Mean Time Between Demand (MTBD) for LRUs assigned to each station type

3. Get overall aggregate MTBD

4. Solve OMS queue as M/M/19 queue

5. Compute mean LRU repair time by station type
   - Weighted average by RTS, NRTS, and RTOK percentages
   - Weighted average by LRU reliability

6. Solve order and ship queue for LRUs awaiting parts

7. Solve test station queues
   - Solve case for single server
   - Solve case for two parallel servers

8. Compute total network waiting time for LRUs by station type

Figure 6. Analytical Queueing Model

these expressions to calculate the M/M/s state probabilities and the queue waiting time. It is also true that the output of a simple exponential (M/M/s) queue is a Poisson process with the same arrival rate as the original input Poisson process. It is also true that when this output Poisson process is channeled to different queues with fixed probabilities, the arrival process at each of the subsequent queues is a Poisson process with a rate equal to the original overall arrival rate multiplied by the probability of the arrival process being channeled to that particular queue. This means that the LRU arrival process at each of the test stations is a Poisson process.

The solution technique for the test station queues is somewhat more involved. The rate diagram for the single server case is shown in Figure 7. The state of the system is now a vector. The LRU repair process is divided into two phases. Since the repair time has an Erlang distribution (with k=2), the time to complete each phase has an exponential distribution. The number in the first entry of the state vector represents the number of LRUs yet to be served; the number in the second entry represents the number of LRUs which have completed the first phase of the repair but have yet to complete the second phase. It is assumed that work on an LRU which has completed the first phase takes priority over work on any more recent LRU arrivals. This means, for the one server case, that the number

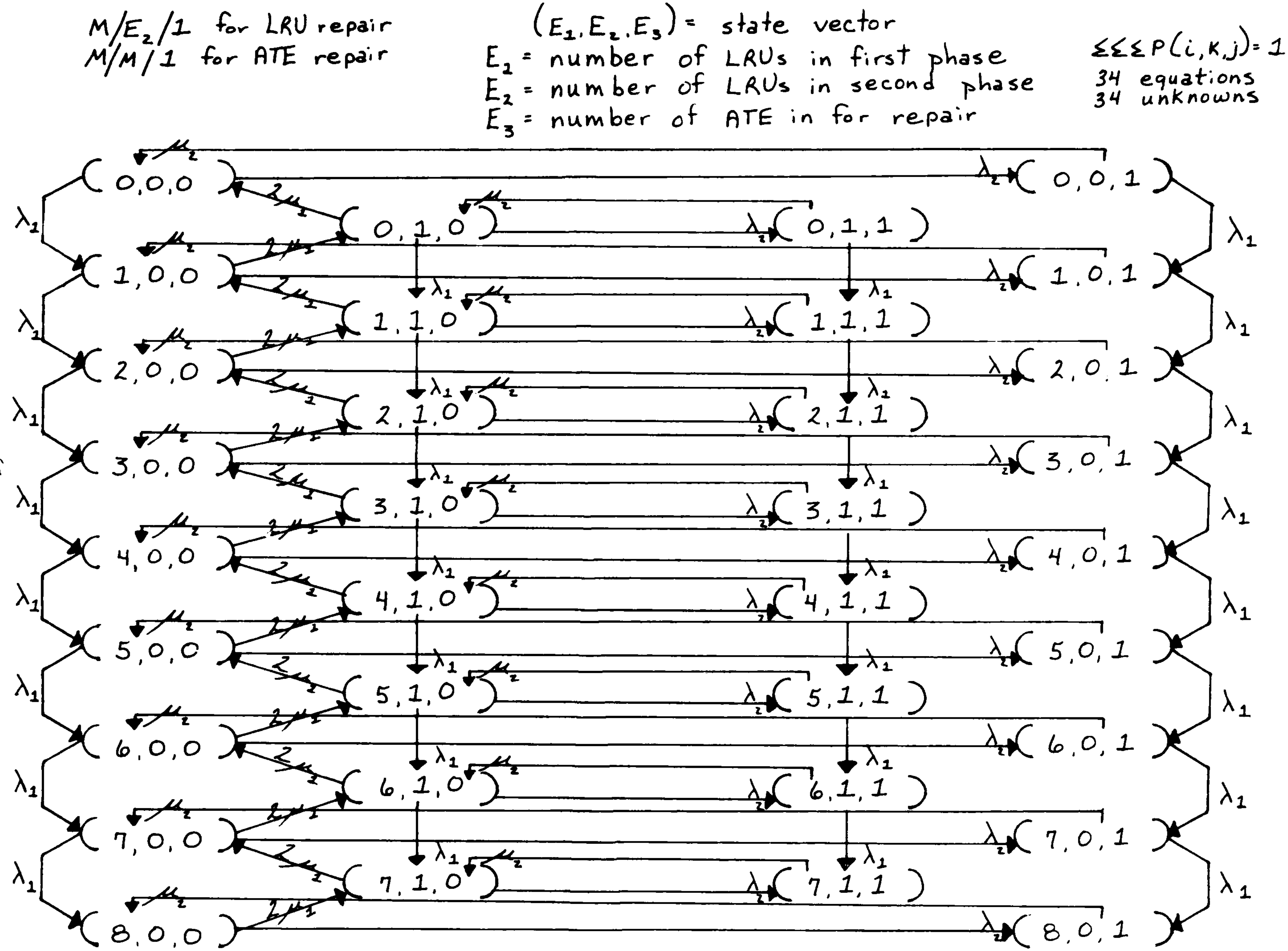


Figure 7. Single Server Rate Diagram

in the second entry of the state vector never exceeds one. The third entry on the state vector is 0 when there are no ATE failures in the queue (the test station is up) and 1 when there is an ATE failure in the queue (the station is down). ATE test station repair always takes priority over any LRU maintenance. In addition, an ATE test station failure preempts any on-going LRU maintenance. For such an event, because of the memoryless property of the exponential distribution, the preemption is equivalent to having the LRU repair phase start over.

No closed form expression for system performance measures may be found for the queueing system in Figure 7. This is due to the preemptive blocking caused by ATE failures. The solution technique is a four step process. First, the state space is approximated by a finite number of terms. In this case, it is assumed that the number of LRUs in the queue never exceeds 8. Second, the rate diagram and the associated balance equations can be used to construct a linear system of equations and unknowns. The balance equations are based on the "rate in" = "rate out" principle. For example, the balance equation for the vector (3,1,1) would be:

$$\lambda_1 P((2,1,1)) + \lambda_2 P((3,1,0)) = (\lambda_1 + \mu_2) P((3,1,1)) \quad (6)$$

In general, the unknowns are the probabilities of each element in the state space. The coefficients of the unknowns are various combinations of the arrival rates and the service rates of the LRU failures and the ATE station failures (denoted by λ_1, λ_2, μ_1 and μ_2). It is also necessary to remove one balance equation and in its place add an equation which states that the sum of all the probabilities is one. Third, the linear system of equations and unknowns is solved numerically. The queueing model developed in this research effort uses IMSL routine LEQT1F to solve the system of equations and unknowns. This routine performs standard Gaussian elimination with equilibration and partial pivoting (19:LEQT1F-1,-3). Fourth, the state probabilities are then used to find L_L, the expected steady-state number of LRUs in the system. This is a simple calculation based on the idea of conditional expectation. Little's Formula can then be used to calculate the total waiting time in the system for the LRUs. This equation would be:

$$W_L = L_L / \lambda_1 \tag{7}$$

This computes the total LRU waiting time for each test station queue.

The model then computes the average base repair cycle time for the entire LRU maintenance process for each station queue. This is the sum of (1) the total time in the system for the OMS queue, (2) the order and ship time multiplied by the fraction of maintenance actions that require SRU spares to be ordered and shipped, and (3) the total time in system for the test station queue.

The case for two servers (two test stations) is handled very similarly. However, the rate diagram is somewhat more complicated. A portion of the two server rate diagram (for states (4,0,0) through (4,1,2)) is shown in Figure 8. Note that ATE maintenance always takes priority over any LRU maintenance. Also, LRU repair of LRUs in the second phase always takes priority over LRUs in the first phase. The solution technique for the two server case follows the same steps as those for the single server case. The FORTRAN computer code listing for the analytical model is included in Appendix C.

$M/E_2/2$ for LRU repair
$M/M/2$ for ATE repair

(E_1, E_2, E_3) = state vector
E_1 = number of LRUs in first phase
E_2 = number of LRUs in second phase
E_3 = number of ATE stations in for repair

72 equations
72 unknowns

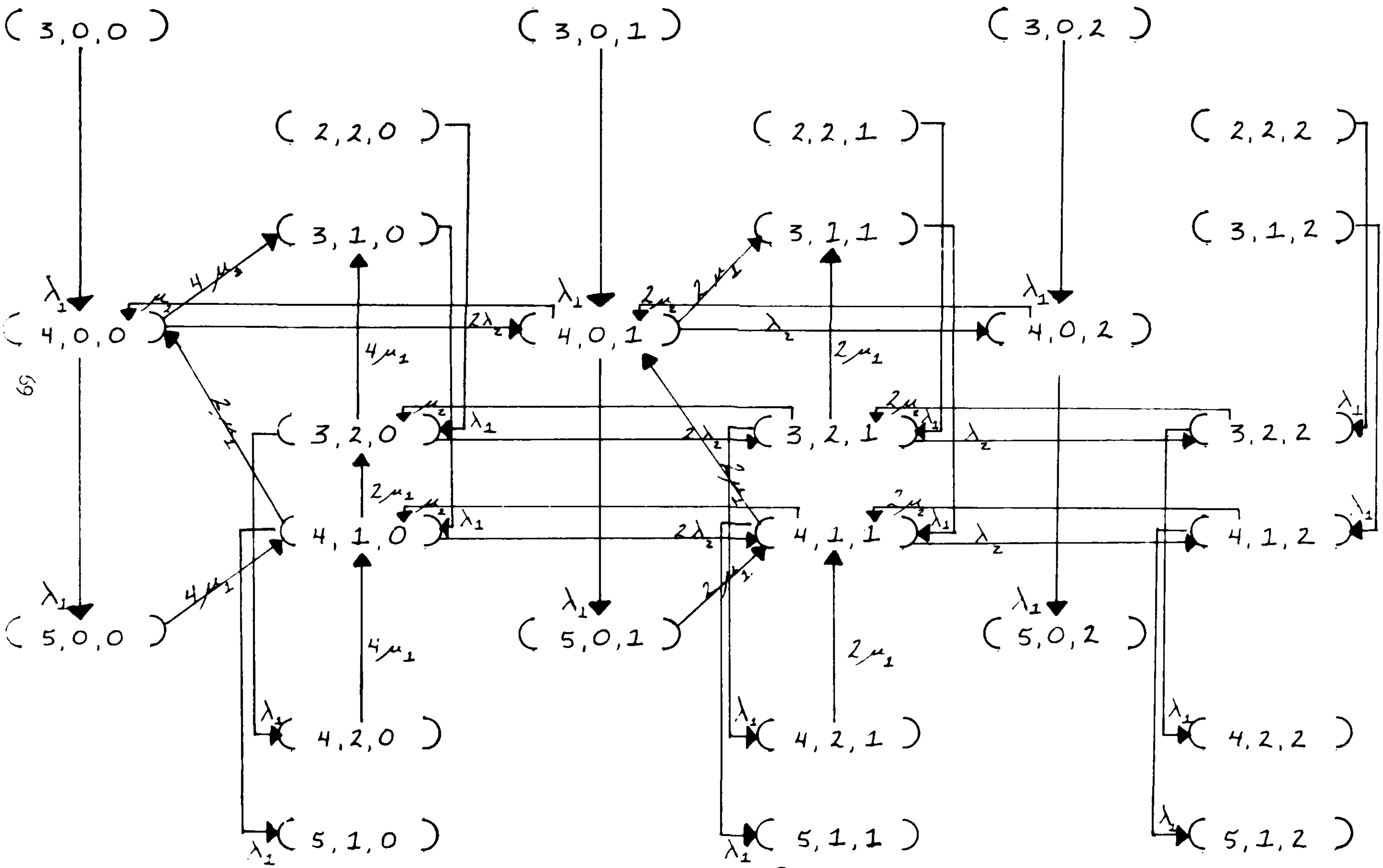


Figure 8. Portion of Two Server Rate Diagram

Model Results

The analytical queueing model was run for the case of 16 aircraft per base. The results are shown in Table VII.

Table VII. Analytical Model Results
Base Repair Cycle Time (Hours)

	1 Station Case	2 Station Case
Digital	23.5	18.9
Digital Analog Video	26.1	19.3
RF	26.3	20.0
R/EW	26.7	20.0

For reasons which will be discussed in the next sub-section, the queueing model estimates for base repair cycle time are *consistently lower* than the estimates obtained from the simulation model. Comparable figures for the 16 aircraft base were derived from the simulation model and are shown in Table III. Each figure is the average of 10 replications.

Table VIII. Simulation Model Results
Base Repair Cycle Time (Hours)

	1 Station Case	2 Station Case
Digital	35.1	25.0
Digital Analog Video	51.8	24.9
RF	69.2	28.7
R/EW	80.4	26.8

Analytical versus Simulation Model

In comparing the analytical model results to the simulation model results, it was found that the analytic estimates of base repair cycle time (total time in syste were consistently lower than the estimates obtained from simulation model. Moreover, it was found that this gap widened as the average station utilization increased. I comparing the one station case of Table VII to Table VII it can be seen how the gap gets larger as the average station utilization gets larger. The major reasons for gap follow:

1. For most queueing situations, the total time in sys depends not only on the mean of the service time but als the variability of the service time. Increasing this variability causes an increase in the total time in syst There is good reason to believe that the analytical mode underestimates the true variability associated with LRU ATE repair. First, for LRU repair, the analytical model assumes that all LRUs have the same mean repair time and uses weighted averages to find that mean. In fact, ther are different means for RTS, RTOK and NRTS actions, and different means for different LRUs. This implies that tl actual distribution of LRU repair time is not a simple Erlang, but rather is a very complicated hyperexponentia

(with a larger variability). Second, a similar problem occurs with ATE test station maintenance. The analytical model allows for only one test station failure rate and one mean test station repair time. In fact, there are two different test station service times depending on whether or not a SRU spare is available at base level. This means that the actual station service time also has a hyperexponential distribution (with a larger variability).

2. The simulation model has a variable LRU failure (arrival) rate. Specifically, the simulation model has a different arrival rate for different days of the week. Moreover, the LRUs arrive in two spikes during each day (once from the morning sorties and once from the night sorties). This means that LRUs are more likely to arrive with other LRUs, causing longer waiting times in queue. On the other hand, the analytical model assumes that the avionics LRUs arrive according to a Poisson process which is homogeneous over the 16 hour maintenance day. This has the effect of leveling out the LRU workload and causing shorter waiting times in queue.

3. The analytical model may have a downward bias in total waiting time since it uses a finite state space to approximate the actual distribution of customers (LRUs) in the system. Although the probability of ever having more

than (say) 8 customers in the system is quite small, the total contribution of 9 or more customers to the true expected number of customers in the system may not be insignificant. After all, these albeit small probabilities are associated with large numbers of customers. The initial analytical model assumed a maximum of 8 LRUs in the system. The model for the single-server case was also run with maximums of 12 and 24 LRUs in the system. This caused the value of base repair cycle time (total time in system) to increase by two or more hours in each case, and the rate of growth did not appear to decline. An analysis of the simulation model output indicated that this problem is quite severe. For the 16 PAA, one station case, the maximum number of LRUs in each queue over a six month period was found to be 4, 24, 58, and 66 for the Digital, Digital Analog Video, RF and R/EW stations, respectively. The conclusion drawn from this is that the finite-state space approximation causes a significant downward bias in the model estimate of the total time in system.

The analytical model, overall, requires many crude and simplifying assumptions; much more so than does the simulation model. Empirical results suggest that these differences in assumptions cause a significant difference between the output of the two models. Since the assumptions of the simulation model are much more realistic, it was assumed that the simulation model has a more realistic output. With this assumption, the simulation model was selected over the analytical queueing model as the best choice of the B-1B System Program Office.

Possible Further Research for the Analytical Model

The previous discussion identified three serious problems with the analytical model developed during this research effort. Further research could be accomplished to see if these problems could be overcome. The first problem was that the present analytical model underestimates the true variability of LRU and ATE repair. A possible solution is to model these repairs by using hyperexponential distributions. This might, however, cause numerical problems, since the present two-server algorithm is already at 72 equations and 72 unknowns. The second problem was that the LRU arrival rate is not constant, which the present analytical model ignores. One possible solution might be to model the LRU arrivals as a bulk arrival process, for which limited queueing results are available (18:199-219). The third problem was caused by the use of a finite state approximation. It may not be computationally feasible to simply expand the size of the finite state space. However, one practical solution might be to assume that the probabilities in the finite space do not sum to 1.0 but rather to some number close to 1.0 (say 0.95). After obtaining a numerical solution to the probabilities of the finite state space, it might then be possible to devise some kind of extrapolation scheme to estimate the remaining probabilites.

VI. Tradeoff Studies

Determining Station Quantity Requirements

A statistically significant improvement in base repair cycle time may have little advantage from a logistics support cost or weapon system availability point of view as discussed in Section IV. The purpose of this section, therefore, is to develop criteria and techniques for determining the best test station quantities by station type for each MOB.

The first point to be considered is that the test stations must be able to accommodate the mean avionics workload. In other words, at a minimum, the test station utilizations must always be smaller than 100%. If this were not the case, the queues would grow indefinitely, and the LRU base repair cycle time would become infinite. The minimum number of stations which achieve station utilization under 100% could therefore be regarded as an absolute floor for the test station quantities. In some cases, however, this approach may not be sufficient. It is possible that in certain situations the base repair cycle time, although finite, may nevertheless be "excessive" is some sense. If a rule or technique could be developed which could indicate when a predicted base repair cycle time was "excessive", it would then be appropriate to select the minimum number of test stations such that no base repair cycle time was "excessive".

One approach would be to compare the predicted base repair cycle time to some established standard. Such a standard should not be an arbitrary number, but should be selected to achieve a necessary level of support. Such support is in the form of the LRU base repair pipeline. For example, suppose that at a given base, two avionics processors fail per day. In addition, suppose that the planned or desired base repair cycle time is five days. This means that the base would require an LRU pipeline of ten spare processors at base level. Of course, the actual spares level computation would be more complex than this. First, it would have to account for the small percentage of time that the avionics LRUs are NRTSed (sent to depot) for repair. Second, it would have to make some distributional assumptions about the variability of the LRU arrivals per day and about the variability of the base repair cycle time. The spares level computation would then add a safety stock level to the average (expected) pipeline quantity. However, the principle remains the same. The approach is to postulate that LRU spares will be procured based on the assumption of a planned base repair cycle time. This planned base repair cycle time could then become the standard to judge whether the test station quantities were sufficiently large. Early in a program when little or no operational data is available, LRU spares are typically procured based on a base repair cycle time of four calendar days (20). It would then be a simple matter to compare the simulation model output to the standard of four days to judge if a given base repair cycle time were "excessive". The model output is based on five working days per week and excludes weekends. Thus, the four calendar day standard must be converted to 2.857 working days (by multiplying by five-sevenths) or 68.57 hours.

Given that four calendar days is to be the standard, there is still some room for judgement as to how to compare the simulation output to the standard. One way would be to perform a one-sided statistical test of hypothesis. Suppose, for example, that the simulation model were very close to the standard of four days. Then, because of the statistical noise present in the simulation model output, it would be impossible to determine if the actual (expected) base repair cycle time were in fact below the standard. For a one-sided statistical test, suppose that the null hypothesis to be tested is that the base repair cycle time is less than or equal to four days, and that the alternative hypothesis is that base repair cycle time is greater than four days. This approach implicitly assumes that it is much worse to buy an unnecessary test station (make a type I error) then it is to buy an insufficient quantity of test stations (make a type II error). Similarly, the role of the null and of the alternative hypotheses can be reversed, and the judgement of the relative importance of the errors would therefore change as well. For cases where the station utilization is under 100%, however, it is not at all obvious as to which type of error is the more serious. If the two types of errors were to be weighed equally, then the one-sided test of hypothesis would not be the correct approach. Assuming that the simulation model output is normally (or at lease symmetrically) distributed, then the way to weigh the two types of errors equally is to simply compare the sample mean of the simulation output to the standard. This was the approach taken for the remainder of this research effort.

Baseline Case and Sensitivity Analysis

The simulation model was run for the baseline case (described in Section III) for each of the MOBs and for each of the test station types. The mean of 10 replications was compared to the four calendar day base repair cycle time standard; *minimum* test station quantities were selected so that the standard could be achieved. These results are shown in Table IX. The baseline case shows an operational requirement for 24 test stations in total.

Table IX. Baseline Test Station Quantities

MOB	Digital	Digital An Video	RF	R/EW
#1 - 26 PAA	1	1	2	2
#2 - 16 PAA	1	1	2	2
#3 - 32 PAA	1	1	2	2
#4 - 16 PAA	1	1	2	2
TOTAL	4	4	8	8

The above baseline computation is based on preliminary contractor data for reliability and maintainability estimates. A second set of reliability figures was obtained for HQ SAC personnel (21) which reflects current experience on like items in current inventory aircraft. This sensitivity is labeled HQ SAC MTBD and is shown in Table X. The first baseline shown above also used the GDE estimates for LRU performance test times. Another sensitivity analysis was run using the RI performance test times (as discussed in Section III). The results for this case are labeled RI performance test times and are shown in Table XI. The HQ SAC MTBD case shows an operational requirement for 33 test stations in total, and the RI performance test time case shows an operational requirement for 29 test stations in total.

Table X. HQ SAC MTBD Estimates

MOB	Digital	Digital An Video	RF	R/EW
#1 - 26 PAA	1	2	3	3
#2 - 16 PAA	1	2	2	2
#3 - 32 PAA	2	2	3	3
#4 - 16 PAA	1	2	2	2
TOTAL	5	8	10	10

Table XI. R1 Performance Test Times

MOB	Digital	Digital An Video	RF	R/EW
#1 - 26 PAA	1	2	2	2
#2 - 16 PAA	1	1	2	2
#3 - 32 PAA	2	2	3	3
#4 - 16 PAA	1	1	2	2
TOTAL	5	6	9	9

Other sensitivity analysis was performed for the 16 PAA case. The baseline test station quantities for this case are one digital station, one digital analog video station, two radio frequency stations, and two radar EW stations. The factors varied were (1) changing the SRU spare availability from 90% to 80%, (2) reducing the AIE reliability by 50%, (3) improving the AIE reliability by 100%, (4) increasing the AIE repair times by 100%, and (5) reducing the AIE repair times by 50%. Only the first two factors had a significant impact on LRU base repair cycle time. These results are shown in Table XII.

Table XII. Other Sensitivity Analysis
LRU Base Repair Cycle Time in Hours
16 PAA per Base

Sensitivity	Digital Qty = 1	Digital An Video Qty = 1	RF Qty = 2	R/EW Qty = 2
Baseline	28.8	46.8	26.3	29.2
SRU Availability at 80%	51.7	92.1	46.9	52.7
Reduce ATE Reliability	42.8	51.2	34.7	36.4
Improve ATE Reliability	29.1	37.3	27.9	27.7
Increase ATE Repair Times	29.0	47.1	26.4	29.4
Reduce ATE Repair Times	28.8	46.4	26.3	29.1

Logistics Support Cost Tradeoff

The first approach in determining test station quantities was to buy a sufficient quantity of test stations such that the predicted base repair cycle time was always under the standard of four calendar days. An alternative approach is to compare the costs of LRU spares (pipeline and safety stock spares) to the cost of test stations. Specifically, an additional test station would be procured as long as the savings in LRU spares (due to the reduced base repair cycle time) were greater than the cost of the additional station. In order for this approach to be valid, it is necessary to assume that the actual procurement of LRU spares will be based on the actual base repair cycle time, and not some standard factor.

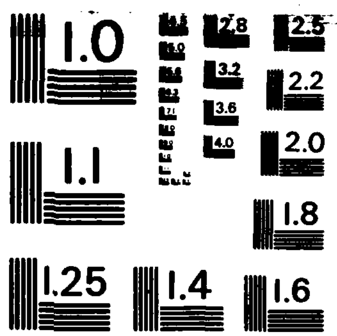
The cost of LRU spares was calculated by use of the Air Force Acquisition Logistics Division (AFALD) Logistics Support Cost (LSC) model. The Mean Time Between Demand (MTBD) for each LRU, the unit cost of the LRU, and the LRU base repair cycle time were the critical inputs. The MTBD estimates were the contractor estimates that were described in Section III. The unit costs of each LRU, measured in FY 81 dollars, were also obtained from contractor estimates. The base repair cycle time was obtained from the output of the simulation model for each of the 12 situations. The LSC model, which calculates the LRU spares (pipeline and safety stock combined) quantity, was then used to compute the total LRU spares dollar investment required for each station type and station quantity at each base. Details on the model can be found in the Logistics Support Cost Model User's Handbook (20). Other LRU logistics support costs, such as maintenance manhour costs or inventory management costs, did not vary with changes in test station quantities and were not considered in this analysis (since they are constants). ATE test stations were assumed to cost 1.5 million dollars (in FY 81 dollars) for each of the four station types. In addition, it was assumed that the marginal cost for ATE SRU spares associated with a second or third station was zero.

Most SRUs, due to their relatively high reliability, have a spare level (pipeline plus safety stock) of only one per base. Thus, adding a second or third station of the same type would usually cause no increase in the spare level (of one). Finally, recurring station maintenance costs (also in FY 81 dollars) were estimated as 10% of the unit cost of the station (or $150,000) per year. However, since this represents outlays over a 20 year period, the recurring station maintenance costs were discounted at a real rate of return of 10% per year. The "present value" of $150,000 per year over a 20 year period is 1.3 million dollars, so the total cost per station is estimated at 2.8 million dollars. The outlays for spares and test stations were treated as "front end" expenditures and therefore not discounted.

The logistics support cost tradeoff (between LRU spares and ATE stations) was estimated for each of the four station types at each of the 3 PAA quantities per base. The results are shown in Tables XIII, XIV, and XV. Interestingly, this second approach (logistics support cost tradeoff) yields results which are very close to the results of the first approach (compare base repair cycle time to four day standard). The results are exactly identical for the 16 PAA and the [illegible] PAA cases. For the [illegible] PAA case, the logistics support cost tradeoff approach indicates that it is cost effective to procure two analog stations and two digital analog video stations rather than one of each.

AD-A141 175 B-1B AVIONICS/AUTOMATIC TEST EQUIPMENT: MAINTENANCE QUEUEING ANALYSIS(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING 2/2

UNCLASSIFIED L M ROARK DEC 83 AFIT/GOR/OS/83D-11 F/G 15/5 NL



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

indicated by the first approach. Thus, the first approach results in an overall quantity of 24 stations for the B-1B fleet, while the second approach results in an overall quantity of 26 stations for the B-1B fleet. Either approach, however, is based on very preliminary data and must be regarded as tentative. Since the results are nearly identical, and since the first approach involves fewer assumptions than does the second, the first approach was selected as the solution technique for the remainder of this research effort.

Table XIII. Baseline Case; 16 Aircraft Per Base
Logistics Support Cost Tradeoff
FY 81 $ in Millions

	Digital Test Station			Digital Analog Video Test Station		
	QTY = 1	QTY = 2	QTY = 3	QTY = 1	QTY = 2	QTY = 3
LRU Spares	28.2	27.0	26.6	18.0	15.9	15.8
Test Stations	2.8	5.6	8.4	2.8	5.6	8.4
Total Cost	31.0	32.6	35.0	20.8	21.5	24.2

	Radio Freq Station			Radar EW Station		
	QTY = 1	QTY = 2	QTY = 3	QTY = 1	QTY = 2	QTY = 3
LRU Spares	35.3	30.3	30.3	22.6	18.4	18.2
Test Stations	2.8	5.6	8.4	2.8	5.6	8.4
Total Cost	38.1	35.9	38.7	25.4	24.0	26.6

Table XIV. Baseline Case; 26 Aircraft Per Base
Logistics Support Cost Tradeoff
FY 81 $ in Millions

	Digital Test Station			Digital Analog Video Test Station		
	QTY = 1	QTY = 2	QTY = 3	QTY = 1	QTY = 2	QTY = 3
LRU Spares	38.5	35.9	35.9	20.1	17.6	17.6
Test Stations	2.8	5.6	8.4	2.8	5.6	8.4
Total Cost	41.3	41.5	44.3	22.9	23.2	26.0

	Radio Freq Station			Radar EW Station		
	QTY = 1	QTY = 2	QTY = 3	QTY = 1	QTY = 2	QTY = 3
LRU Spares	X	45.5	43.7	X	26.9	26.2
Test Stations	X	5.6	8.4	X	5.6	8.4
Total Cost	X	51.1	52.1	X	32.5	34.6

Table XV. Baseline Case; 32 Aircraft Per Base
Logistics Support Cost Tradeoff
FY 81 $ in Millions

	Digital Test Station			Digital Analog Video Test Station		
	QTY = 1	QTY = 2	QTY = 3	QTY = 1	QTY = 2	QTY = 3
LRU Spares	46.1	42.4	42.3	22.1	18.7	18.2
Test Stations	2.8	5.6	8.4	2.8	5.6	8.4
Total Cost	48.9	48.0	50.7	24.9	24.3	26.6

	Radio Freq Station			Radar EW Station		
	QTY = 1	QTY = 2	QTY = 3	QTY = 1	QTY = 2	QTY = 3
LRU Spares	X	53.4	51.3	X	31.8	31.8
Test Stations	X	5.6	8.4	X	5.6	8.4
Total Cost	X	59.0	59.7	X	37.4	40.2

Deployment for a Major Conventional War

All analysis discussed so far has been restricted to peacetime maintenance and support. The peacetime scenario calls for aircraft on daily alert and for aircrew training missions. In times of crisis, however, some B-1Bs might be dispersed to a satellite base. Only organizational level (and not intermediate level) maintenance would be performed at these bases, thus no additional test stations would be required to support such a dispersal (15:26-27). There is also no plan to use the B-1B ATE to support operations during a sustained nuclear war. Again, only organizational maintenance would be performed to support such operations. After all, the B-1B ATE is not hardened for protection against electromagnetic pulse (EMP) events. Another possibile wartime mission would be a major conventional war. Although there is no formally documented requirement for such a mission, the potential conventional role for the B-1B is largely undefined. The analysis that follows is entirely hypothetical and does not constitute any formal SAC plan for actual usage of the B-1B.

The B-1B fleet consists of 5 squadrons of 16 PAA each and 1 squadron of 10 PAA for combat crew training. In this analysis, it was assumed that a flight of 6 PAA would be taken from each of the first 5 squadrons and that 10 PAA would remain behind for purposes of strategic alert. It was also assumed that the 10 PAA squadron would also remain at its normal location. Thus, a total of 30 aircraft would be deployed while 60 aircraft would remain at the MOBs. It was also assumed that the 30 deployed aircraft would be sent to two sites overseas; one site would receive 18 aircraft, and the other would receive 12 aircraft. The final allocation of aircraft is shown in Table XVI.

Table XVI. Deployment of B-1B Fleet to Support Major Conventional War

Location	Before Deployment PAA Aircraft	After Deployment PAA Aircraft	Mission
MOB #1	26	20	Strategic alert, training
MOB #2	16	10	Strategic alert
MOB #3	32	20	Strategic alert
MOB #4	16	10	Strategic alert
Deployment Site #1	0	18	Conventional war
Deployment Site #2	0	12	Conventional war

At the deployment sites, it was assumed that the aircraft would fly three times as many flying hours as in peacetime, and that the aircraft would fly the same amount every day for seven days per week. It was also assumed that the maintenance shifts would be expanded from two 8-hour shifts per day to two 12-hour shifts per day, and that the maintenance shifts would be expanded from five days per week to seven days per week. It was also assumed that the reliability and maintainability characteristics of the LRUs and ATE test stations would be the same in wartime as in peacetime. The model was adjusted to account for the expanded maintenance shifts and used to determine the minimum test station quantities required to support a four calendar day base repair cycle time. The total requirement to support the hypothetical deployment was found to be 31 test stations. These results are shown in Table XVII.

Table XVII. Test Station Quantities to Support Hypothetical Deployment

Site	Digital	Digital An Video	RF	R/EW
MOB #1	1	1	2	2
MOB #2	1	1	1	1
MOB #3	1	1	2	2
MOB #4	1	1	1	1
Deployment Site #1	1	1	2	2
Deployment Site #2	1	1	1	2
Total	6	6	9	10

VII. Summary and Recommendations

Overview

The purpose of this research effort was to develop a technique to determine B-1B automatic test equipment (ATE) station quantities required to support the B-1B fleet at base level. The ATE stations are essential for the support of over 100 B-1B line replaceable units (LRUs). The decision as to how many stations to procure not only affects whether the B-1B avionics LRUs can be supported, but also involves expenditures of several millions of dollars. The remainder of this section provides a summary of the major results of this research effort and presents the B-1B System Program Office (SPO) with a package of options for test station acquisition strategy. The summary describes the simulation model of B-1B avionics maintenance that was developed, describes the techniques developed to determine station quantity requirements, and compares the simulation model to a second model, based on analytical queueing theory, also developed as part of the research effort.

Summary

The most significant product of this research effort is a detailed simulation model developed in the Q-GERT simulation language. Had this model not been developed, the B-1B SPO would have had to rely on the General Dynamics station loading model described in Section I. There are several deficiencies in the contractor model which have been remedied in the Q-GERT model. First, the contractor estimates of mean LRU maintenance times failed to account for manual troubleshooting or additional testing which sometimes occur in real-world maintenance. The contractor estimates have been adjusted, as explained in Section III, to account for both effects. Second, the contractor model assumes that the avionics LRU arrival rate is constant over the maintenance day. However, current SAC planning suggests that the B-1B flying hours are not spread evenly over different times of the day or different days of the week as explained in Section III. The Q-GERT simulation model was developed to include this distribution. Third, the contractor model fails to include the technician travel time to obtain a shop replaceable unit (SRU) spare necessary to complete a LRU repair. Estimates of these travel times were obtained from HQ SAC personnel and incorporated into the Q-GERT model as described in Section IV. Fourth, the contractor model implicitly assumes that SRU spares are available on base 100% of the time. The Q-GERT model, on the other hand, is more realistic; it explicitly assumes SRU spares are available only 90% of the time. This is important because the SRU spare stockouts have a significant effect on station availability. The main point overall is that the contractor model is consistently optimistic in estimating the workload of avionics LRUs on ATE test stations. The Q-GERT model was developed in an iterative fashion with a great deal of feedback and constructive criticism from personnel from HQ SAC and the B-1B SPO. This helped ensure model realism.

The second major product of this research effort was the development of techniques to determine the best choice of test station quantities. To accomplish this, the simulation model was expanded to include organizational (flight-line) maintenance and various administrative delays so that the model output is the (complete) LRU base repair cycle time. This is the time from LRU failure to repair and return to base supply. Two approaches were then developed in determining the best choice of station quantities. The first approach was to buy sufficient quantities such that the LRU base repair cycle time was shorter than some established standard. This standard would be the planned base repair cycle time used to determine the avionics LRU spare (pipeline and safety stock) quantities. The second approach was to perform a cost-benefit analysis on procurement of additional test stations versus procurement of additional LRU spares. This approach compared the costs of additional test stations (and the benefits of shorter base repair cycle times) to the costs of additional LRU spares (and the benefits of fewer test stations). The two approaches yield nearly identical results.

A second model of B-1B avionics maintenance was also developed during this research effort. The analytical model is based on the theory of queueing networks and other queueing techniques. The analytical model still required many more crude and simplifying assumptions than did the simulation model, and the results obtained from the analytical model were not very satisfactory. The reasons for the poor results (and recommendations for future research which might correct these problems) are explained in Section V. The Q-GERT simulation model was selected as the best choice for future use by the B-1B SPO.

Recommended Management Options for the B-1B SPO

The first choice to be made concerns the selection of reliability and maintainability inputs. Relying on the associate contractor estimates for LRU reliability and the ATE vendor's estimates for LRU performance test times (as defined in Section III) is financially prudent since these inputs lead to the minimum required quantities. However, there is some risk for B-1B avionics supportability since these estimates might be excessively optimistic. If this were to happen, the station quantities would not be sufficient to support the avionics workload. One course of action would be to accept the contractor estimates for the time being, and therefore make a tentative decision to buy only the minimum number of stations. With this course of action, the B-1B SPO should still retain some flexibility to obtain additional test stations should the need arise. This flexibility could be preserved by a provision for separately priced contractual options for additional test stations. Another way to preserve flexibility would be to procure stations collectively for intermediate level maintenance (which was addressed in this research effort), depot level maintenance, contractor use, and maintenance training (which were not addressed in this research effort) with a few additional stations designated for management reserve. A second course of action would be to procure test stations based on the more pessimistic reliability and maintainability inputs explained in Section III. This course of action involves less risk for B-1B avionics supportability, but also leads to greater quantities of stations and therefore larger expenditures. Some of these expenditures might turn out to have been unjustified if the baseline contractor estimates turn out to be reasonable. The first course of action, therefore, is probably the wisest as long as the B-1B SPO is able to preserve flexibility to procure additional stations as required.

Assuming that the B-1B SPO indeed retains some flexibility for a range of station quantities, the B-1B SPO should periodically review and refine its estimates of test station requirements. It is likely that, over time, better quality estimates of the reliability and maintainability inputs will become available. Presumably, the associate contractors estimates should become more refined as the B-1B avionics go through various reliability qualification tests and maintainability demonstrations. A review of test station requirements could take place periodically (say every six months) by running the Q-GERT simulation model with the most recent information available. In addition, it might be desirable to task staff organizations (such as ASD/EN or AFALC/PT) for assistance in determining that the contractor estimates are reasonable, or in obtaining better estimates if needed.

The second choice to be made is the methodology to determine test station quantities. As explained in Section VI, the first method is to buy sufficient test stations to support a four calender day base repair cycle time; the alternative second method is to buy sufficient test stations to achieve the lowest possible logistics support cost (including the cost of ATE test stations and avionics LRU spares). There are many issues to be considered before such a choice could be made. The first issue is the potential impact of funding constraints. For example, if B-1B spares funding were to be severely constrained in the future, it would tend to favor the alternative second method (lowest logistics support costs). This second method leads to larger station quantities, shorter repair cycle times, and therefore reduced LRU spares requirements. On the other hand, if B-1B peculiar support equipment (which includes ATE) funding were to be severely constrained in the future, it would tend to favor the first method (support a four day base repair cycle time) since it leads to lower test station quantities. The second issue to be considered is coordination with other organizations. The first method (support a four day base repair cycle time) could be accomplished unilaterally by the B-1B SPO. The alternative second method would require an integrated ATE/LRU spares acquisition strategy. Both ATE procurement and avionics LRU spares procurement would have to be based on the same logistics factors (LRU reliability and base repair cycle time) to actually achieve the lowest logistics support cost. Accomplishing such an integrated strategy would require close coordination between the SPO, the B-1B System Manager, and many equipment specialists and item managers located at many ALCs.

The third choice to be made concerns buying test station quantities to support peacetime or wartime. One approach to this issue would be to only procure, at least for the time being, test stations to support peacetime only.

However, analysis indicates that peacetime quantities, even with expanded maintenance shifts, will not be sufficient to support a major conventional deployment. Should the requirement for a conventional deployment ever emerge, additional test stations would have to be borrowed (from depot or other operational sources) or procured at that time. An alternative approach would be to develop the most likely conventional scenario and procure sufficient test stations to support such a scenario. It would be difficult to justify adopting this alternative approach unless the requirement for a conventional deployment were formally documented in an official planning document such as the B-1B Program Managemet Directive (PMD).

Even if the Q-GERT simulation model were perfectly accurate, there is simply too much uncertainty regarding the reliability and maintainability inputs to determine the precise base level test station requirements. Rather, at this time, it is only possible to determine a reasonable range of quantities. The actual product of this research effort is therefore not the final estimate of test station quantities, but rather a simulation model with which other techniques can be used by the B-1B SPO over the next several years to continually update and refine its estimate of test station quantities. In addition, the B-1B SPO can now select from a variety of approaches (which were described in Sections IV and VI) to determine the best assessment of station quantities. The selection of the approach to this problem is a matter of management judgement, which of course should be reserved for the B-1B SPO. A summary of the results for the various approaches is shown again for review in Table XVIII.

Table XVIII. Summary of Test Station Quantities to Support B-1B Operational Fleet at Base Level

Approach	Digital	Digital Analog Video	RF	R/EW	Total
Baseline	4	4	8	8	24
Lowest Logistics Support Cost	5	5	8	8	26
HQ SAC MTBD Estimates	5	8	10	10	33
RI Performance Test Time Estimates	5	6	9	9	29
Conventional Deployment	6	6	9	10	31

Appendix A: Simulation Model User's Guide

List of Inputs

The following inputs are stored in FORTRAN data statements in FORTRAN Subroutine UI. The ATE test station inputs are one-dimensional arrays of size four; one entry corresponds to each station type. The inputs must be stored in the correct order (Digital, Digital Analog Video, RF, and REW). The ATE test station inputs are:

TSMTBF - Test Station Mean Time Between Failures

ATEQTY - Quantity of stations by station type

ATERP1 - Average time for setup and fault isolation

ATERP2 - Average time for station repair and teardown

The LRU inputs are one-dimensional arrays of (up to) size 200. Each entry in each array corresponds to one LRU. The inputs may be stored in any order, but the order must be the same for all arrays. The LRU inputs are:

XMTBD - Mean Time Between Demand (in flying hours)

QPA antity per aircraft

STNRE Station Requirement:
) = Digital
) = Digital Analog Video
.0 = Radio Frequency
-- 4.0 = Radar Electronic Warfare

AFSC - Intermediate Level Technician Requirement
-- 1.0 = Communication Navigation
-- 2.0 = Auto Flt Controls Instruments
-- 3.0 = Offensive Avionics
-- 4.0 = Defensive Avionics

SETUP - Time to set-up LRU on station

TSSITA - Time to run ITA confidence check

WARMUP - Time to warm up LRU

PERFT - Time to run one complete performance test

FRRTS - Fraction of maintenance actions that are Repairable This Station

FRRTOK - Fraction of maintenance actions that are Retest Okay

FRNRTS - Fraction of maintenance actions that are Not Repairable This Station

TEARDN - Time to tear-down LRU from station

REPAIR - Time to repair LRU (remove and replace failed SRU).

Other inputs stored in FORTRAN data statements in UI are:

ACBASE - Number of aircraft per base

SRUAVL - Fraction of the time that a required SRU spare will be available on base

FHACMO - Flight hours per aircraft per month

FLYPER - Time length of interval over which sorties are launched

FACTDY - Fraction of weekly flying hours by day of the week; an array of size five

FACTTM - Fraction of flying hours by time of day; an array of size two (for morning sorties and night sorties)

NLRU - Number of LRUs; must be less than or equal to 200

Conversion of Flying Hours to Real Time

The LRU MTBD values must be input in flying hours. FORTRAN Subroutine UI takes the reciprocal of each MTBD to find the LRU arrival rate. These LRU arrival rates are then added to determine the aggregate arrival rate. The reciprocal of this aggregate arrival rate is the aggregate MTBD in flying hours; this is FORTRAN variable DEMFH in the model. The aggregate MTBD is then converted to real time by the following equation:

$$DEMSH = \frac{DEMFH * (FLYPER * 4.333)}{FACTDY(IAT1) * FACTTM(IFN) * ACBASE * FHACMO}$$

4.333 is the number of weeks per month. IAT1 is an integer from 1 through 5 to denote the day of the week. IFN is an integer (either 1 or 2) to denote the time of day (morning or night). The time interval (FLYPER) for LRU arrivals is assumed to be 4.0 hours as explained in Section IV.

How to Run the Model

The simulation model is run in batch mode on the ASD CDC Cyber. For user convenience, the model will be furnished in three versions for the 16 PAA, 26 PAA, and 32 PAA cases. These models are named MODEL16, MODEL26, and MODEL32. Output must be obtained in the computer room in AFIT/EN, Bldg 640 or wherever the output is designated. The batch command for AFIT/EN would be: BA,MODEL16,AF.

How to Change Station Quantities

Unfortunately, changing station quantities requires changes to both FORTRAN and Q-GERT code. The quantities must be input in the correct order (Digital, Digital Analog Video, RF and R/EW). The FORTRAN code which must be changed is:

```
DATA ATEQTY/1.0,1.0,1.0,1.0/
```

Each entry represents the number of stations at the base by station type.

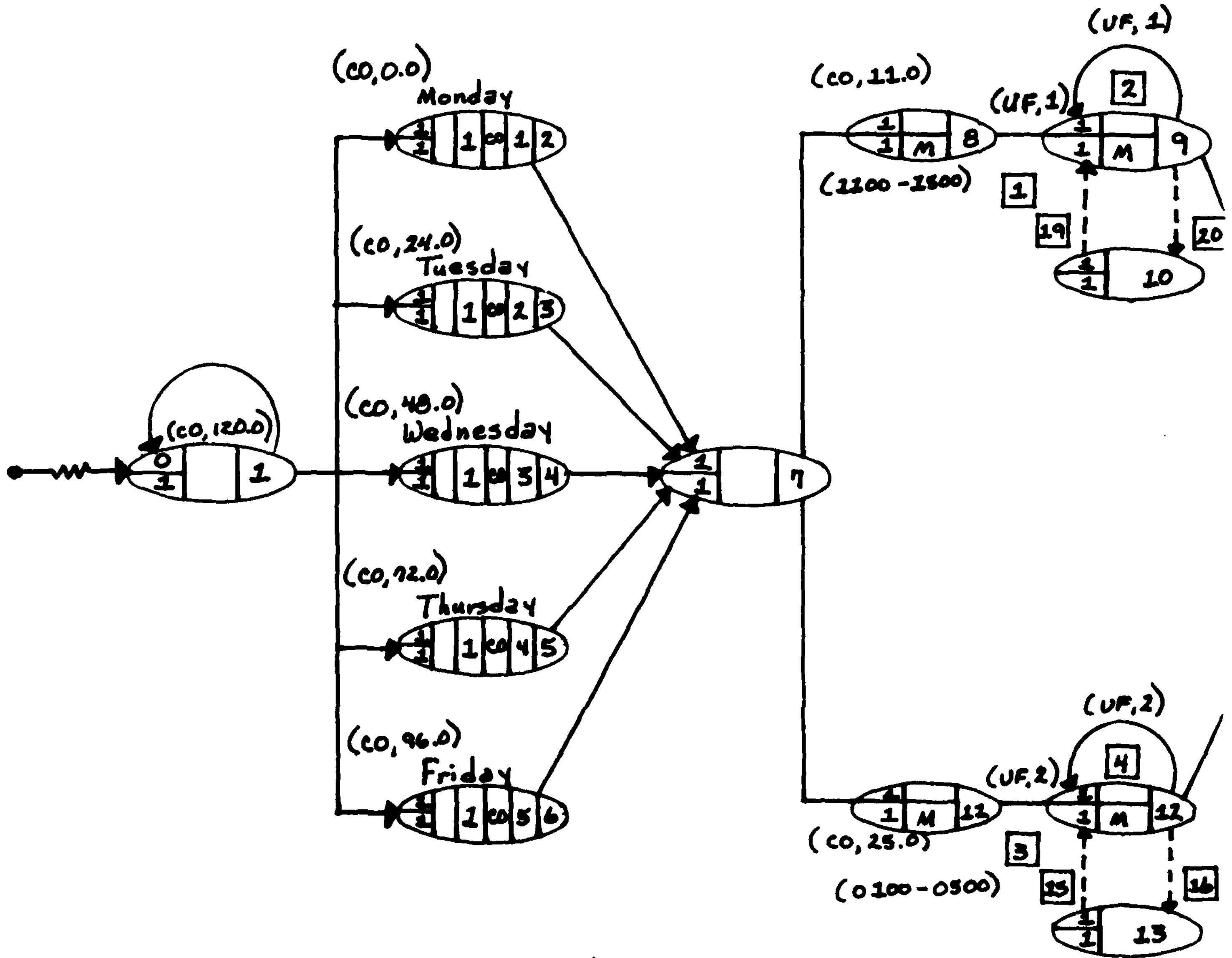
The Q-GERT lines which must be changed are:

```
RES,2/DIGITAL,1,66,28*
RES,3/DIGAV,1,67,29*
RES,4/RF,1,68,30*
RES,5/RADAREW,1,69,31*

ALT,112,D,2,-1,66,28*
ALT,113,D,3,-1,67,29*
ALT,114,D,4,-1,68,30*
ALT,115,D,5,-1,69,31*

ALT,130,D,2,1,66,28*
ALT,131,D,3,1,67,29*
ALT,132,D,4,1,68,30*
ALT,133,D,5,1,69,31*
```

There are thus twelve lines of Q-GERT code which must be changed to change input test station quantities. For the RESOURCE lines (which start RES,), the quantity of stations is the third entry (1 in this example). For the ALTER node lines (which start ALT,), the quantity of stations is the fifth entry. For the ALTER nodes 112 through 115, the test station quantities are input as negative integers to denote the end of a maintenance shift. For the ALTER nodes 130 through 133, the test station quantities are input as positive integers to denote the start of a maintenance shift.

The remainder of this appendix consists of the network Q-GERT diagram and the model listing.

Sortie Generation - Failure Generation

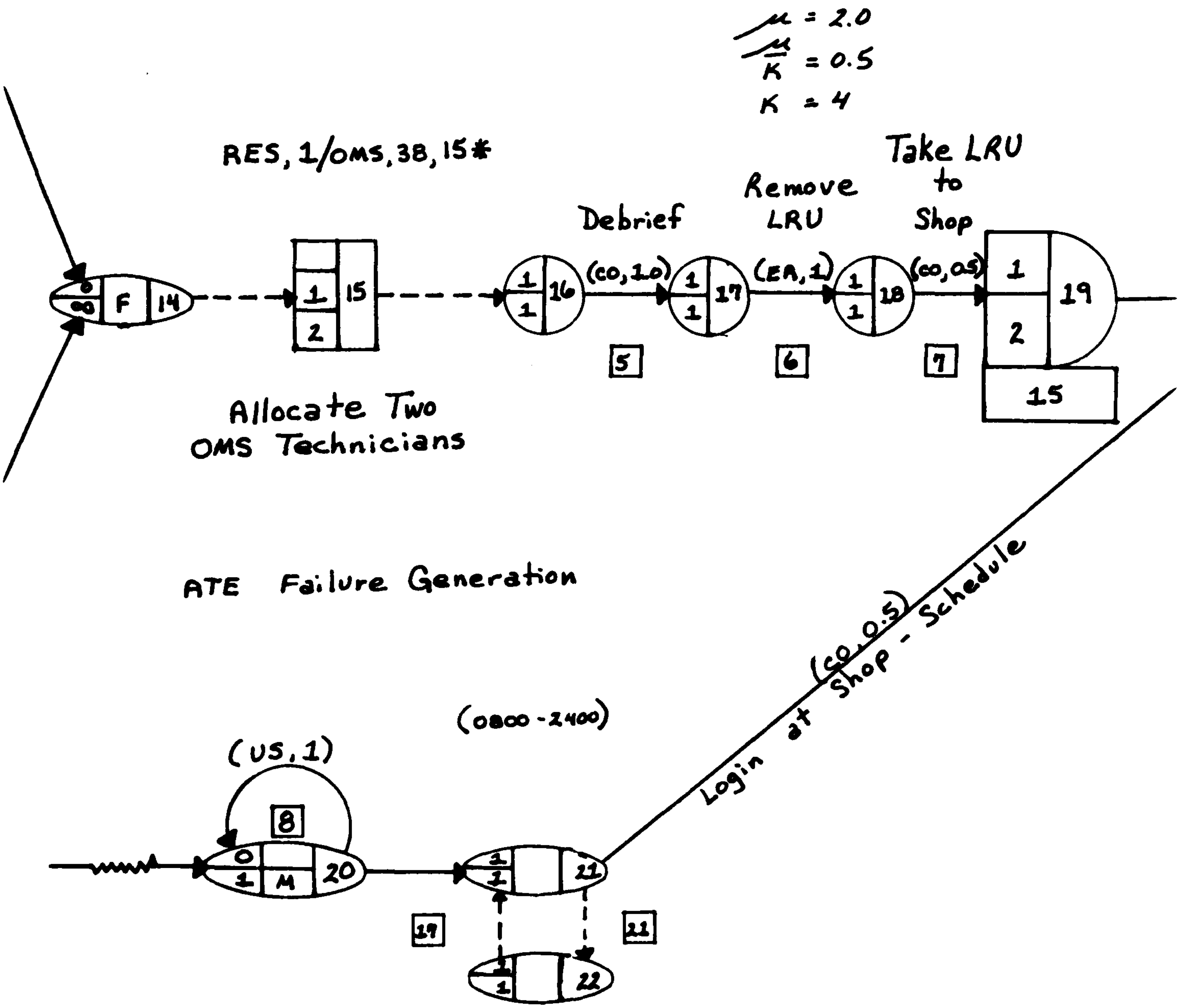


Sorties Start at: Day - 0600 to 1000
Night - 2000 to 2400

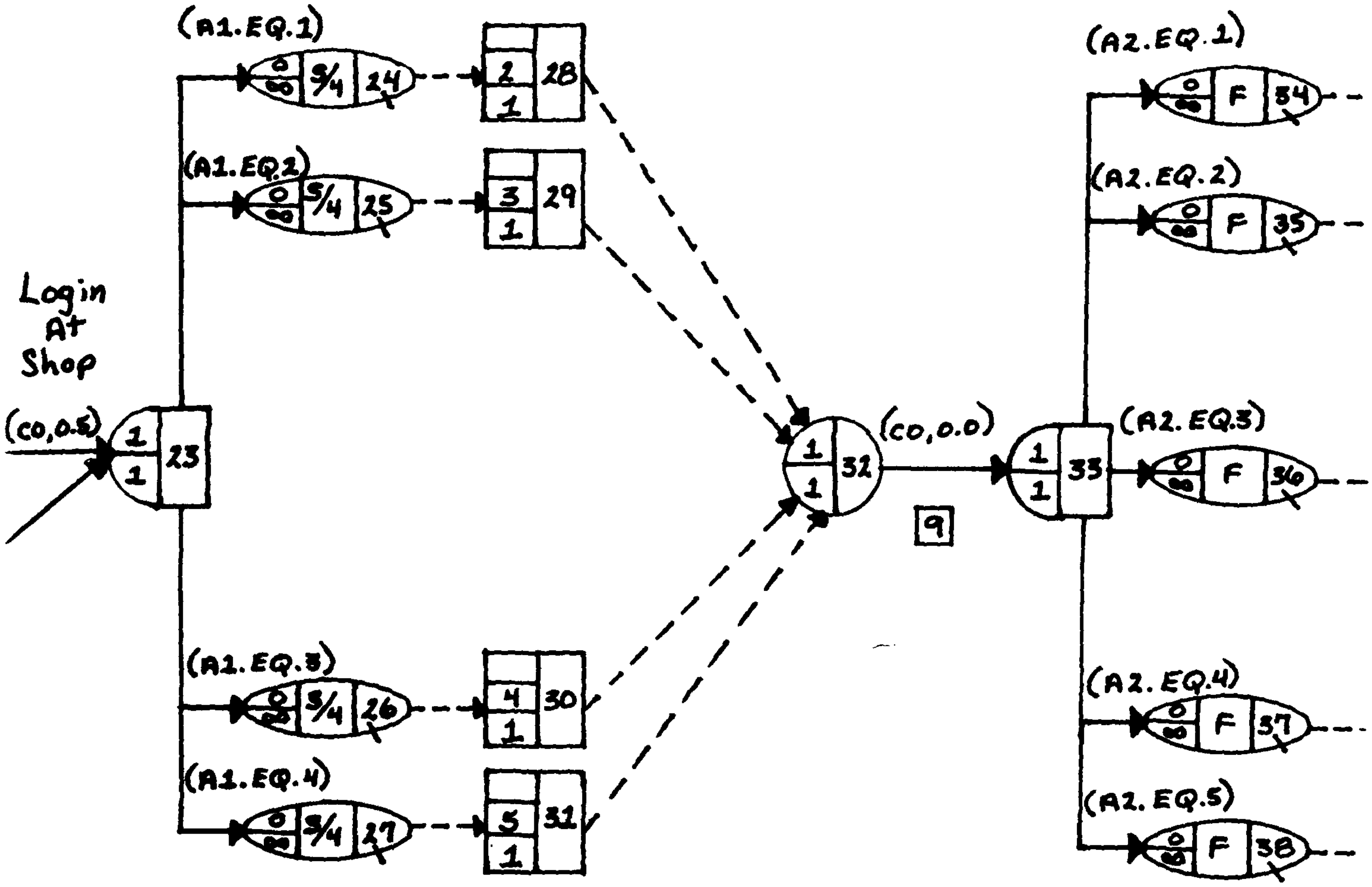
Add 5 hours for Sortie Duration

Failures Arrive at: Day - 1100 to 1500
Night - 0100 to 0500

Flight Line Maintenance



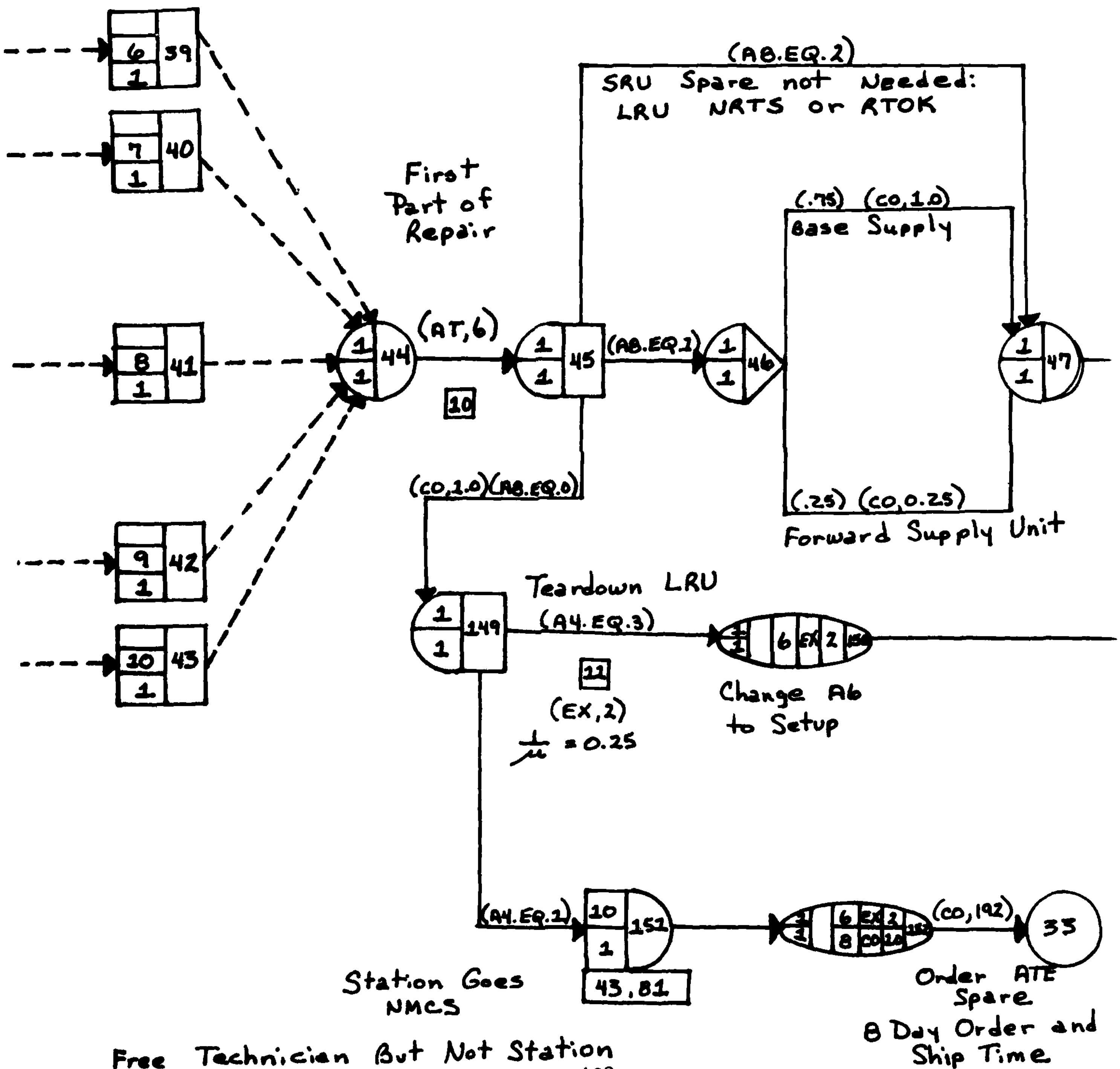
Allocate Station

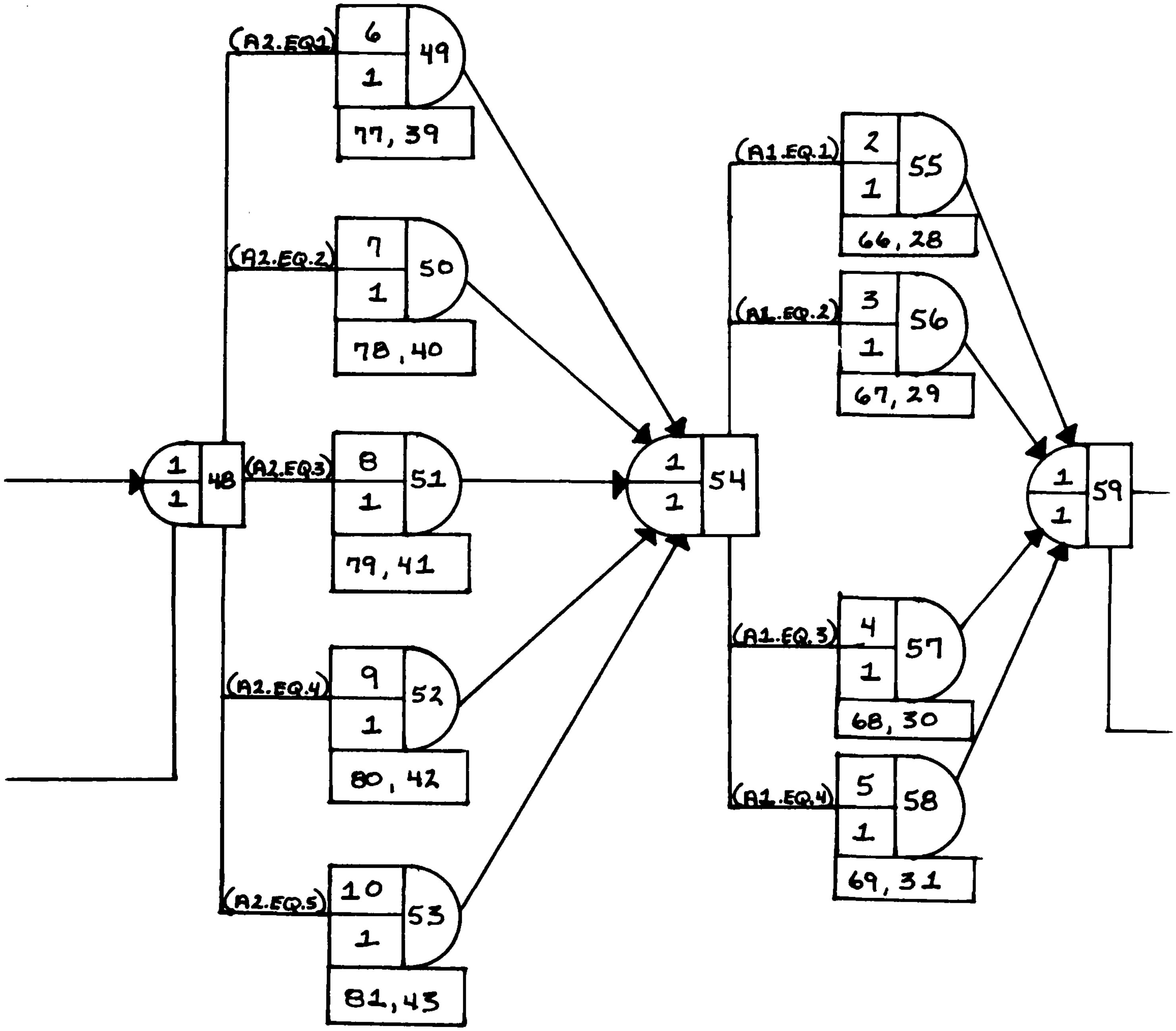


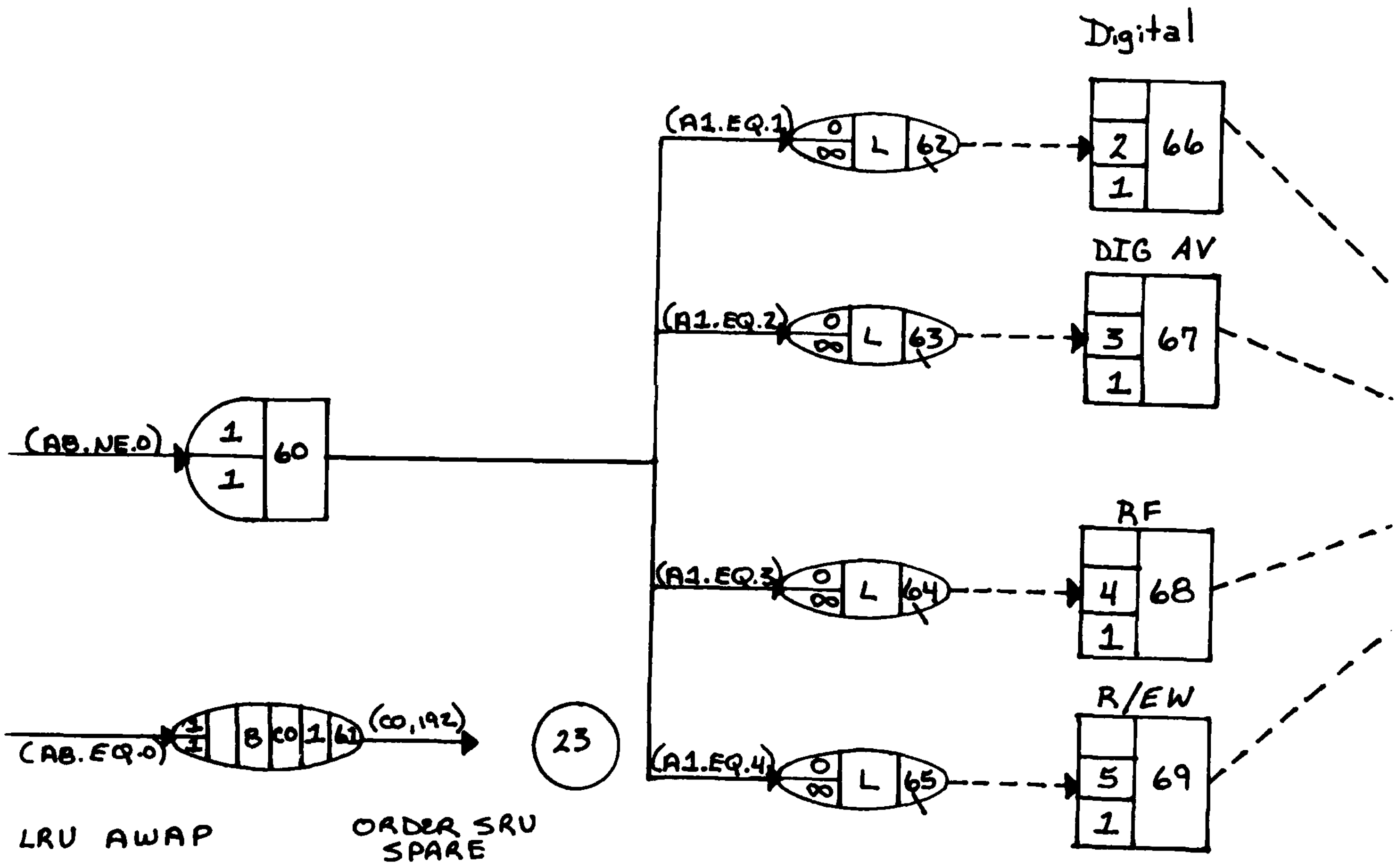
RES, 2/DIGITAL, 1, 66, 28 *
RES, 3/DIGAV, 1, 67, 29 *
RES, 4/RF, 1, 68, 30 *
RES, 5/REW, 1, 69, 31 *

RES, 6/COMMNAV, 7, 77, 39 *
RES, 7/AFCINS, 4, 78, 40 *
RES, 8/OFFAV, 16, 79, 41 *
RES, 9/DEFAV, 10, 80, 42 *
RES, 10/PMEL, 5, 81, 43 *

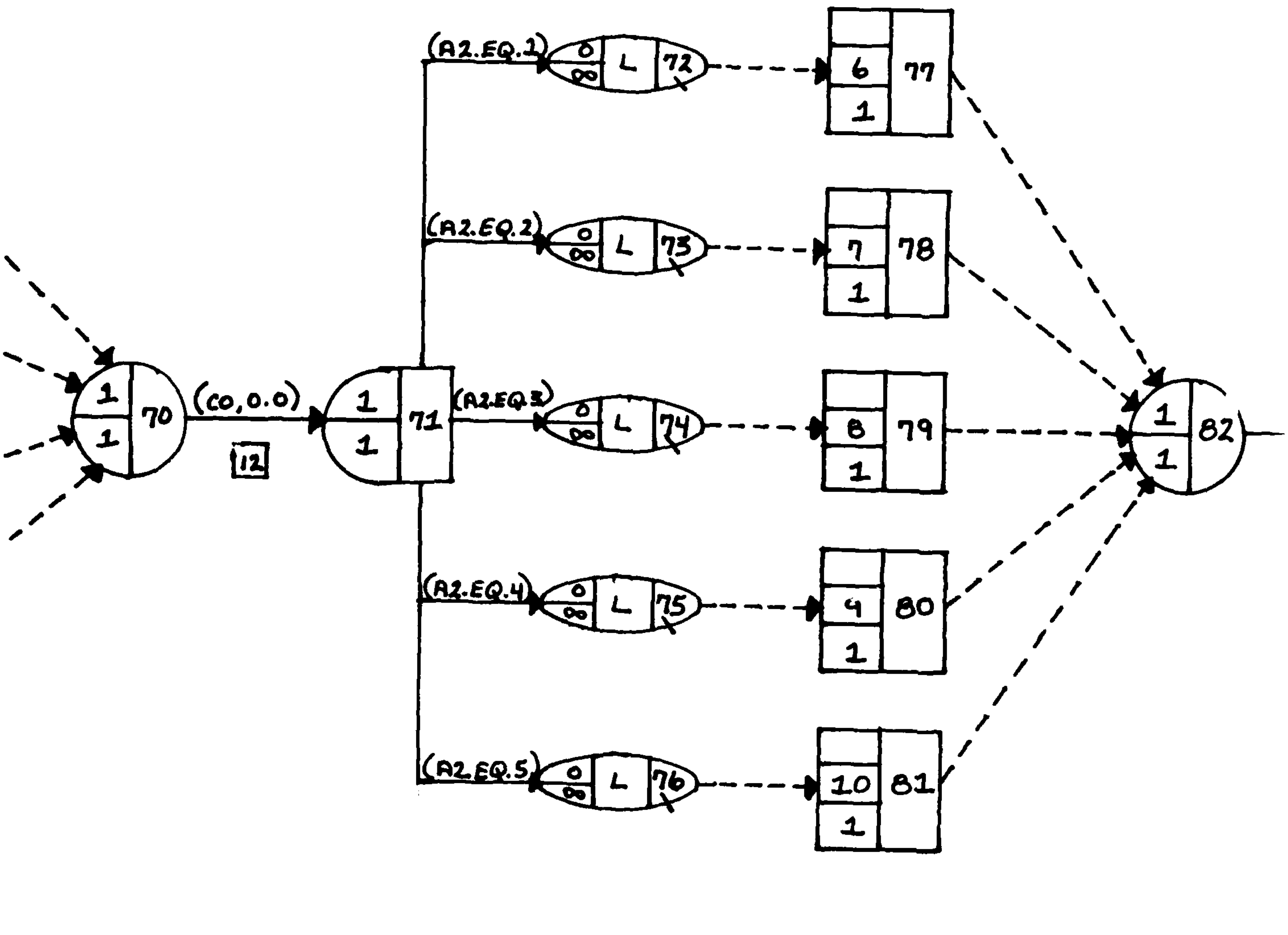
Allocate Technician



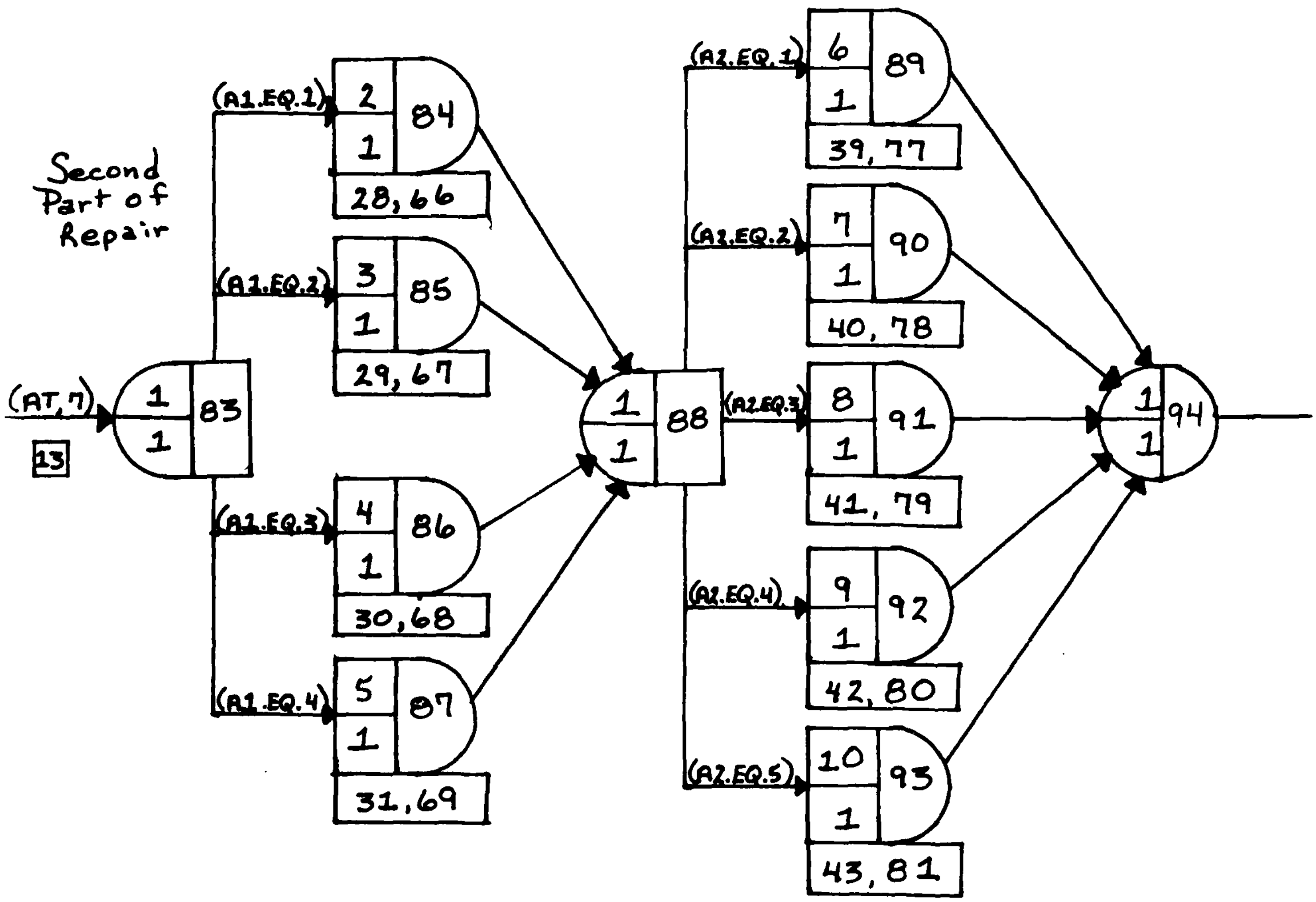

(A2.EQ.1)
6
1
49
77, 39
(A2.EQ.2)
7
1
50
78, 40
1
1
48
(A2.EQ.3)
8
1
51
79, 41
(A2.EQ.4)
9
1
52
80, 42
(A2.EQ.5)
10
1
53
81, 43
1
1
54
(A1.EQ.1)
2
1
55
66, 28
(A1.EQ.2)
3
1
56
67, 29
(A1.EQ.3)
4
1
57
68, 30
(A1.EQ.4)
5
1
58
69, 31
1
1
59

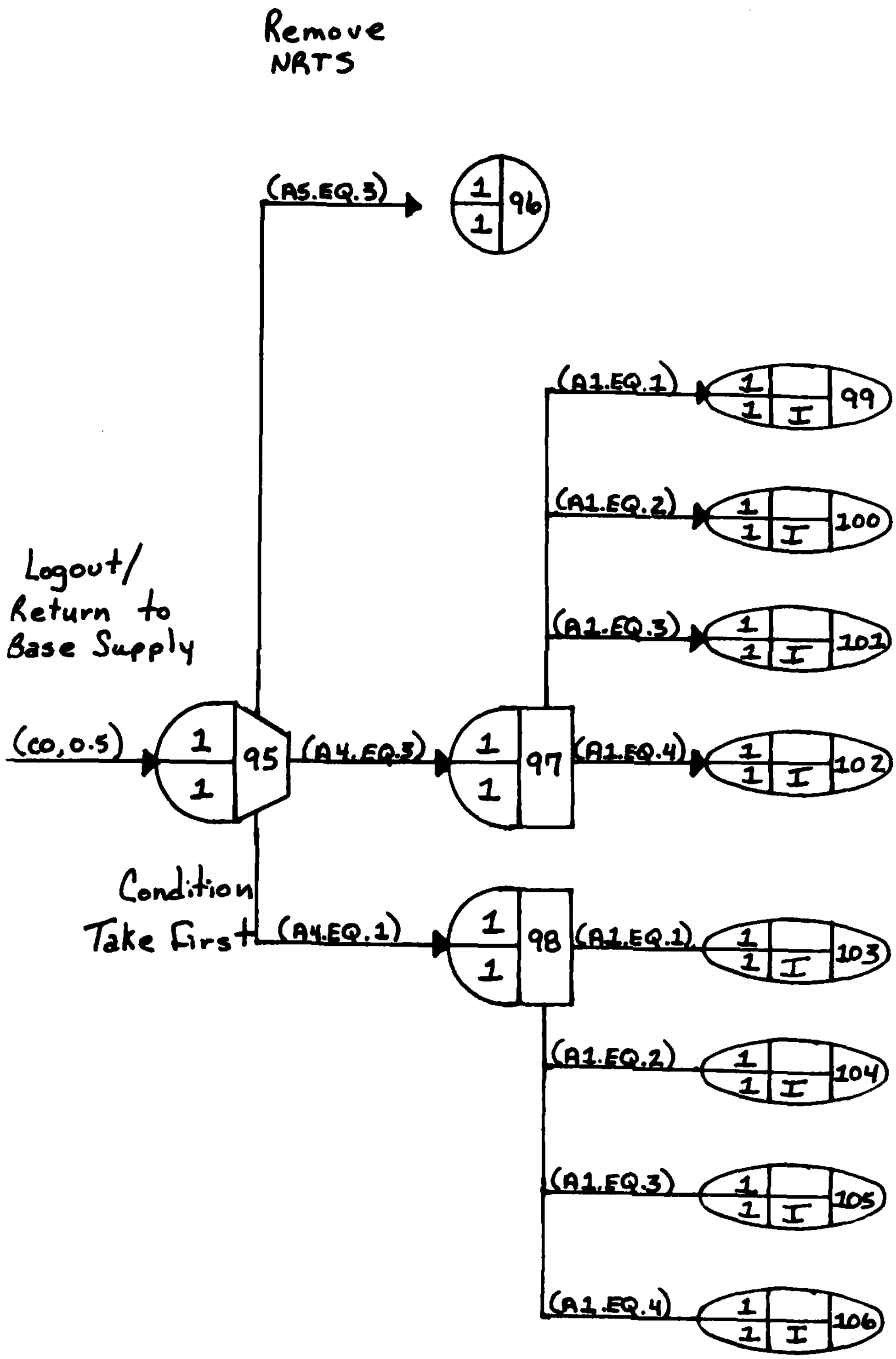


Digital
DIG AV
RF
R/EW
(A1.EQ.1)
(A1.EQ.2)
(A1.EQ.3)
(A1.EQ.4)
(AB.NE.0)
(AB.EQ.0)
(∞,192)
60
62
63
64
65
66
67
68
69
23
LRU AWAP
ORDER SRU SPARE



1
1
70
(CO,0.0)
12
1
1
71
(A2.EQ.1)
0
∞
L
72
(A2.EQ.2)
0
∞
L
73
(A2.EQ.3)
0
∞
L
74
(A2.EQ.4)
0
∞
L
75
(A2.EQ.5)
0
∞
L
76
6
1
77
7
1
78
8
1
79
9
1
80
10
1
81
1
1
82

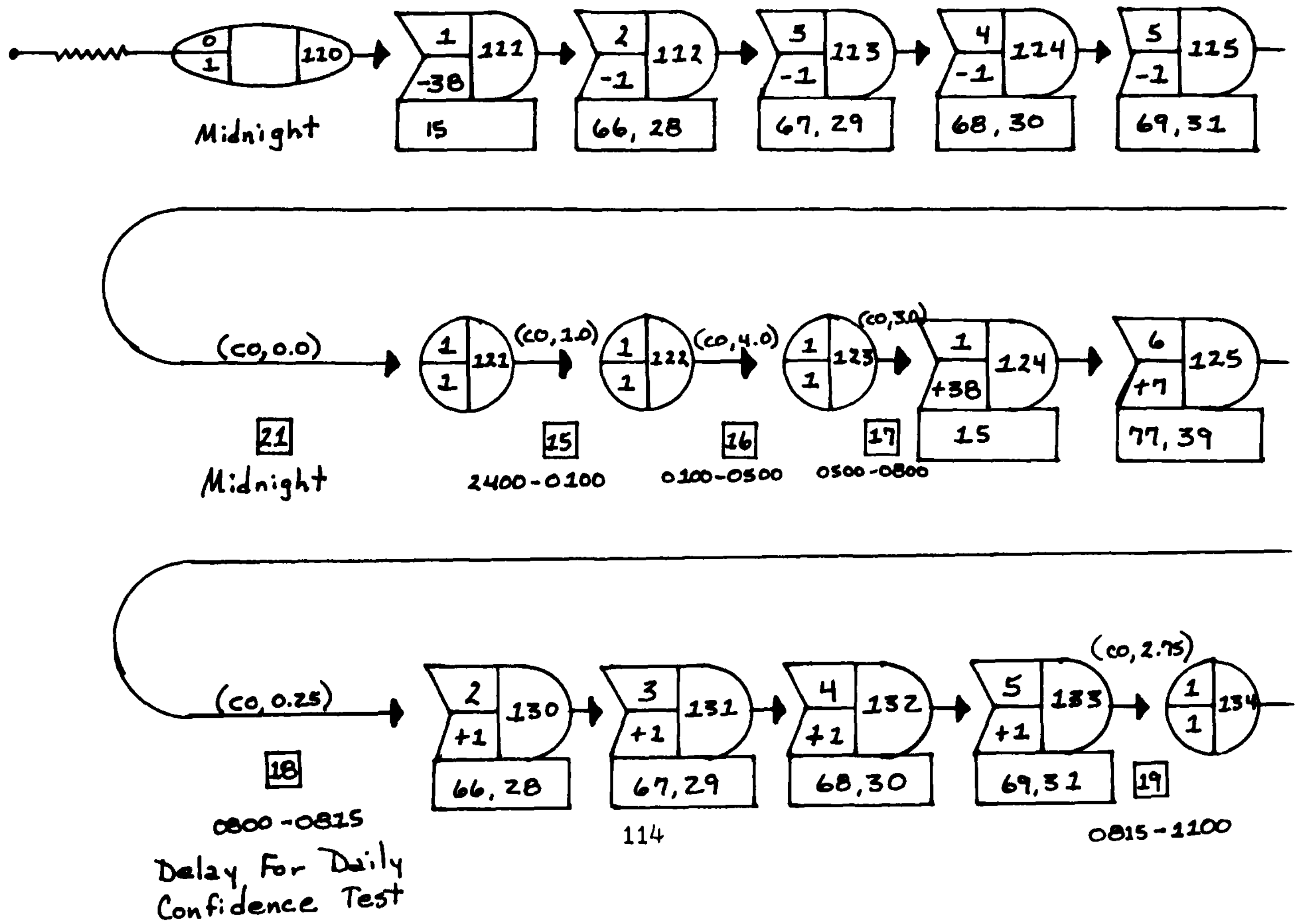

Second Part of Repair
(AT,7)
13
1
1
83
(A1.EQ.1)
2
1
84
28,66
(A1.EQ.2)
3
1
85
29,67
(A1.EQ.3)
4
1
86
30,68
(A1.EQ.4)
5
1
87
31,69
1
1
88
(A2.EQ.1)
6
1
89
39,77
(A2.EQ.2)
7
1
90
40,78
(A2.EQ.3)
8
1
91
41,79
(A2.EQ.4)
9
1
92
42,80
(A2.EQ.5)
10
1
93
43,81
1
1
94



Remove
NRTS
(A5.EQ.3)
1
1
96
(A1.EQ.1)
1
1
I
99
(A1.EQ.2)
1
1
I
100
Logout/
Return to
Base Supply
(A1.EQ.3)
1
1
I
101
(CO,0.5)
1
1
95
(A4.EQ.3)
1
1
97
(A1.EQ.4)
1
1
I
102
Condition
Take First
(A4.EQ.1)
1
1
98
(A1.EQ.1)
1
1
I
103
(A1.EQ.2)
1
1
I
104
(A1.EQ.3)
1
1
I
105
(A1.EQ.4)
1
1
I
106

24 Hour Clock to Control Events

At 1: Day of the Week
At 1: Test Station Requirement
At 2: I-Level AFSC Requirement by Branch
At 3: Actual Type of Station Used; Now No Longer Needed
At 4: Type of Maintenance Action
= 1 ATE Repair
= 3 LRU Repair

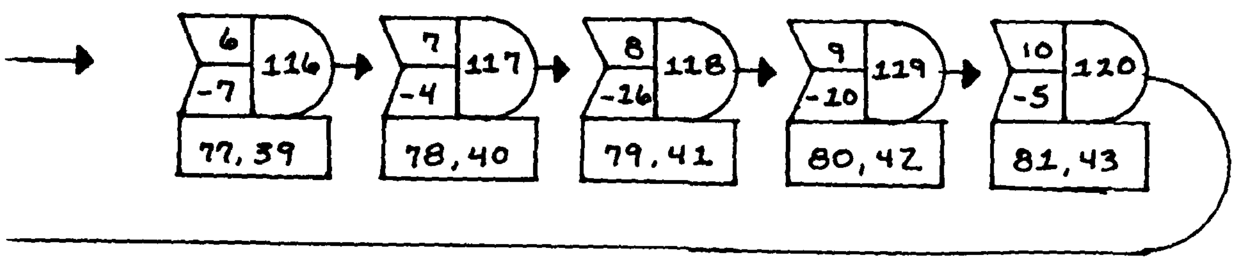


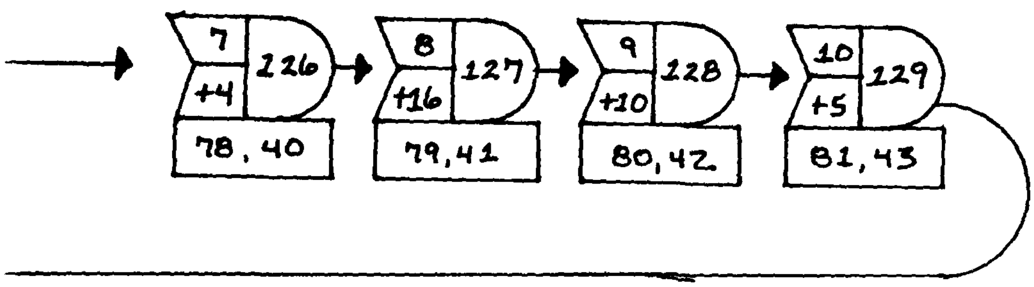
AT 5: Type of Repair
= 1 RTS
= 2 RTOK
= 3 NRTS

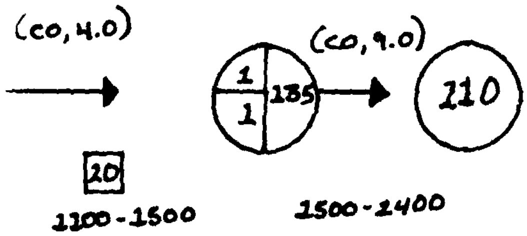
AT 6: Hours for First Part of Repair

AT 7: Hours for Second Part of Repair

AT 8: SRU Spare Part Availability
= 0 Not in Stock
= 1 Available
= 2 Not Needed (RTOK or NRTS)







..LIST,ALL

```
LMR,CM177000,T400,IO200.     T830662,ROARK,4533.
ATTACH,IMSL,IMSL,ID=LIBRARY,SN=ASD.
LIBRARY,IMSL.
ATTACH,PROCFIL,QGERTPROC,ID=AFIT.
FTN5,ANSI=0.
BEGIN,QGERT,PROCFIL,M=LGO,MODE=X.
*EOR
      FUNCTION UF(IFN)
      COMMON/QVAR/NDE,NFTBU(500),NREL(500),NRELP(500),
     1   NREL2(500),NRUN,NRUNS,NTC(500),PARAM(100,4),TBEG,TNOW
      COMMON/UCOM1/DEMFH,FLYPER,ACBASE,FHACMO,
     1   FACTDY(5),FACTTM(2)
      COMMON/UCOM2/CUMPRB(200),STNREQ(200),AFSC(200),FRRTS(200),
     1   FRRTOK(200),FRNRTS(200),SETUP(200),TSSITA(200),
     2   WARMUP(200),PERFT(200),REPAIR(200),TEARDN(200)
      COMMON/UCOM3/DSEED,SRUAVL
      DOUBLE PRECISION DSEED
      DSEED = DSEED + (100000.*NRUN)
C     ATTRIBUTE 1 IS DAY OF THE WEEK
      AT1 = GATRB(1)
      IAT1 = AT1
C     CONVERT RELIABILITY IN FLYING HOURS TO
C     RELIABILITY IN ACTUAL HOURS
      DEMSH = (DEMFH*FLYPER*4.333)/(FACTDY(IAT1)*
     1          FACTTM(IFN)*ACBASE*FHACMO)
C     UNIF IS UNIFORM(0,1)
C     UF IS SIMULATED EXPONENTIAL ARRIVAL TIME
      UNIF = GGUBFS(DSEED)
      UF = -1.0*DEMSH*ALOG(UNIF)
      IF(UF .GT. 16.0) UF = 16.001
C     DETERMINE WHICH LRU HAS FAILED BY SECOND UNIF(0,1)
      UNIF = GGUBFS(DSEED)
      I = 1
      IF(UNIF .LT. CUMPRB(I)) GO TO 110
  100 I = I + 1
      J = I - 1
      IF((CUMPRB(J).LE.UNIF) .AND. (UNIF.LT.CUMPRB(I))) GO TO 110
      GO TO 100
  110 CONTINUE
C     ATTRIBUTE 1 -- STATION REQUIREMENT
```

```
      A1 = STNREQ(I)
      CALL PATRB(A1,1)
C     ATTRIBUTE 2 -- TECHNICIAN (AFSC) REQUIREMENT
      A2 = AFSC(I)
      CALL PATRB(A2,2)
C     ATTRIBUTE 4 -- THREE FOR LRU REPAIR
      A4 = 3.0
      CALL PATRB(A4,4)
C     DETERMINE TYPE OF LRU REPAIR (RTS,RTOK, OR NRTS)
C     BY UNIF(0,1)
      UNIF = GGUBFS(DSEED)
      XLOW = FRRTS(I)
      XMID = FRRTS(I) + FRRTOK(I)
      XHIGH = XMID + FRNRTS(I)
      IF(UNIF .LT. XLOW) GO TO 120
      IF(UNIF .LT. XMID) GO TO 130
      IF(UNIF .LE. XHIGH) GO TO 140
C     IF RTS (REPAIR THIS STATION)
  120 A5 = 1.0
C     ATTRIBUTE 5 -- 1.0 FOR RTS
      CALL PATRB(A5,5)
C     SUM IS MEAN REPAIR TIME FOR ITH LRU
      SUM1 = SETUP(I) + TSSITA(I) + WARMUP(I) + 0.5*PERFT(I)
      SUM2 = (0.75)*REPAIR(I) + (0.25)*2.0*REPAIR(I)
     1       + PERFT(I) + TEARDN(I)
      SUM = SUM1 + SUM2
C     SIMULATE ERLANG WITH K = 2
      ERLANG = 0.0
      DO 125 K = 1,2
        UNIF = GGUBFS(DSEED)
        DRWEXP = -1.0*(SUM/2.0)*ALOG(UNIF)
        ERLANG = ERLANG + DRWEXP
  125 CONTINUE
C     ATTRIBUTE 6 -- TIME FOR FIRST PART OF REPAIR
      A6 = (SUM1/SUM)*ERLANG
      CALL PATRB(A6,6)
C     ATTRIBUTE 7 -- TIME FOR SECOND PART OF REPAIR
      A7 = (SUM2/SUM)*ERLANG
      CALL PATRB(A7,7)
C     DETERMINE IF SRU SPARE WILL BE AVAILABLE
      UNIF = GGUBFS(DSEED)
      IF(UNIF .LT. SRUAVL) A8 = 1.0
      IF(UNIF .GE. SRUAVL) A8 = 0.0
      CALL PATRB(A8,8)
```

```
      RETURN

C     IF RETEST OKAY (RTOK)
  130 A5 = 2.0
      CALL PATRB(A5,5)

C     SUM IS MEAN RTOK TIME FOR ITH LRU
      SUM1 = SETUP(I) + TSSITA(I) + WARMUP(I) + PERFT(I)
      SUM2 = 0.3*PERFT(I) + TEARDN(I)
      SUM = SUM1 + SUM2

C     SIMULATE ERLANG WITH K = 5
      ERLANG = 0.0
      DO 135 K = 1,5
        UNIF = GGUBFS(DSEED)
        DRWEXP = -1.0*(SUM/5.0)*ALOG(UNIF)
        ERLANG = ERLANG + DRWEXP
  135 CONTINUE

C     ATTRIBUTE 6 -- TIME FOR FIRST PART OF REPAIR
      A6 = (SUM1/SUM)*ERLANG
      CALL PATRB(A6,6)

C     ATTRIBUTE 7 -- TIME FOR SECOND PART OF REPAIR
      A7 = (SUM2/SUM)*ERLANG
      CALL PATRB(A7,7)

C     ATTRIBUTE 8 -- SRU SPARE NOT NEEDED FOR RTOK
      A8 = 2.0
      CALL PATRB(A8,8)

      RETURN

C     IF NOT REPAIRABLE THIS STATION (NRTS)
  140 A5 = 3.0
      CALL PATRB(A5,5)

C     SUM IS MEAN NRTS TIME FOR ITH LRU
      SUM1 = SETUP(I) + TSSITA(I) + WARMUP(I) + 0.5*PERFT(I)
      SUM2 = TEARDN(I)
      SUM = SUM1 + SUM2

C     SIMULATE ERLANG WITH K = 5
      ERLANG = 0.0
      DO 145 K = 1,5
        UNIF = GGUBFS(DSEED)
        DRWEXP = -1.0*(SUM/5.0)*ALOG(UNIF)
        ERLANG = ERLANG + DRWEXP
  145 CONTINUE

C     ATTRIBUTE 6 -- TIME FOR FIRST PART OF NRTS
      A6 = (SUM1/SUM)*ERLANG
      CALL PATRB(A6,6)

```

```
C     ATTRIBUTE 7 -- TIME FOR SECOND PART OF NRTS
      A7 = (SUM2/SUM)*ERLANG
      CALL PATRB(A7,7)

C     ATTRIBUTE 8 -- SRU SPARE NOT NEEDED FOR NRTS
      A8 = 2.0
      CALL PATRB(A8,8)

      RETURN
      END


      SUBROUTINE US(ISN,DTIM)

C     ISN IS DUMMY ARGUMENT; DTIM IS TIME BETWEEN ATE FAILURES

      COMMON/QVAR/NDE,NFTBU(500),NREL(500),NRELP(500),
     1   NREL2(500),NRUN,NRUNS,NTC(500),PARAM(100,4),TBEG,TNOW

      COMMON/UCOM3/DSEED,SRUAVL

      COMMON/UCOM4/ATEREL,ATEPRB(4),ATERP1(4),ATERP2(4)

C     ATEREL IS AGGREGATE STATION RELIABILITY
C     ATEPRB(I) IS CUM % RELIABLILTY FOR ITH STATION TYPE

      DOUBLE PRECISION DSEED
      DSEED = DSEED + (100000.*NRUN)

C     SIMULATE TIME BETWEEN ATE FAILURES
      UNIF = GGUBFS(DSEED)
      DTIM = -1.0*ATEREL*ALOG(UNIF)

C     DETERMINE WHICH STATION TYPE FAILED
C     1 = DIGITAL
C     2 = DIGITAL ANALOG VIDEO
C     3 = RADIO FREQ
C     4 = RADAR EW
      UNIF = GGUBFS(DSEED)
      I = 1
      IF(UNIF .LT. ATEPRB(1)) GO TO 220
  210 I = I + 1
      J = I - 1
      IF((UNIF.GE.ATEPRB(J)) .AND. (UNIF.LT.ATEPRB(I))) GO TO 220
      GO TO 210
  220 CONTINUE

C     ATTRIBUTE 1 -- TYPE OF STATION
      A1 = I
      CALL PATRB(A1,1)

C     ATTRIBUTE 2 -- TECHNICIAN REQUIREMENT (PMEL)
      A2 = 5.0
      CALL PATRB(A2,2)
```

```
C     ATTRIBUTE 4 -- 1.0 FOR ATE MAINTENANCE
      A4 = 1.0
      CALL PATRB(A4,4)

C     ATTRIBUTE 5 -- 1.0 FOR ATE; NO RTOKS OR NRTS ASSUMED
      A5 = 1.0
      CALL PATRB(A5,5)

      SUM1 = ATERP1(I)
      SUM2 = ATERP2(I)
C     SUM IS MEAN REPAIR TIME FOR ITH STATION
      SUM = SUM1 + SUM2
C     SIMULATE ERLANG WITH K = 2
      ERLANG = 0.0
      DO 225 K = 1,2
        UNIF = GGUBFS(DSEED)
        DRWEXP = -1.0*(SUM/2.0)*ALOG(UNIF)
        ERLANG = ERLANG + DRWEXP
  225 CONTINUE

C     ATTRIBUTE 6 -- TIME FOR FIRST PART OF REPAIR
      A6 = (SUM1/SUM)*ERLANG
      CALL PATRB(A6,6)

C     ATTRIBUTE 7 -- TIME FOR SECOND PART OF REPAIR
      A7 = (SUM2/SUM)*ERLANG
      CALL PATRB(A7,7)

C     DETERMINE SRU SPARE PART AVAILABILITY
      UNIF = GGUBFS(DSEED)
      IF(UNIF .LT. SRUAVL) A8 = 1.0
      IF(UNIF .GE. SRUAVL) A8 = 0.0
      CALL PATRB(A8,8)

      RETURN
      END


      SUBROUTINE UI

      COMMON/UCOM1/DEMFH,FLYPER,ACBASE,FHACMO,FACTDY(5),FACTTM(2)

      COMMON/UCOM2/CUMPRB(200),STNREQ(200),AFSC(200),FRRTS(200),
     1   FRRTOK(200),FRNRTS(200),SETUP(200),TSSITA(200),
     2   WARMUP(200),PERFT(200),REPAIR(200),TEARDN(200)

      COMMON/UCOM3/DSEED,SRUAVL

      COMMON/UCOM4/ATEREL,ATEPRB(4),ATERP1(4),ATERP2(4)

      REAL TSMTBF(4),ATEQTY(4),XMTBD(200),QPA(200)

      DOUBLE PRECISION DSEED
```

```

      DATA TSMTBF/256.,145.,167.,130./
      DATA ATEQTY/1.0,1.0,1.0,1.0/
      DATA ATERP1/4*0.5/
      DATA ATERP2/4*0.5/
      DATA ACBASE/16.0/
      DATA SRUAVL/0.9/
      DATA FHACMO/29.2/
      DATA FLYPER/4.0/
      DATA FACTDY/0.14,2*0.29,0.19,0.09/
      DATA FACTTM/2*0.50/
      DATA XMTBD/16458.,1199.,707.,1488.,2024.,1576.,952.,100000.
,
     1      1923.,11731.,151.,560.,590.,780.,2260.,5690.,330.,1010
.,
     2      620.,740.,1800.,460.,232.,272.,3803.,4218.,424.,1180.,
     3      1923.,2085.,446.,2175.,1931.,3653.,3538.,372.,2019.,38
2.,
     4      13600.,100000.,1530.,41.,14223.,8509.,1391.,2085.,8611
.,
     5      9667.,5856.,967.,5186.,12171.,5877.,6385.,3176.,5037.,
     6      2203.,36000.,3030.,198.,289.,478.,282.,418.,1391.,437.
,
     7      245.,1597.,1597.,221.,7838.,847.,1380.,3030.,3030.,
     8      159.,225.,208.,486.,191.,269.,225.,156.,109.,344.,185.
,
     9      157.,223.,136.,111.,265.,198.,136.,159.,58.,449.,449.,
     A      422.,422.,422.,216.,216.,175.,175.,50.,2906.,82.,
     B      706.,4480./
      DATA QPA/31.,3*2.,1.,3*2.,5.,1.,3.,8.,1.,3.,2.,1.,1.,3.,
     1      8*1.,2*1.,2.,1.,2*2.,1.,3.,2*1.,2.,4*1.,2.,1.,3.,
     2      2*1.,2.,5*1.,2.,5*1.,2.,7*1.,4*2.,10.,1.,2.,1.,3.,
     3      1.,2.,3.,3*3.,7*1.,2*3.,1.,2.,2*1.,3.,1.,2.,1.,
     4      1.,1.,2.,1.,2.,2.,1.,2.,2.,1.,1./
      DATA STNREQ/41*2.0,34*1.0,18*4.0,16*3.0/
      DATA AFSC/3.0,6*2.0,3*3.0,4.0,9*3.0,4.0,1.0,4*3.0,7*2.0,
     1      3*3.0,2.0,4.0,4*3.0,13*2.0,3*3.0,6*4.0,5*2.0,2*3.0,
     2      2.0,19*4.0,2*3.0,14*4.0,2*3.0/

      DATA SETUP/2*.23,2*.33,.28,.18,.33,.18,2*.28,2*.33,2*.28,
     1      .33,.18,.33,2*.18,.28,.33,.28,.33,.28,.18,.28,.33,
     2      3*.28,3*.33,.28,.23,.33,.18,.33,2*.18,2*.33,3*.23,
     3      .18,.23,.18,2*.23,2*.18,2*.18,.23,.28,.28,.18,.18,
     4      .33,.33,.28,.33,.28,.23,.23,.28,.18,.23,.33,.33,
     5      .23,5*.18,.23,5*.23,.28,.18,5*.28,3*.33,2*.28,
     6      7*.18,2*.23,.23,2*.18,.28,.18/
      DATA TSSITA/109*0.17/
      DATA WARMUP/109*0.0/
      DATA PERFT/.20,.59,1.44,.37,1.08,.29,1.31,.16,.75,.61,.05,
     1      .83,.55,.55,.75,.74,.95,.95,.89,1.25,.51,.65,1.63,
     2      .57,.63,.55,.64,.68,.55,1.15,.97,.31,.57,.55,.65,
     3      .77,.23,.13,.27,.27,.71,.32,.12,.25,.12,1.09,.72,
     4      .29,.25,.32,.23,.36,.36,.56,.72,.28,.68,.27,1.16,
     5      .24,.19,.28,.24,.09,.13,.85,1.35,.43,.12,1.71,1.04,
```

```
     6      .99,.89,1.16,1.16,.73,.81,.21,1.04,.21,.08,1.52,
     7      .38,1.29,1.11,1.16,1.59,.20,.59,.99,1.33,.53,.61,
     8      2.19,1.37,.31,.31,.60,.60,.60,.63,.63,.79,.79,
     9      .27,.17,.29,2.65,.41/
      DATA FRRTS/.8,.45,.45,.5,.65,.45,.5,.85,.50,.55,.55,.65,
     1      .75,.8,.65,.8,.5,.85,.5,.45,.45,.6,.85,.8,.75,.8,
     2      .65,.7,.55,.7,.55,.7,.7,.75,.85,.45,.6,.5,.8,.8,
     3      .85,.75,.75,.75,.75,.5,.6,.8,.8,.8,.8,.65,3*.60,
     4      .75,.85,.8,.75,.55,.5,.6,.55,.8,.7,.5,.6,.6,.8,
     5      .45,.45,.55,.60,.75,.75,.8,.8,.8,.7,.8,.7,.7,
     6      .65,.55,.55,.5,.55,.7,.7,.65,.6,.8,.8,.6,.65,.7,
     7      .80,.8,.8,.8,.8,.8,.7,.7,.7,2*.8,2*.85/
      DATA FRRTOK/.1,.45,.45,.40,.25,.45,.4,.05,.4,.35,.35,.25,
     1      .15,.1,.25,.1,.4,.05,.4,.45,.45,.3,.05,.1,.15,.1,
     2      .25,.2,.35,.2,.35,.2,.2,.15,.05,.45,.3,.4,.1,.1,.05,
     3      .15,.15,.15,.15,.4,.3,.1,.1,.1,.1,.25,3*.3,.15,.05,
     4      .1,.15,.35,.4,.3,.35,.1,.2,.4,.3,.3,.1,.45,.45,.35,
     5      .3,.15,.15,.1,.1,.1,.2,.1,.2,.2,.25,.35,.35,.4,.35,
     6      .2,.2,.25,.3,.1,.1,.3,.25,.2,.1,.1,.1,.1,.1,.1,.2,
     7      .2,.2,.1,.1,.05,.05/
      DATA FRNRTS/109*0.10/
      DATA TEARDN/2*.20,2*.27,.23,.17,.27,.17,.23,.23,.27,.27,
     1      .23,.23,.27,.20,.27,.17,.17,.23,.27,.23,.27,.23,.17,
     2      .27,.27,.23,.23,.23,.27,.27,.27,.23,.20,.27,.17,.27,
     3      .17,.17,.27,.27,.20,.20,.20,.17,.20,.17,.20,.20,.17,
     4      .17,2*.17,.2,.23,.23,.17,.17,.27,.27,.23,.27,.23,.2,
     5      .2,.23,.17,.2,.27,.27,.2,.17,.17,.17,.3,.3,.2,5*.20,
     6      .23,.23,.23,4*.23,3*.27,.23,.23,7*.17,2*.20,.20,
     7      .17,.17,.23,.17/
      DATA REPAIR/2*.37,2*.50,.43,.30,.50,.30,.43,2*.50,3*.43,
     1      .50,.37,.50,2*.30,.42,.50,.43,.50,.43,.23,.43,.50,
     2      3*.43,3*.50,.43,.37,.50,.30,.50,2*.30,.43,.50,3*.37,
     3      .30,.37,.30,.37,.37,.30,.30,2*.30,.37,.43,.43,.30,
     4      .30,2*.50,.43,.50,.43,2*.37,.43,.30,.37,2*.50,.37,
     5      5*.30,6*.37,.43,.30,5*.43,3*.50,2*.43,7*.30,3*.37,
     6      2*.30,.43,.30/
      NLRU = 109
      DSEED = 123457.DO

      SUM = 0.0
      DO 300 I = 1,NLRU
        SUM = SUM + (QPA(I)/XMTBD(I))
  300 CONTINUE
      DEMFH = 1.0/SUM

      CUMPRB(1) = QPA(1)*DEMFH/XMTBD(1)
      DO 310 I = 2,NLRU
        J = I - 1
        PROB = QPA(I)*DEMFH/XMTBD(I)
        CUMPRB(I) = CUMPRB(J) + PROB
  310 CONTINUE

      NTYPE = 4
      FAILRT = 0.0
```

```

      DO 320 I=1,NTYPE
        FAILRT = FAILRT + (ATEQTY(I)/TSMTBF(I))
  320 CONTINUE
      ATEREL = 1.0/FAILRT

      ATEPRB(1) = ATEQTY(1)*ATEREL/TSMTBF(1)
      DO 330 I = 2,NTYPE
        J = I - 1
        PROB = ATEQTY(I)*ATEREL/TSMTBF(I)
        ATEPRB(I) = ATEPRB(J) + PROB
  330 CONTINUE
      RETURN
      END
*EOR
GEN,ROARK,MODEL5,10,5,1983,8,,,6240.0,5,E,0,8*
SOU,1,0,1*                                START DAILY ARRIVAL PROCESS
ACT,1,1,CO,120.0*                         RE-START EVERY FIVE DAYS
ACT,1,2,CO,0.0*                           MONDAY
ACT,1,3,CO,24.0*                          TUESDAY
ACT,1,4,CO,48.0*                          WEDNESDAY
ACT,1,5,CO,72.0*                          THURSDAY
ACT,1,6,CO,96.0*                          FRIDAY
REG,2,1,1*                                MONDAY
VAS,2,1,CO,1.0*
REG,3,1,1*                                TUESDAY
VAS,3,1,CO,2.0*
REG,4,1,1*                                WEDNESDAY
VAS,4,1,CO,3.0*
REG,5,1,1*                                THURSDAY
VAS,5,1,CO,4.0*
REG,6,1,1*                                FRIDAY
VAS,6,1,CO,5.0*
ACT,2,7*
ACT,3,7*
ACT,4,7*
ACT,5,7*
ACT,6,7*
REG,7,1,1*                                MERGE DAILY ARRIVAL STARTS
ACT,7,8,CO,11.0*                          ELEVEN AM
REG,8,1,1,D,M*
ACT,8,9,UF,1,1*                           START AM POISSON PROCESS
REG,9,1,1,D,M*
ACT,9,9,UF,1,2*                           CONTINUE AM POISSON PROCESS
ACT,9,14*                                 ROUTE TO OMS QUEUE
REG,10,1,1*                               DEAD END TO STOP PROCESS
MOD,20,9,10*                              TO SHUT OFF PROCESS
MOD,19,10,9*                              TO RE-START PROCESS
ACT,7,11,CO,25.0*                         ONE AM
REG,11,1,1,D,M*
ACT,11,12,UF,2,3*                         START PM POISSON PROCESS
REG,12,1,1,D,M*
ACT,12,12,UF,2,4*                         CONTINUE PM POISSON PROCESS
ACT,12,14*                                ROUTE TO OMS QUEUE
```

```
  4330=REG,13,1,1*                       DEAD END TO STOP PROCESS
  4340=MOD,16,12,13*                     TO SHUT OFF PROCESS
  4350=MOD,15,13,12*                     TO RE-START PROCESS
  4360=QUE,14/FLTLINE,(10)15*            QUEUE FOR OMS
  4370=RES,1/OMS,38,15*                  OMS TECHNICIANS
  4380=ALL,15,POR,1,2,14/16*             ALLOCATE TWO OMS TECHNICIANS
  4390=REG,16,1,1*                       START OMS (FLIGHT LINE) MAINTENA
NCE
  4400=ACT,16,17,CO,1.0,5/DEBRIEF*       DEBRIEF
  4410=REG,17,1,1*
  4420=ACT,17,18,ER,1,6/REMOVAL*         REMOVE LRU
  4430=PAR,1,0.5,,,4*                    MEAN REMOVAL TIME IS TWO HOURS
  4440=REG,18,1,1*
  4450=ACT,18,19,CO,0.5,7/PUTAWAY*       TAKE LRU TO SHOP
  4460=FRE,19,D,1,2,15*                  FREE TWO OMS TECHNICIANS
  4470=ACT,19,23,CO,0.5*                 LOGIN AND SCHEDULE SHOP MAINTENA
NCE
  4480=SOU,20,0,1,D,M*                   START ATE FAILURES
  4490=ACT,20,20,US,1,8*                 TIME BETWEEN ATE FAILURES
  4500=ACT,20,21*
  4510=REG,21,1,1*                       FAILURES FROM EIGHT AM TO MIDNIG
HT
  4520=REG,22,1,1*                       NO FAILURES FROM MIDNIGHT TO EIG
HT
  4530=MOD,21,21,22*                     TO SHUT OFF FAILURES
  4540=MOD,17,22,21*                     TO OPEN UP FAILURES
  4550=ACT,21,23,CO,0.5*                 LOGIN AND SCHEDULE AT SHOP
  4560=REG,23,1,1,A*                     SELECT STATION TYPE
  4570=ACT,23,24,(9)A1.EQ.1*             ROUTE TO CORRECT QUEUE
  4580=ACT,23,25,(9)A1.EQ.2*
  4590=ACT,23,26,(9)A1.EQ.3*
  4600=ACT,23,27,(9)A1.EQ.4*
  4610=QUE,24/DIGITAL,(6)S/4,(10)28*     QUEUE FOR AVAILABLE STATION
  4620=RES,2/DIGITAL.1,66,28*            ONE DIGITAL STATION
  4630=ALL,28,POR,2,1,24/32*             ALLOCATE ONE STATION
  4640=QUE,25/DIGAV,(6)S/4,(10)29*
  4650=RES,3/DIGAV,1,67,29*              ONE DIGITAL ANALOG VIDEO STATION
  4660=ALL,29,POR,3,1,25/32*
  4670=QUE,26/RF,(6)S/4,(10)30*
  4680=RES,4/RF,1,68,30*                 ONE RF STATION
  4690=ALL,30,POR,4,1,26/32*
  4700=QUE,27/RADAREW,(6)S/4,(10)31*
  4710=RES,5/RADAREW,1,69,31*            ONE RADAR EW STATION
  4720=ALL,31,POR,5,1,27/32*
  4730=REG,32,1,1*
  4740=ACT,32,33,CO,0.0,9*               DO NOTHING
  4750=REG,33,1,1,A*                     SELECT TECHNICIAN TYPE
  4760=ACT,33,34,(9)A2.EQ.1*             ROUTE TO CORRECT QUEUE
  4770=ACT,33,35,(9)A2.EQ.2*
  4780=ACT,33,36,(9)A2.EQ.3*
  4790=ACT,33,37,(9)A2.EQ.4*
  4800=ACT,33,38,(9)A2.EQ.5*
  4810=QUE,34/COMMNAV,(10)39*            QUEUE FOR AVAILABLE TECHNICIAN
  4820=RES,6/COMMNAV,7,77,39*            SEVEN COMM NAV TECHNICIANS
```

```
  4830=ALL,39,POR,6,1,34/44*              ALLOCATE ONE TECHNICIAN
  4840=QUE,35/AFCINS,(10)40*
  4850=RES,7/AFCINS,4,78,40*              FOUR AUTO FLT CNTLS INST TECHNIC
IANS
  4860=ALL,40,POR,7,1,35/44*
  4870=QUE,36/OFFAV,(10)41*
  4880=RES,8/OFFAV,16,79,41*              SIXTEEN OFF AVIONICS TECHNICIANS
  4890=ALL,41,POR,8,1,36/44*
  4900=QUE,37/DEFAV,(10)42*
  4910=RES,9/DEFAV,10,80,42*              TEN DEFENSIVE AVIONICS TECHNICIA
NS
  4920=ALL,42,POR,9,1,37/44*
  4930=QUE,38/PMEL,(10)43*
  4940=RES,10/PMEL,5,81,43*               FIVE PMEL TECHNICIANS
  4950=ALL,43,POR,10,1,38/44*
  4960=REG,44,1,1*
  4970=ACT,44,45,AT,6,10*                 SETUP AND FAULT ISOLATION
  4980=REG,45,1,1,A*
  4990=ACT,45,47,(9)A8.EQ.2*              SRU SPARE NOT NEEDED
  5000=ACT,45,46,(9)A8.EQ.1*              GET SRU SPARE FOR LRU REPAIR
  5010=REG,46,1,1,P*
  5020=ACT,46,47,CO,1.0,(8)0.75*          GET SRU SPARE FROM BASE SUPPLY
  5030=ACT,46,47,CO,0.25,(8)0.25*         GET SRU FROM FORWARD SUPPLY POIN
T
  5040=REG,47,1,1*
  5050=ACT,47,48*
  5060=ACT,45,149,CO,1.0,(9)A8.EQ.0*      NO SPARE AVAILABLE ON BASE
  5070=REG,149,1,1,A*
  5080=ACT,149,150,EX,2,11,(9)A4.EQ.3*    TEAR DOWN LRU
  5090=PAR,2,0.25*                        FIFTEEN MINUTE TEAR DOWN
  5100=REG,150,1,1*
  5110=VAS,150,6,EX,2*                    CHANGE AT6 TO SETUP
  5120=ACT,150,48*                        LRU WILL GO AWAP
  5130=ACT,149,151,(9)A4.EQ.1*            STATION GOES NMCS
  5140=FRE,151,D,10,1,43,81*              FREE TECHNICIAN BUT NOT STATION
  5150=ACT,151,152*
  5160=REG,152,1,1*
  5170=VAS,152,6,EX,2,8,CO,1.0*           CHANGE AT6 TO SETUP
  5180=ACT,152,33,CO,192.0*               EIGHT DAY ORDER AND SHIP TIME
  5190=REG,48,1,1,A*
  5200=ACT,48,49,(9)A2.EQ.1*
  5210=ACT,48,50,(9)A2.EQ.2*
  5220=ACT,48,51,(9)A2.EQ.3*
  5230=ACT,48,52,(9)A2.EQ.4*
  5240=ACT,48,53,(9)A2.EQ.5*
  5250=FRE,49,D,6,1,77,39*                FREE COMM NAV TECHNICIAN
  5260=ACT,49,54*
  5270=FRE,50,D,7,1,78,40*                FREE AFCINS TECHNICIAN
  5280=ACT,50,54*
  5290=FRE,51,D,8,1,79,41*                FREE OFF AV TECHNICIAN
  5300=ACT,51,54*
  5310=FRE,52,D,9,1,80,42*                FREE DEF AV TECHNICIAN
  5320=ACT,52,54*
  5330=FRE,53,D,10,1,81,43*               FREE PMEL TECHNICIAN
```

```
5340=ACT,53,54*
5350=REG,54,1,1,A*
5360=ACT,54,55,(9)A1.EQ.1*
5370=FRE,55,D,2,1,66,28*                    FREE DIGITAL STATION
5380=ACT,55,59*
5390=ACT,54,56,(9)A1.EQ.2*
5400=FRE,56,D,3,1,67,29*                    FREE DIGITAL ANALOG VIDEO STATIO
N
5410=ACT,56,59*
5420=ACT,54,57,(9)A1.EQ.3*
5430=FRE,57,D,4,1,68,30*                    FREE RF STATION
5440=ACT,57,59*
5450=ACT,54,58,(9)A1.EQ.4*
5460=FRE,58,D,5,1,69,31*                    FREE RADAR EW STATION
5470=ACT,58,59*
5480=REG,59,1,1,A*
5490=ACT,59,61,(9)A8.EQ.0*                  AWAP LRU
5500=REG,61,1,1*
5510=VAS,61,8,CO,1.0*                       ORDER SRU SPARE
5520=ACT,61,23,CO,192.0*                    EIGHT DAY ORDER AND SHIP TIME
5530=ACT,59,60,(9)A8.NE.0*
5540=REG,60,1,1,A*                          ON TO NEXT REPAIR PHASE
5550=ACT,60,62,(9)A1.EQ.1*                  ROUTE TO CORRECT QUEUES
5560=ACT,60,63,(9)A1.EQ.2*
5570=ACT,60,64,(9)A1.EQ.3*
5580=ACT,60,65,(9)A1.EQ.4*
5590=QUE,62/DIGITAL,(6)L,(10)66*            WAIT FOR AVAILABLE STATION
5600=QUE,63/DIGAV,(6)L,(10)67*
5610=QUE,64/RF,(6)L,(10)68*
5620=QUE,65/REW,(6)L,(10)69*
5630=ALL,66,POR,2,1,62/70*                  ALLOCATE AVAILABLE STATION
5640=ALL,67,POR,3,1,63/70*
5650=ALL,68,POR,4,1,64/70*
5660=ALL,69,POR,5,1,65/70*
5670=REG,70,1,1*
5680=ACT,70,71,CO,0.0,12*                   DO NOTHING
5690=REG,71,1,1,A*
5700=ACT,71,72,(9)A2.EQ.1*                  ROUTE TO CORRECT QUEUES
5710=ACT,71,73,(9)A2.EQ.2*
5720=ACT,71,74,(9)A2.EQ.3*
5730=ACT,71,75,(9)A2.EQ.4*
5740=ACT,71,76,(9)A2.EQ.5*
5750=QUE,72/COMMNAV,(6)L,(10)77*            WAIT FOR AVAILABLE TECHNICIAN
5760=QUE,73/AFCINS,(6)L,(10)78*
5770=QUE,74/OFFAV,(6)L,(10)79*
5780=QUE,75/DEFAV,(6)L,(10)80*
5790=QUE,76/PMEL,(6)L,(10)81*
5800=ALL,77,POR,6,1,72/82*                  ALLOCATE AVAILABLE TECHNICIAN
5810=ALL,78,POR,7,1,73/82*
5820=ALL,79,POR,8,1,74/82*
5830=ALL,80,POR,9,1,75/82*
5840=ALL,81,POR,10,1,76/82*
5850=REG,82,1,1*
5860=ACT,82,83,AT,7,13*                     REPAIR AND TEAR DOWN
```

```
5870=REG,83,1,1,A*
5880=ACT,83,84,(9)A1.EQ.1*                    ROUTE TO CORRECT FREE NODES
5890=ACT,83,85,(9)A1.EQ.2*
5900=ACT,83,86,(9)A1.EQ.3*
5910=ACT,83,87,(9)A1.EQ.4*
5920=FRE,84,D,2,1,28,66*                      FREE STATIONS
5930=ACT,84,88*
5940=FRE,85,D,3,1,29,67*
5950=ACT,85,88*
5960=FRE,86,D,4,1,30,68*
5970=ACT,86,88*
5980=FRE,87,D,5,1,31,69*
5990=ACT,87,88*
6000=REG,88,1,1,A*                            ROUTE TO CORRECT FREE NODES
6010=ACT,88,89,(9)A2.EQ.1*
6020=ACT,88,90,(9)A2.EQ.2*
6030=ACT,88,91,(9)A2.EQ.3*
6040=ACT,88,92,(9)A2.EQ.4*
6050=ACT,88,93,(9)A2.EQ.5*
6060=FRE,89,D,6,1,39,77*                      FREE TECHNICIANS
6070=ACT,89,94*
6080=FRE,90,D,7,1,40,78*
6090=ACT,90,94*
6100=FRE,91,D,8,1,41,79*
6110=ACT,91,94*
6120=FRE,92,D,9,1,42,80*
6130=ACT,92,94*
6140=FRE,93,D,10,1,43,81*
6150=ACT,93,94*
6160=REG,94,1,1*                              REPAIR COMPLETED
6170=ACT,94,95,CO,0.5*                        RETURN LRU TO BASE SUPPLY & LOGO
UT
6180=REG,95,1,1,F*                            CONDITION TAKE FIRST
6190=ACT,95,96,(8)1,A5.EQ.3*                  REMOVE NRTS LRUS FROM STATS
6200=ACT,95,97,(8)2,A4.EQ.3*                  ALL OTHER LRUS (RTS,RTOK)
6210=ACT,95,98,(8)3,A4.EQ.1*                  ATE MAINTENANCE
6220=REG,96,1,1*
6230=REG,97,1,1,A*                            COLLECT STATS ON LRUS BY STATION
6240=ACT,97,99,(9)A1.EQ.1*
6250=STA,99/DIGITAL,1,1,D,I*
6260=ACT,97,100,(9)A1.EQ.2*
6270=STA,100/DIGAV,1,1,D,I*
6280=ACT,97,101,(9)A1.EQ.3*
6290=STA,101/RF,1,1,D,I*
6300=ACT,97,102,(9)A1.EQ.4*
6310=STA,102/REW,1,1,D,I*
6320=REG,98,1,1,A*                            COLLECT STATS ON ATE MAINTENANCE
6330=ACT,98,103,(9)A1.EQ.1*
6340=STA,103/DIGITAL,1,1,D,I*
6350=ACT,98,104,(9)A1.EQ.2*
6360=STA,104/DIGAV,1,1,D,I*
6370=ACT,98,105,(9)A1.EQ.3*
6380=STA,105/RF,1,1,D,I*
6390=ACT,98,106,(9)A1.EQ.4*
```

```
   6400=STA,106/REW,1,1,D,I*
   6410=SOU,110,0,1*                    BEGIN CLOCK AT END OF SECOND SHI
FT
   6420=ACT,110,111*                    WHICH IS AT MIDNIGHT
   6430=ALT,111,D,1,-38,15*             SHUT DOWN ALL RESOURCES AT MIDNI
GHT
   6440=ACT,111,112*
   6450=ALT,112,D,2,-1,66,28*
   6460=ACT,112,113*
   6470=ALT,113,D,3,-1,67,29*
   6480=ACT,113,114*
   6490=ALT,114,D,4,-1,68,30*
   6500=ACT,114,115*
   6510=ALT,115,D,5,-1,69,31*
   6520=ACT,115,116*
   6530=ALT,116,D,6,-7,77,39*
   6540=ACT,116,117*
   6550=ALT,117,D,7,-4,78,40*
   6560=ACT,117,118*
   6570=ALT,118,D,8,-16,79,41*
   6580=ACT,118,119*
   6590=ALT,119,D,9,-10,80,42*
   6600=ACT,119,120*
   6610=ALT,120,D,10,-5,81,43*
   6620=ACT,120,121,CO,0.0,21*          MIDNIGHT -- SEE NODES 21,22
   6630=REG,121,1,1*
   6640=ACT,121,122,CO,1.0,15*          ONE AM -- SEE NODES 12,13
   6650=REG,122,1,1*
   6660=ACT,122,123,CO,4.0,16*          FIVE AM -- SEE NODES 12,13
   6670=REG,123,1,1*
   6680=ACT,123,124,CO,3.0,17*          EIGHT AM -- SEE NODES 21,22
   6690=ALT,124,D,1,38,15*              START FIRST SHIFT AT EIGHT AM
   6700=ACT,124,125*
   6710=ALT,125,D,6,7,77,39*
   6720=ACT,125,126*
   6730=ALT,126,D,7,4,78,40*
   6740=ACT,126,127*
   6750=ALT,127,D,8,16,79,41*
   6760=ACT,127,128*
   6770=ALT,128,D,9,10,80,42*
   6780=ACT,128,129*
   6790=ALT,129,D,10,5,81,43*
   6800=ACT,129,130,CO,0.25,18*         FIFTEEN MINUTE DELAY FOR STATION
   6810=ALT,130,D,2,1,66,28*            DAILY CONFIDENCE CHECK
   6820=ACT,130,131*
   6830=ALT,131,D,3,1,67,29*
   6840=ACT,131,132*
   6850=ALT,132,D,4,1,68,30*
   6860=ACT,132,133*
   6870=ALT,133,D,5,1,69,31*
   6880=ACT,133,134,CO,2.75,19*         ELEVEN AM -- SEE NODES 9,10
   6890=REG,134,1,1*
   6900=ACT,134,135,CO,4.0,20*          THREE PM -- SEE NODES 9,10
   6910=REG,135,1,1*
```

```
6920=ACT,135,110,CO,9.0*          AND BACK TO MIDNIGHT
6930=FIN*                         THAT'S ALL, FOLKS!
6940=*EOR
```

Appendix B: Design of Simulation Experiment

Purpose of the Experiment

The simulation experiment has just one response (dependent) variable, which is base repair cycle time. The factor to be varied is test station quantities; this factor has three levels (quantities of 1, 2, or 3 test stations). The purpose of the experiment is to determine if varying test station quantities will cause a statistically significant difference in repair cycle time. This experiment is performed a total of 12 times, once for each combination of the three aircraft quantities (16, 26, or 32 PAA) and the four station types (Digital, Digital Analog Video, RF, or R/EW). The aircraft quantities and station types were not regarded as factors since a separate management decision (how many stations to buy) must be made for each of the 12 combinations.

Variance Reduction

To make the simulation experiment as powerful as possible (for a given sample size), it is desirable to remove as much variation (caused by the simulation model) as possible. This can be accomplished by the variance reduction technique of common random numbers. Through use of a FORTRAN SAVE statement, it was possible to ensure that each level (treatment) faced the same random numbers which determined LRU interarrival times, LRU identification, LRU type of maintenance action (RTS, RTOK, or NRTS), and LRU maintenance task times. The FORTRAN user function UF, as modified to ensure common random numbers, is attached at the end of this appendix. Since the test station quantities were varied, it was not possible to ensure common random numbers for test station failure interarrival times or repair times. However, model results indicate that at least 95% of the random numbers are common.

The method of common random numbers would be useless unless the simulation experiment can isolate variation due to different random number streams from variation due to random error. This isolation can be accomplished by blocking, where each block corresponds to a random number stream. The linear model for such an experiment would then be:

$$Y_{ij} = \mu + \beta_i + \tau_j + \varepsilon_{ij}$$

where Y_{ij} = dependent variable resulting from ith block, jth level

μ = overall mean

β_i = ith block effect

τ_j = jth level effect

ε_{ij} = random error term for ith block, jth level

In a blocking experiment, the blocking effect is assumed to be significant. In addition, it is also assumed that there is no block-level interaction of effect.

ANOVA Layout

In this experimental design, there are ten replications performed, which is the maximum permitted in a single Q-GERT run. Each replication has a different stream of random numbers and thus corresponds to a block in the simulation experiment. The level or treatment corresponds, to the test station quantities considered. The layout for such an experiment would be:

	FACTOR		
BLOCK	QTY=1	QTY=2	QTY=3
1	Y	Y	Y
2	Y	Y	Y
3	Y	Y	Y
4	Y	Y	Y
5	Y	Y	Y
6	Y	Y	Y
7	Y	Y	Y
8	Y	Y	Y
9	Y	Y	Y
10	Y	Y	Y

The degrees of freedom for such an experiment would be as follows:

Treatment or Level	-- 3-1 = 2
Block	-- 10-1 = 9
Error	-- (3-1) x (10-1) = 18
Total	-- 30-1 = 29

The null nypothesis to be tested is that varying test station quantities does not cause a statistically significant change in base repair cycle time. In statistical terms, this is represented by:

$$H_0: \tau_1 = \tau_2 = \tau_3 = 0$$

ANOVA Assumptions

As part of the standard (normal distribution) ANOVA, it is necessary to assume that the error terms, ε_{ij} , have zero mean, have constant variance, are independent, and follow a normal probability distribution. When this experiment was performed, it soon became quite obvious that the variance for different levels was not constant. It was therefore necessary to resort to Friedman's test, which is the nonparametric equivalent of the one-way ANOVA with blocking. The only disadvantage to a nonparametric test is that it might not be as powerful as an ANOVA. As will be seen, this is not a concern for this particular situation.

Experimental Results

The results for the 12 simulation experiments are shown in Table XVIII. Significance levels for each of the 12 combinations were obtained from Friedman's test.

Table XVIII. Significance Levels

	Digital	Digital An Video	RF	R/EW
16 PAA	.045	.000	.000	.000
26 PAA	.002	.000	.000	.000
32 PAA	.000	.000	.000	.000

The conclusion that can be drawn is that varying test station quantities causes a statistically significant difference in base repair cycle time for each of the 12 combinations. It is also possible to perform 3 pairwise comparisons for each of the 12 experiments. For $\alpha = 0.05$, 32 out of 36 pairwise comparisons were found to be statistically significant. For the remainder of this research effort, therefore, it was assumed that varying test station quantities (over the range of one to three stations) always caused a statistically significant difference in base repair cycle time.

For comparison purposes, a one-way ANOVA with blocking was performed for each station type for the 16 PAA case. In each case, the null hypothesis was rejected for $\alpha = 0.5$.

Although the variance is not constant, the ANOVA is often quite robust when the number of replications per cell is constant. This gives further credibility to the results from Friedman's test.

```
..LIST,10001500
LMR,CM177000,T600,IO200.     T830662,ROARK,4533.
ATTACH,IMSL,IMSL,ID=LIBRARY,SN=ASD.
LIBRARY,IMSL.
ATTACH,PROCFIL,QGERTPROC,ID=AFIT.
FTN5,ANSI=0.
BEGIN,QGERT,PROCFIL,M=LGO,MODE=X.
*EOR

      FUNCTION UF(IFN)

      COMMON/QVAR/NDE,NFTBU(500),NREL(500),NRELP(500),
     1   NREL2(500),NRUN,NRUNS,NTC(500),PARAM(100,4),TBEG,TNOW

      COMMON/UCOM1/DEMFH,FLYPER,ACBASE,FHACMO,
     1   FACTDY(5),FACTTM(2)

      COMMON/UCOM2/CUMPRB(200),STNREQ(200),AFSC(200),FRRTS(200),
     1   FRRTOK(200),FRNRTS(200),SETUP(200),TSSITA(200),
     2   WARMUP(200),PERFT(200),REPAIR(200),TEARDN(200)

      COMMON/UCOM3/DSEED,SRUAVL

      DOUBLE PRECISION DSEED,XSEED
      SAVE XSEED
      DSEED = DSEED + (100000.*NRUN)
      IF(TNOW .LE. 11.001) XSEED = 754321.D0 + 100000.*NRUN

      AT1 = GATRB(1)
      IAT1 = AT1

      DEMSH = (DEMFH*FLYPER*4.333)/(FACTDY(IAT1)*
     1         FACTTM(IFN)*ACBASE*FHACMO)

      UNIF = GGUBFS(XSEED)
      UF = -1.0*DEMSH*ALOG(UNIF)
      IF(UF .GT. 16.0) UF = 16.001

      UNIF = GGUBFS(XSEED)
      I = 1
      IF(UNIF .LT. CUMPRB(I)) GO TO 110
  100 I = I + 1
      J = I - 1
      IF((CUMPRB(J).LE.UNIF) .AND. (UNIF.LT.CUMPRB(I))) GO TO 110
      GO TO 100
  110 CONTINUE

      A1 = STNREQ(I)
      CALL PATRB(A1,1)

      A2 = AFSC(I)
      CALL PATRB(A2,2)

      A4 = 3.0
```

```
      CALL PATRB(A4,4)

      UNIF = GGUBFS(XSEED)
      XLOW = FRRTS(I)
      XMID = FRRTS(I) + FRRTOK(I)
      XHIGH = XMID + FRNRTS(I)
      IF(UNIF .LT. XLOW) GO TO 120
      IF(UNIF .LT. XMID) GO TO 130
      IF(UNIF .LE. XHIGH) GO TO 140

  120 A5 = 1.0
      CALL PATRB(A5,5)

      SUM1 = SETUP(I) + TSSITA(I) + WARMUP(I) + 0.5*PERFT(I)
      SUM2 = (0.75)*REPAIR(I) + (0.25)*2.0*REPAIR(I)
     1       + PERFT(I) + TEARDN(I)
      SUM = SUM1 + SUM2

      ERLANG = 0.0
      DO 125 K = 1,2
        UNIF = GGUBFS(XSEED)
        DRWEXP = -1.0*(SUM/2.0)*ALOG(UNIF)
        ERLANG = ERLANG + DRWEXP
  125 CONTINUE

      A6 = (SUM1/SUM)*ERLANG
      CALL PATRB(A6,6)

      A7 = (SUM2/SUM)*ERLANG
      CALL PATRB(A7,7)

      UNIF = GGUBFS(DSEED)
      IF(UNIF .LT. SRUAVL) A8 = 1.0
      IF(UNIF .GE. SRUAVL) A8 = 0.0
      CALL PATRB(A8,8)

      RETURN

  130 A5 = 2.0
      CALL PATRB(A5,5)

      SUM1 = SETUP(I) + TSSITA(I) + WARMUP(I) + PERFT(I)
      SUM2 = 0.3*PERFT(I) + TEARDN(I)
      SUM = SUM1 + SUM2

      ERLANG = 0.0
      DO 135 K = 1,5
        UNIF = GGUBFS(XSEED)
        DRWEXP = -1.0*(SUM/5.0)*ALOG(UNIF)
        ERLANG = ERLANG + DRWEXP
  135 CONTINUE

      A6 = (SUM1/SUM)*ERLANG
      CALL PATRB(A6,6)
```

```
      A7 = (SUM2/SUM)*ERLANG
      CALL PATRB(A7,7)

      A8 = 2.0
      CALL PATRB(A8,8)

      RETURN

  140 A5 = 3.0
      CALL PATRB(A5,5)

      SUM1 = SETUP(I) + TSSITA(I) + WARMUP(I) + 0.5*PERFT(I)
      SUM2 = TEARDN(I)
      SUM = SUM1 + SUM2

      ERLANG = 0.0
      DO 145 K = 1,5
        UNIF = GGUBFS(XSEED)
        DRWEXP = -1.0*(SUM/5.0)*ALOG(UNIF)
        ERLANG = ERLANG + DRWEXP
  145 CONTINUE

      A6 = (SUM1/SUM)*ERLANG
      CALL PATRB(A6,6)

      A7 = (SUM2/SUM)*ERLANG
      CALL PATRB(A7,7)

      A8 = 2.0
      CALL PATRB(A8,8)

      RETURN
      END
```

Appendix C: Analytical Queueing Model Program Listing

..LIST,ALL

```
LMR,CM125000,T100,I050.  T830662,ROARK,4533.
ATTACH,IMSL,IMSL5,ID=LIBRARY,SN=ASD.
LIBRARY,IMSL.
FTN5.
LGO.
*EOR
      PROGRAM QUEUE4

      COMMON/UCOM/XMTBD(109),QPA(109),STNREQ(109),SETUP(109),
     1   TSSITA(109),WARMUP(109),PERFT(109),FRRTS(109),
     2   FRRTOK(109),FRNRTS(109),TEARDN(109),REPAIR(109),
     3   ATEREL(4),ATEQTY(4),ATEREP(4)

C     COMMON BLOCK UCOM IS USED TO TRANSFER DATA VALUES
C     FROM BLOCK DATA SUBROUTINE

      DIMENSION BMHAVG(4),DEMFH(4),DEMSH(4)

C     NUMBER OF AIRCRAFT FOR THIS BASE
      DATA ACBASE/16.0/

C     FLIGHT HOURS PER AIRCRAFT PER MONTH
      DATA FHACMO/29.2/

C     NUMBER OF MAINTENANCE HOURS PER WORKDAY -- TWO SHIFTS
      DATA HRSDAY/16.0/

C     NUMBER OF DAYS PER WEEK -- NO MAINTENANCE ON WEEKENDS
      DATA DAYWK/5.0/

C     4.333 WEEKS PER MONTH
      DATA WEEKMO/4.333/

C     HOURS PER MAINTENANCE DEBRIEFING
      DATA DBRIEF/1.0/

C     HOURS TO REMOVE LRU FROM AIRCRAFT
      DATA REMOVE/2.0/

C     HOURS TO TAKE LRU TO AMS
      DATA PUTAWY/0.5/

C     19 PAIRS OF OMS TECHNICIANS
      DATA NUMOMS/19/

      DATA BMHAVG/4*0.0/
      DATA RTSRT/0.0/
      DATA SRUAVL/0.9/

C     TRAVEL TIME TO OBTAIN SRU SPARE
      TRAVEL = (0.25)*0.25 + (0.75)*1.0
```

```
C     EIGHT DAY ORDER AND SHIP TIME
      HRSOST = 8.0*16.0

C     109 LRUS
      NLRU = 109

C     COMPUTE TOTAL LRU ARRIVAL RATE BY STATION TYPE

      DO 110 J = 1,4

        REALJ = J
        SUM = 0.0
        DO 100 I = 1,NLRU
          IF(STNREQ(I) .EQ. REALJ) THEN
            SUM = SUM + QPA(I)/XMTBD(I)
          END IF
  100   CONTINUE

C     DEMFH IS AGGREGATE MTBD FOR JTH STATION TYPE LRUS
        DEMFH(J) = 1.0/SUM

C     CONVERT FLYING HOURS TO MAINTENANCE SHIFT HOURS
        DEMSH(J) = DEMFH(J)*(HRSDAY*DAYWK*WEEKMO)/
     1                   (ACBASE*FHACMO)
  110 CONTINUE

      SUM = 0.0

C     COMPUTE TOTAL LRU ARRIVAL RATE -- ALL STATIONS COMBINED
      DO 120 J = 1,4
        SUM = SUM + (1.0/DEMSH(J))
  120 CONTINUE

C     COMBINED AVIONICS RELIABILITY
      XMTBF = 1.0/SUM

C     O-LEVEL REMOVAL TIME (MEAN)
      XMTTR = DBRIEF + REMOVE + PUTAWY

C     SUBROUTINE FOR M/M/S QUEUE
      CALL MMS(XMTBF,XMTTR,NUMOMS,RHOOMS,WOMS)

C     TOTAL TIME FOR OMS QUEUE; CONVERT 16 HOUR DAY TO REAL TIME
      WOMS = (24.0/HRSDAY)*WOMS
      PRINT *,' WOMS = ',WOMS

C     FOR ALL LRUS -- COMPUTE WEIGHTED AVEREAGES
      DO 130 I = 1,NLRU

C       % REPAIR THIS STATION
        RTSRT = RTSRT + (QPA(I)*XMTBF/XMTBD(I))*FRRTS(I)

C       MEAN REPAIR TIME FOR RTS
```

```
            BMH1 = SETUP(I) + TSSITA(I) + WARMUP(I)
     1          + 0.5*PERFT(I) + TRAVEL +0.75*REPAIR(I)
     2          + 0.25*2.0*REPAIR(I) + PERFT(I) + TEARDN(I)

C           MEAN TASK TIME FOR RTOK
            BMH2 = SETUP(I) + TSSITA(I) + WARMUP(I)
     1          + PERFT(I) + 0.3*PERFT(I) + TEARDN(I)

C           MEAN TASK TIME FOR NRTS
            BMH3 = SETUP(I) + TSSITA(I) + WARMUP(I)
     1          + 0.5*PERFT(I) + TEARDN(I)

C           MEAN TASK TIME OVERALL
            BMHLRU = FRRTS(I)*BMH1 + FRRTOK(I)*BMH2 + FRNRTS(I)*BMH3

C           PARTITION AVERAGES BY STATION TYPE
            DO 140 J = 1,4
              REALJ = J
              IF(STNREQ(I) .EQ. REALJ) THEN
                HOLD = (QPA(I)*DEMFH(J)/XMTBD(I))*BMHLRU
                BMHAVG(J) = BMHAVG(J) + HOLD
              END IF
  140       CONTINUE
  130     CONTINUE

C         POST -- % OF DEMANDS WHICH CAUSE LRU AWAP
          POST = RTSRT*(1.0-SRUAVL)

C         AVERAGE TIME FOR ORDER AND SHIP TIME
          WOST = POST*8.0*24.0
          PRINT *,' WOST = ',WOST

          DO 160 J = 1,4
            IF(J .EQ. 1) PRINT *,'DIGITAL STATION'
            IF(J .EQ. 2) PRINT *,'DIGITAL ANALOG VIDEO STATION'
            IF(J .EQ. 3) PRINT *,'RADIO FREQUENCY STATION'
            IF(J .EQ. 4) PRINT *,'RADAR EW STATION'
            PRINT *,' DEMSH = ',DEMSH(J)
            PRINT *,' BMHAVG = ',BMHAVG(J)

C           MEAN TIME BETWEEN STATION NMCS
            ATEREL(J) = ATEREL(J)/(1.0 - SRUAVL)

C           MEAN ORDER AND SHIP TIME
            ATEREP(J) = HRSOST

C           EITHER ONE (K = 1) OR TWO (K = 2) STATIONS
            DO 150 K = 1,2

              IF(K .EQ. 1) THEN
C               SUBROUTINE FOR ONE STATION CASE
                CALL ME21(DEMSH(J),ATEREL(J),BMHAVG(J),
     1                  ATEREP(J),RHO,W)
              END IF
```

```

            IF(K .EQ. 2) THEN
C             SUBROUTINE FOR TWO STATION CASE
              CALL ME22(DEMSH(J),ATEREL(J),BMHAVG(J),
     1                    ATEREP(J),RHO,W)
            END IF

C           RHO IS STATION UTILIZATION
C           W IS TOTAL TIME IN STATION QUEUE + SERVICE TIME
C           W IS CONVERTED FROM 16 HOUR TO 24 HOUR DAYS
C           WTOT IS TOTAL BASE REPAIR CYCLE TIME

            W = (24.0/HRSDAY)*W
            WTOT = WOMS + W + WOST



            IF (RHO .LT. 1.0) THEN
              PRINT *,'  K = ',K,' RHO = ',RHO
              PRINT *,'  W = ',W,' WTOT = ',WTOT
            END IF

            IF (RHO .GE. 1.0) THEN
              PRINT *,'  K = ',K,' RHO = ',RHO
            END IF
  150     CONTINUE
  160 CONTINUE
      STOP
      END

      SUBROUTINE MMS(XMTBF,XMTTR,NUMSRV,RHO,W)

      REAL NUMER,LQ

      FR = 1.0/XMTBF
      SR = 1.0/XMTTR
      S = NUMSRV

      RHO = (FR)/(S*SR)

      SUM = 0.0
      LIMIT = NUMSRV - 1

      DO 400 N = 0,LIMIT

        XN = N
        DENOM = FACT(XN)
        NUMER = (FR/SR)**N
        HOLD = NUMER/DENOM
        SUM = SUM + HOLD
  400 CONTINUE

      NUMER = (FR/SR)**S
      DENOM = FACT(S)
```

```
      DENOM = DENOM*(1.0-RHO)
      HOLD = NUMER/DENOM
      SUM = SUM + HOLD
      PO = 1.0/SUM
      NUMER = PO*NUMER*RHO
      DENOM = DENOM*(1.0-RHO)
      LQ = NUMER/DENOM
      WQ = LQ/FR
      W = WQ + (1.0/SR)
      RETURN
      END
      FUNCTION FACT(X)
      FACT = 1.0
      IX = X + 0.5
      IF(IX .GT. 1) THEN
        DO 500 I = 2,IX
          FACT = FACT*I
500     CONTINUE
      END IF
      RETURN
      END
      SUBROUTINE ME21(XMTBF1,XMTBF2,XMTTR1,XMTTR2,RHO,WAIT)
      DIMENSION A(100,100),B(100,1),WKAREA(100)
      DO 290 I = 1,100
        DO 280 J = 1,100
          A(I,J) = 0.0
280     CONTINUE
        B(I,1) = 0.0
290   CONTINUE
      M = 1
      NMAX = 8
      N = 4*NMAX + 2
      IA = 100
      IDGT = 3
```

```
      FR1 = 1.0/XMTBF1
      FR2 = 1.0/XMTBF2
      SR1 = 1.0/XMTTR1
      SR2 = 1.0/XMTTR2
      A(1,1) = -1.0*(FR1 + FR2)
      A(1,2) = SR2
      A(1,3) = 2.0*SR1
      A(2,1) = FR2
      A(2,2) = -1.0*(FR1 + SR2)
      A(3,3) = -1.0*(FR1 + FR2 + 2.0*SR1)
      A(3,4) = SR2
      A(3,5) = 2.0*SR1
      A(4,3) = FR2
      A(4,4) = -1.0*(FR1 + SR2)
      LIMIT = NMAX - 2
      DO 300 K = 1,LIMIT
         I1 = 4*K + 1
         I2 = 4*K + 2
         I3 = 4*K + 3
         I4 = 4*K + 4
         A(I1,I1-4) = FR1
         A(I1,I1) = -1.0*(FR1 + FR2 + 2.0*SR1)
         A(I1,I1+1) = SR2
         A(I1,I1+2) = 2.0*SR1
         A(I2,I2-4) = FR1
         A(I2,I2-1) = FR2
         A(I2,I2) = -1.0*(FR1 + SR2)
         A(I3,I3-4) = FR1
         A(I3,I3) = -1.0*(FR1 + FR2 + 2.0*SR1)
         A(I3,I3+1) = SR2
         A(I3,I3+2) = 2.0*SR1
         A(I4,I4-4) = FR1
         A(I4,I4-1) = FR2
         A(I4,I4) = -1.0*(FR1 + SR2)
  300 CONTINUE
      K = LIMIT + 1
      I1 = 4*K + 1
      I2 = 4*K + 2
      I3 = 4*K + 3
      I4 = 4*K + 4
      A(I1,I1-4) = FR1
      A(I1,I1) = -1.0*(FR1 + FR2 + 2.0*SR1)
      A(I1,I1+1) = SR2
      A(I1,I1+2) = 2.0*SR1
      A(I2,I2-4) = FR1
      A(I2,I2-1) = FR2
```

```
      A(I2,I2) = -1.0*(FR1 + SR2)
      A(I3,I3-4) = FR1
      A(I3,I3) = -1.0*(FR2 + 2.0*SR1)
      A(I3,I3+1) = SR2
      A(I3,I3+2) = 2.0*SR1
      A(I4,I4-4) = FR1
      A(I4,I4-1) = FR2
      A(I4,I4) = -1.0*SR2
      I1 = I1 + 4
      I2 = I2 + 4
      A(I1,I1-4) = FR1
      A(I1,I1) = -1.0*(FR2 + 2.0*SR1)
      A(I1,I1+1) = SR2
      DO 310 K = 1,I2
        A(I2,K) = 1.0
  310 CONTINUE
      B(I2,1) = 1.0
      CALL LEQT1F(A,M,N,IA,B,IDGT,WKAREA,IER)
      PRINT *,' ME21 IER = ',IER
      SRAVG = (FR1*SR1 + FR2*SR2)/(FR1 + FR2)
      RHO = (FR1 + FR2)/SRAVG
      XL = 0.0
      DO 320 K = 1,NMAX
        I1 = 4*(K-1) + 3
        I2 = 4*(K-1) + 4
        I3 = 4*(K-1) + 5
        I4 = 4*(K-1) + 6
        REALK = K
        HOLD = REALK*(B(I1,1) + B(I2,1) + B(I3,1) + B(I4,1))
        XL = XL + HOLD
  320 CONTINUE
      WAIT = XL/FR1
      RETURN
      END
      SUBROUTINE ME22(XMTBF1,XMTBF2,XMTTR1,XMTTR2,RHO,WAIT)
```

```
      DIMENSION A(100,100),B(100,1),WKAREA(100)

      DO 395 I = 1,100
        DO 385 J = 1,100
          A(I,J) = 0.0
385     CONTINUE
        B(I,1) = 0.0
395   CONTINUE

      M = 1
      NMAX = 8
      N = 9*NMAX
      IA = 100
      IDGT = 3

      FR1 = 1.0/XMTBF1
      FR2 = 1.0/XMTBF2
      SR1 = 1.0/XMTTR1
      SR2 = 1.0/XMTTR2

      A(1,1) = -1.0*(FR1 + 2.0*FR2)
      A(1,2) = SR2
      A(1,4) = 2.0*SR1
      A(2,1) = 2.0*FR2
      A(2,2) = -1.0*(FR1 + FR2 + SR2)
      A(2,5) = 2.0*SR1
      A(2,3) = 2.0*SR2
      A(3,2) = FR2
      A(3,3) = -1.0*(FR1 + 2.0*SR2)
      A(4,4) = -1.0*(FR1 + 2.0*FR2 + 2.0*SR1)
      A(4,5) = SR2
      A(4,7) = 2.0*SR1
      A(4,10) = 4.0*SR1
      A(5,4) = 2.0*FR2
      A(5,5) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
      A(5,6) = 2.0*SR2
      A(5,8) = 2.0*SR1
      A(5,11) = 2.0*SR1
      A(6,5) = FR2
      A(6,6) = -1.0*(FR1 + 2.0*SR2)
      A(7,1) = FR1

      A(7,7) = -1.0*(FR1 + 2.0*FR2 + 2.0*SR1)
      A(7,8) = SR2
      A(7,13) = 2.0*SR1
      A(8,2) = FR1
      A(8,7) = 2.0*FR2
      A(8,8) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
      A(8,9) = 2.0*SR2
      A(8,14) = 2.0*SR1
      A(9,3) = FR1
      A(9,8) = FR2
      A(9,9) = -1.0*(FR1 + 2.0*SR2)
```

```
      A(10,10) = -1.0*(FR1 + 2.0*FR2 + 4.0*SR1)
      A(10,11) = SR2
      A(10,13) = 2.0*SR1
      A(11,10) = 2.0*FR2
      A(11,11) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
      A(11,12) = 2.0*SR2
      A(12,11) = FR2
      A(12,12) = -1.0*(FR1 + 2.0*SR2)
      A(13,4) = FR1
      A(13,13) = -1.0*(FR1 + 2.0*FR2 + 4.0*SR1)
      A(13,14) = SR2
      A(13,16) = 4.0*SR1
      A(13,19) = 4.0*SR1
      A(14,5) = FR1
      A(14,13) = 2.0*FR2
      A(14,14) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
      A(14,15) = 2.0*SR2
      A(14,17) = 2.0*SR1
      A(14,20) = 2.0*SR1
      A(15,6) = FR1
      A(15,14) = FR2
      A(15,15) = -1.0*(FR1 + 2.0*SR2)

      LIMIT = NMAX - 2

      DO 400 K = 2,LIMIT

        I1 = 9*(K-1) + 7
        I2 = I1 + 1
        I3 = I2 + 1
        I4 = I3 + 1
        I5 = I4 + 1
        I6 = I5 + 1
        I7 = I6 + 1
        I8 = I7 + 1
        I9 = I8 + 1

        A(I1,I1-9) = FR1
        A(I1,I1) = -1.0*(FR1 + 2.0*FR2 + 4.0*SR1)
        A(I1,I2) = SR2
        A(I1,I7) = 2.0*SR1
        A(I2,I2-9) = FR1
        A(I2,I1) = 2.0*FR2
        A(I2,I2) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
        A(I2,I3) = 2.0*SR2
        A(I2,I8) = 2.0*SR1
        A(I3,I3-9) = FR1
        A(I3,I2) = FR2
        A(I3,I3) = -1.0*(FR1 + 2.0*SR2)
        A(I4,I4-9) = FR1
        A(I4,I4) = -1.0*(FR1 + 2.0*FR2 + 4.0*SR1)
        A(I4,I5) = SR2
        A(I4,I7) = 2.0*SR1
        A(I5,I5-9) = FR1
```

```
        A(I5,I4) = 2.0*FR2
        A(I5,I5) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
        A(I5,I6) = 2.0*SR2
        A(I6,I6-9) = FR1
        A(I6,I5) = FR2
        A(I6,I6) = -1.0*(FR1 + 2.0*SR2)
        A(I7,I7-9) = FR1
        A(I7,I7) = -1.0*(FR1 + 2.0*FR2 + 4.0*SR1)
        A(I7,I8) = SR2
        A(I7,I1+9) = 4.0*SR1
        A(I7,I4+9) = 4.0*SR1
        A(I8,I8-9) = FR1
        A(I8,I7) = 2.0*FR2
        A(I8,I8) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
        A(I8,I9) = 2.0*SR2
        A(I8,I2+9) = 2.0*SR1
        A(I8,I5+9) = 2.0*SR1
        A(I9,I9-9) = FR1
        A(I9,I8) = FR2
        A(I9,I9) = -1.0*(FR1 + 2.0*SR2)

  400 CONTINUE

      I1 = I1 + 9
      I2 = I2 + 9
      I3 = I3 + 9
      I4 = I4 + 9
      I5 = I5 + 9
      I6 = I6 + 9
      I7 = I7 + 9
      I8 = I8 + 9
      I9 = I9 + 9

      A(I1,I1-9) = FR1
      A(I1,I1) = -1.0*(FR1 + 2.0*FR2 + 4.0*SR1)
      A(I1,I2) = SR2
      A(I1,I7) = 2.0*SR1
      A(I2,I2-9) = FR1
      A(I2,I1) = 2.0*FR2
      A(I2,I2) = -1.0*(FR1 + FR2 + 2.0*SR1 + SR2)
      A(I2,I3) = 2.0*SR2
      A(I2,I8) = 2.0*SR1
      A(I3,I3-9) = FR1
      A(I3,I2) = FR2
      A(I3,I3) = -1.0*(FR1 + 2.0*SR2)
      A(I4,I4-9) = FR1
      A(I4,I4) = -1.0*(2.0*FR2 + 4.0*SR1)
      A(I4,I5) = SR2
      A(I4,I7) = 2.0*SR1
      A(I5,I5-9) = FR1
      A(I5,I4) = 2.0*FR2
      A(I5,I5) = -1.0*(FR2 + 2.0*SR1 + SR2)
      A(I5,I6) = 2.0*SR2
      A(I6,I6-9) = FR1
```

```
      A(I6,I5) = FR2
      A(I6,16) = -1.0*(2.0*SR2)
      A(I7,I7-9) = FR1
      A(I7,I7) = -1.0*(2.0*FR2 + 4.0*SR1)
      A(I7,I8) = SR2
      A(I7,I1+9) = 4.0*SR1
      A(I8,I8-9) = FR1
      A(I8,I7) = 2.0*FR2
      A(I8,I8) = -1.0*(FR2 + 2.0*SR1 + SR2)
      A(I8,I9) = 2.0*SR2
      A(I8,I2+9) = 2.0*SR1
      A(I9,I9-9) = FR1
      A(I9,I8) = FR2
      A(I9,I9) = -1.0*(2.0*SR2)

      I1 = I1 + 9
      I2 = I2 + 9
      I3 = I3 + 9
      A(I1,I1-9) = FR1
      A(I1,I1) = -1.0*(2.0*FR2 + 4.0*SR1)
      A(I1,I2) = SR2
      A(I2,I2-9) = FR1
      A(I2,I1) = 2.0*FR2
      A(I2,I2) = -1.0*(FR2 + 2.0*SR1 + SR2)
      A(I2,I3) = 2.0*SR2

      DO 410 K = 1,N
        A(I3,K) = 1.0
  410 CONTINUE
      B(I3,1) = 1.0

      CALL LEQT1F(A,M,N,IA,B,IDGT,WKAREA,IER)

      PRINT *,' ME22 IER = ',IER

      SRAVG = (FR1*SR1 + FR2*SR2)/(FR1 + FR2)
      RHO = (FR1 + FR2)/(2.0*SRAVG)

      XL = 0.0
      XL = B(4,1) + B(5,1) + B(6,1)
      XL = XL + B(7,1) + B(8,1) + B(9,1)

      DO 420 K = 2,NMAX
        REALK = K
        I1 = 9*(K-1) + 1
        SUM = B(I1,1) + B(I1+1,1) + B(I1+2,1)
        SUM = SUM + B(I1+3,1) + B(I1+4,1) + B(I1+5,1)
        SUM = SUM + B(I1+6,1) + B(I1+7,1) + B(I1+8,1)
        XL = XL + SUM*REALK

  420 CONTINUE

      WAIT = XL/FR1
```

```
      RETURN
      END


      BLOCK DATA
      COMMON/UCOM/XMTBD(109),QPA(109),STNREQ(109),SETUP(109),
     1   TSSITA(109),WARMUP(109),PERFT(109),FRRTS(109),FRRTOK(109),
     2   FRNRTS(109),TEARDN(109),REPAIR(109)
     3   ,ATEREL(4),ATEQTY(4),ATEREP(4)
      DATA XMTBD/16458.,1199.,707.,1488.,2024.,1576.,952.,100000.,
     1       1923.,11731.,151.,560.,590.,780.,2260.,5690.,330.,1010.,
     2       620.,740.,1800.,460.,232.,272.,3803.,4218.,424.,1180.,
     3       1923.,2085.,446.,2175.,1931.,3653.,3538.,372.,2019.,382.,
     4       13600.,100000.,1530.,41.,14223.,8509.,1391.,2085.,8611.,
     5       9667.,5856.,967.,5186.,12171.,5877.,6385.,3176.,5037.,
     6       2203.,36000.,3030.,198.,289.,478.,282.,418.,1391.,437.,
     7       245.,1597.,1597.,221.,7838.,847.,1380.,3030.,3030.,
     8       159.,225.,208.,486.,191.,269.,225.,156.,109.,344.,185.,
     9       157.,223.,136.,111.,265.,198.,136.,159.,58.,449.,449.,
     A       422.,422.,422.,216.,216.,175.,175.,50.,2906.,82.,
     B       706.,4480./
      DATA QPA/31.,3*2.,1.,3*2.,5.,1.,3.,8.,1.,3.,2.,1.,1.,3.,
     1       8*1.,2*1.,2.,1.,2*2.,1.,3.,2*1.,2.,4*1.,2.,1.,3.,
     2       2*1.,2.,5*1.,2.,5*1.,2.,7*1.,4*2.,10.,1.,2.,1.,3.,
     3       1.,2.,3.,3*3.,7*1.,2*3.,1.,2.,2*1.,3.,1.,2.,1.,
     4       1.,1.,2.,1.,2.,2.,1.,2.,2.,1.,1./
      DATA STNREQ/41*2.0,34*1.0,18*4.0,16*3.0/

      DATA SETUP/2*.23,2*.33,.28,.18,.33,.18,2*.28,2*.33,2*.28,
     1       .33,.18,.33,2*.18,.28,.33,.28,.33,.28,.18,.28,.33,
     2       3*.28,3*.33,.28,.23,.33,.18,.33,2*.18,2*.33,3*.23,
     3       .18,.23,.18,2*.23,2*.18,2*.18,.23,.28,.28,.18,.18,
     4       .33,.33,.28,.33,.28,.23,.23,.28,.18,.23,.33,.33,
     5       .23,5*.18,.23,5*.23,.28,.18,5*.28,3*.33,2*.28,
     6       7*.18,2*.23,.23,2*.18,.28,.18/
      DATA TSSITA/109*0.17/
      DATA WARMUP/109*0.0/
      DATA PERFT/.20,.59,1.44,.37,1.08,.29,1.31,.16,.75,.61,.05,
     1       .83,.55,.55,.75,.74,.95,.95,.89,1.25,.51,.65,1.63,
     2       .57,.63,.55,.64,.68,.55,1.15,.97,.31,.57,.55,.65,
     3       .77,.23,.13,.27,.27,.71,.32,.12,.25,.12,1.09,.72,
     4       .29,.25,.32,.23,.36,.36,.56,.72,.28,.68,.27,1.16,
     5       .24,.19,.28,.24,.09,.13,.85,1.35,.43,.12,1.71,1.04.
     6       .99,.89,1.16,1.16,.73,.81,.21,1.04,.21,.08,1.52,
     7       .38,1.29,1.11,1.16,1.59,.20,.59,.99,1.33,.53,.61,
     8       2.19,1.37,.31,.31,.60,.60,.60,.63,.63,.79,.79,
     9       .27,.17,.29,2.65,.41/
```

```
      DATA FRRTS/.8,.45,.45,.5,.65,.45,.5,.85,.50,.55,.55,.65,
     1      .75,.8,.65,.8,.5,.85,.5,.45,.45,.6,.85,.8,.75,.8,
     2      .65,.7,.55,.7,.55,.7,.7,.75,.85,.45,.6,.5,.8,.8,
     3      .85,.75,.75,.75,.75,.5,.6,.8,.8,.8,.8,.65,3*.60,
     4      .75,.85,.8,.75,.55,.5,.6,.55,.8,.7,.5,.6,.6,.8,
     5      .45,.45,.55,.60,.75,.75,.8,.8,.8,.7,.8,.7,.7,
     6      .65,.55,.55,.5,.55,.7,.7,.65,.6,.8,.8,.6,.65,.7,
     7      .80,.8,.8,.8,.8,.8,.7,.7,.7,2*.8,2*.85/
      DATA FRRTOK/.1,.45,.45,.40,.25,.45,.4,.05,.4,.35,.35,.25,
     1      .15,.1,.25,.1,.4,.05,.4,.45,.45,.3,.05,.1,.15,.1,
     2      .25,.2,.35,.2,.35,.2,.2,.15,.05,.45,.3,.4,.1,.1,.05,
     3      .15,.15,.15,.15,.4,.3,.1,.1,.1,.1,.25,3*.3,.15,.05,
     4      .1,.15,.35,.4,.3,.35,.1,.2,.4,.3,.3,.1,.45,.45,.35,
     5      .3,.15,.15,.1,.1,.1,.2,.1,.2,.2,.25,.35,.35,.4,.35,
     6      .2,.2,.25,.3,.1,.1,.3,.25,.2,.1,.1,.1,.1,.1,.1,.2,
     7      .2,.2,.1,.1,.05,.05/
      DATA FRNRTS/109*0.10/
      DATA TEARDN/2*.20,2*.27,.23,.17,.27,.17,.23,.23,.27,.27,
     1      .23,.23,.27,.20,.27,.17,.17,.23,.27,.23,.27,.23,.17,
     2      .27,.27,.23,.23,.23,.27,.27,.27,.23,.20,.27,.17,.27,
     3      .17,.17,.27,.27,.20,.20,.20,.17,.20,.17,.20,.20,.17,
     4      .17,2*.17,.2,.23,.23,.17,.17,.27,.27,.23,.27,.23,.2,
     5      .2,.23,.17,.2,.27,.27,.2,.17,.17,.17,.3,.3,.2,5*.20,
     6      .23,.23,.23,4*.23,3*.27,.23,.23,7*.17,2*.20,.20,
     7      .17,.17,.23,.17/
      DATA REPAIR/.37,.37,.50,.50,.43,.30,.50,.30,.43,
     1      2*.50,3*.43,.50,.37,.50,.30,.30,.42,.50,
     2      .43,.50,.43,.23,.43,.50,3*.43,3*.50,.43,
     3      .37,.50,.30,.50,.30,.30,.43,.50,.37,.37,
     4      .37,.30,.37,.30,.37,.37,2*.30,2*.30,.37,
     5      .43,.43,2*.30,2*.50,.43,.50,.43,2*.37,
     6      .43,.30,.37,2*.50,.37,5*.30,.37,5*.37,
     7      .43,.30,5*.43,3*.50,2*.43,7*.30,2*.37,
     8      .37,.30,.30,.43,.30/
      DATA ATEQTY/4*1.0/
      DATA ATEREP/4*1.0/
      DATA ATEREL/256.,145.,167.,130./
      END
*EOR
```

Bibliography

1. Morse, Philip M. Queues, Inventories and Maintenance. New York: John Wiley & Sons, Inc., 1958.

2. Sauer, Charles H. and K. Mani Chandy. "Approximate Solution of Queueing Models," Computer: 25-31 (April 1980).

3. Ross, Sheldon M. Introduction to Probability Models. New York: Academic Press, Inc., 1980.

4. Cooper, Robert B. Introduction to Queueing Theory. New York: North Holland, 1981.

5. Kleinrock, Leonard. Queueing Systems. Volume I: Theory. New York: John Wiley & Sons, Inc., 1975.

6. Kleinrock, Leonard. Queueing Systems. Volume II: Computer Applications. New York: John Wiley & Sons, Inc., 1976.

7. Basket, Forest, et al. "Open, Closed and Mixed Networks of Queues with Different Classes of Customers," Journal of the Association of Computing Machinery, 22:248-260 (April 1975).

8. Cox, Michael H. Multi-Class Analytical Models of the DECsystem-10 Job-Swapping Behavior. MS thesis. Wright-Patterson AFB, Ohio: Air Force Institute of Technology, December 1981. (GOR/MA/81D-4).

9. Shanthikumar, J. G. "M/G/1 Queues with Scheduling within Generations and Removable Server," Operations Research, 29: 1010-1018 (September-October 1981).

10. Carroll, J. L., et al. "Solutions of M/G/1//N-type Loops with Extensions to M/G/1 and GI/M/1 queues," Operations Research, 30:490-514 (May-June 1982).

11. Neuts, Marcel F. "Explicit Steady-state Solutions to Some Elementary Queueing Models," Operations Research, 30:480-489 (May-June 1982).

12. Clark, Thomas D. and Mary K. Allen. "A Logistical Analysis of the F-111 Automatic Test Equipment: A Network Simulation Approach," AFALD Presentation, Wright-Patterson Air Force Base, Ohio.

13. General Dynamics, Fort Worth Division. Station Loading Model User's Manual. General Dynamics document 16PR1345 (12 June 1980).

14. Bryson, Gary C., et al. A Decision Support System of Acquisition of F-16 Avionics Intermediate Shop Test Sets Using the System Science Paradigm and Q-GERT. MS Thesis. Wright-Patterson AFB, Ohio: Air Force Institute of Technology, 1982. (LSSR 11-82).

15. Strategic Air Command. Maintenance Portion of the System Operational Concept for the B-1B. HQ SAC Planning Document. Offutt AFB, Nebraska: HQ SAC, 1983.

16. Deputy for B-1B. B-1B Integrated Logistics Support Plan. B-1B SPO Planning Document. Wright-Patterson AFB, Ohio: ASD/B1, January 1983.

17. Hermes, Phillip H. SAC Base Operational and Maintenance Data. Informal Report. Wright-Patterson AFB, Ohio: ASD/YYEE, 1983.

18. Giffin, Walter C. Queueing. Columbus: Grid, Inc., 1978.

19. IMSL, Inc. IMSL Library Reference Manual, Volume 2. Houston: IMSL, Inc. 1982.

20. Concepts and Analysis Directorate, Acquisition Logistics Division, Air Force Logistics Command. Logistics Support Cost Model User's Handbook. Version 1.1. AFALD/XRSC, Wright-Patterson AFB, Ohio. January 1979.

21. Church, Capt Ted, et al. Personal interviews with many personnel from HQ SAC/LGXB and ASD/B1L. June through November 1982.

22. Shannon, Robert E. Systems Simulation. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1975.

VITA

Captain Lance M. Roark was born on August 24, 1955 in Burbank, California. He graduated from high school in Miraleste, California in 1972 and attended Harvey Mudd College in Claremont, California from which he received the degree of Bachelor of Science in Mathematics in June 1976. Upon graduation, he was employed as a member of the technical staff for Rockwell International Corporation, B-1 Division. In October 1978, he received a commission in the USAF as a distinguished graduate of the Officer Training School. He then served as an operations research analyst in the F-16 System Program Office until entering the School of Engineering, Air Force Institute of Technology, in June 1982.

Permanent address: 6645 W. Coley Avenue
Las Vegas, Nevada 89102

END

FILMED

6-84

DTIC

12. Clark,
Analys
Networ
Wright