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Integrating O&S Models During Conceptual Design - PART III

Simulation of Maintenance and Logistics
Support of Proposed Space Systems Using SLAM II

Annual Report, Part III
December 31, 1994

Prepared for

National Aeronautics and Space Administration

Langley Research Center

under

Grant No. NAG1-1-1327

Prepared by

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Preface

This document is one of three prepared under NASA (Langley Research Center) grant number NAG1-1-1327. Collectively these documents form the technical report covering the research activites for the period of time from July 1, 1994 to December 31, 1994. The three documents consist of the following:

1. Integrating O&S Models During Conceptual Design - Part I

Summarizes the overall study, objectives, and results. Discusses in detail enhancements made to the models developed under this grant.

2. Integrating O&S Models During Conceptual Design - Part II
Reliability and Maintainability Model (RAM), User and Maintenance Manual

Provides detailed documentation on the RAM model, its execution, and procedures for conducting a study using the model. A complete source listing is provided.

3. Integrating O&S Models During Conceptual Design - Part III
Simulation of Maintenance and Logistics Support of Proposed Space Systems Using SLAM II.

Documents the SLAM maintenance simulation model which provides for more accurate determination of maintenance manpower requirements. A complete example of its use is provided.

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manpower and vehicle requirements for the proposed vehicle to meet its desired mission rate.

This model has been developed under a grant from NASA and is described in detail herein. The grant is a continuation of an earlier grant given to Dr. Charles Ebeling of the School of Engineering of the University of Dayton, Dayton, Ohio to develop and implement a methodology for predicting the reliability and maintainability of proposed space vehicles. The predicted reliability and maintainability values are inputs to this model. The outputs of this model are used as inputs to a model used to estimate the life cycle costs of proposed space vehicles that Dr. Ebeling has also developed under the same grant with NASA. (University of Dayton Research Institute proposal R-9657)

A. Background

Dr. Charles Ebeling of the University of Dayton has developed a methodology for estimating measures of reliability and maintainability such as the mean time between maintenance actions (MTBM), maintenance hours per maintenance action (MH/MA) which is used in calculating the mean time to repair (MTTR), average crew size per maintenance task (CREW), and spares requirements for proposed space vehicles (Ebeling).

Equations for estimating these measures as functions of vehicle design and performance specifications were obtained through regression analysis on a large data base of actual aircraft and space shuttle subsystem reliability and maintainability data. For example, the Air Force and Navy keep data on the times between maintenance actions of their aircraft health monitoring avionics subsystems. Design and performance specifications of these aircraft, such as number of engines, BTU cooling capacity, vehicle length plus wing span, and subsystem weights, are also known. Multiple regression analysis of the maintenance data against the design and performance specifications has

CHAPTER I

INTRODUCTION

Space vehicles, such as the Space Shuttle, require intensive ground support prior to, during, and after each mission. Maintenance is a significant part of that ground support. All space vehicles require scheduled maintenance to ensure operability and performance. In addition, components of any vehicle are not one-hundred percent reliable so they exhibit random failures. Once detected, a failure initiates unscheduled maintenance on the vehicle. Maintenance decreases the number of missions which can be completed by keeping vehicles out of service so that the time between the completion of one mission and the start of the next is increased. Maintenance also requires resources such as people, facilities, tooling, and spare parts. Assessing the mission capability and resource requirements of any new space vehicle, in addition to performance specifications, is necessary to predict the life cycle cost and success of the vehicle.

Maintenance and logistics support has been modeled by computer simulation to estimate mission capability and resource requirements for evaluation of proposed space vehicles. The simulation was written with Simulation Language for Alternative Modeling II (SLAM II) for execution on a personal computer. For one or a fleet of space vehicles, the model simulates the preflight maintenance checks, the mission and return to earth, and the post flight maintenance in preparation to be sent back into space. The model enables prediction of the number of missions possible and vehicle turn-time (the time between completion of one mission and the start of the next) given estimated values for component reliability and maintainability. The model also facilitates study of the resulted in the following equation for MTBM of the health monitoring avionics subsystem:

$$MTBM = 323.913 - 16.0757\sqrt{ave\_wt} + 16.974(len + wing) + .1735(ave\_wt)$$
$$+ 23.8(nbr\_diff\_subsys) - 2.305(ave\_wt / nbr\_ave\_subsys)$$

The MTBM of all the subsystems are calculated similarly and are then used to calculate the vehicle's MTBM. The other reliability and maintainability measures are estimated in a similar way.

Information is, of course, limited for conceptual systems. Therefore, the design and performance specifications as well as subsystem weights, if not known, can be estimated by equations which are functions of variables known early in the design stage: vehicle weight, vehicle's length plus it's wing span, crew size, number of passengers, and number of main engines. These equations were obtained from multiple regression analysis on a data base of actual aircraft and space shuttle data by the same method described in the above paragraph.

Dr. Ebeling has written a computer program which allows the user to input the overall vehicle parameters, to input the subsystem weights if known, or input the subsystem weights and design and performance specifications if known. The program then calculates the various reliability and maintainability measures and displays them in tabular form. These calculated measures such as manpower (CREW) and spares requirements, in addition to operations, logistics, and systems support, facility and hardware, and development requirements, can be used to compute the proposed vehicle's total life cycle costs.

Dr. Ebeling has also developed a model to estimate operating and support costs throughout the life of a system, i.e., operating, logistic support, and maintenance costs, facility and tooling costs, and manpower and spares costs. The manpower and spare requirements as calculated by the Reliability and Maintainability Model are two of the many inputs to a computer program which implements the Life Cycle Costing Model.

The program calculates the various costs and then outputs them by function (operations, development, etc.), by subsystem (health monitoring avionics, propulsion, etc.), and by configuration (orbiter, boosters, etc.).

B. Problem Statement

The values for manpower and spare parts requirements from the Reliability and Maintainability Model do not account for the stochastic nature of vehicle failure and repair times. Subsystem manpower requirements are calculated from equations obtained by regression analysis of known average crew sizes against the proposed vehicle's design specifications (body length, vehicle dry weight, etc.) as described in Section A. If there was not a significant fit of the data, the average crew size was used. The values for manpower, therefore, do not take into account that some repairs will take longer than others and that failures which require the same maintenance crew will occur close in time because the failure and repair times are not deterministic but probabilistic. During actual operation, mission capability could be reduced and costs increased as a vehicle is out of service longer (long turnaround times) and other vehicles which require the same service must wait (thereby increasing turnaround times even more). A simulation of the operation of a fleet of vehicles based on the reliability (MTBM) and maintainability (MTTR) of the vehicle's subsystems for a given mission duration can more accurately predict the manpower and vehicle requirements needed to meet a desired mission rate. These values can be input into the Life Cycle Costing Model instead of the Reliability and Maintainability Model's values for more accurate cost estimation.

C. Objectives

The primary objective of this effort has been to develop a methodology to estimate the number of crews, the number of vehicles, and the maintenance turn around time required to meet established mission plans for proposed space vehicles. The first goal has been to develop a computer simulation which uses the Reliability and Maintainability Model's deterministic values of MTBM and MTTR as mean values for probability distributions in a model of the pre-flight loading and maintenance, the mission and return to earth, and post-flight maintenance for one or a fleet of proposed space vehicles. The second goal has been to write a detailed description of the model and extensive guidelines for using the model to obtain valid estimates for the number of crews and vehicles needed as the model will be used by NASA personnel in conjunction with the Reliability and Maintainability Model and Life Cycle Costing Model during conceptual design of space vehicles.

D. Overview

The simulation model and its application are presented in detail in the remaining chapters of this thesis. A literature search resulted in a few very relevant publications to this subject. Summaries of these publications are in Chapter 2. A description of the model and the assumptions made during the development of the model are presented in Chapter 3. Guidelines for how to use the model and an example of running the model with actual data are given in Chapter 4. Concluding remarks are presented in the final chapter.

CHAPTER II

REVIEW OF CURRENT LITERATURE

Some literature pertinent to this simulation study was provided by Dr. Charles Ebeling. In addition, literature was obtained through the library at Wright State University and the Technical Information Center at General Electric Aircraft Engines. A discussion of the most relevant literature follows.

W.D. Morris, T.A. Talay, and D.G. Eide used SLAM to model the resources and activities necessary to support the operation of a proposed reusable space vehicle designed to deliver cargo to the space station and then return to earth for maintenance, loading, and another launch into space. The model permitted study of the number of vehicles, size of cargo bay, number of facilities, and inclination angle (to determine best launch window) needed to meet the required cargo delivery rate as efficiently as possible. Failure rates for the vehicle were not modeled and various maintenance times were postulated to determine the effect of maintenance on number of vehicles, size of cargo bay, etc. Although this model does not parallel the simulation in this study, the discussion of the advantages of using simulation to study the operations of space vehicles to ensure mission readiness and to estimate the entire life cycle cost of the vehicle instead of focusing entirely on performance is relevant and accurate. (Morris, W.D., Talay, T.A., and Eide)

In his Master's Thesis "A Simulation Model for Determining the Effect of Reliability and Maintainability on Maintenance Manpower Requirements and Mission

Capabilities," Captain Myron Lewellen describes his use of SLAM II to model the operations of a squadron of twenty-four fighter aircraft for one year. Captain Lewellen modeled the pre-flight inspection, the mission completion given daylight and acceptable weather, the post-flight inspection, and the reuse of an aircraft for another mission or the removal of an aircraft from service for unscheduled or scheduled maintenance. Each aircraft was modeled as having twenty-one subsystems each with its own reliability (mean time to failure) and maintainability (mean time to repair) parameters (values determined from historical data) and requiring four scheduled maintenance actions. When a subsystem failed or the aircraft was due for scheduled maintenance, the aircraft was removed from service for the length of time of the required maintenance action at a subsystem dedicated facility. Captain Lewellen's efforts focused on determining the effect of improving the reliability and maintainability of the subsystems on the availability of fighters to complete missions as measured in number of sorties flown and the required manpower as measured by number of man-hours to meet a desired (target) sortie rate. His strategy of modeling an aircraft as a collection of subsystems each with its own reliability and maintenance requirements was used in this study. (Lewellen)

CHAPTER III

SIMULATION MODEL

A simulation model has been written with Simulation Language for Alternative Modeling (SLAM) on a personal computer. The model uses the mean time between maintenance (MTBM), mean time to repair (MTTR), and other values from the Reliability and Maintainability Model to estimate the manpower requirements, the effect of spares support, and the mean operation and processing turnaround time for proposed space vehicles. An overview of the vehicle operation and support processes, the assumptions made during development of the model, and a detailed description of the model follows.

A. Vehicle Operation and Support Processes

The model simulates all of the operation and support processes required for one or a fleet of proposed space vehicles to meet the overall mission/project goals. A diagram of a vehicle's processing and mission is presented in figure 1. An available vehicle is matched with a scheduled mission. The vehicle then undergoes integration (the boosters and payload are installed), pad processing (launch preparation and final inspection), and launch. For a small percentage of missions, a critical failure will occur resulting in a mission abort with a subsequent delay to replace the affected vehicle. Otherwise, the vehicle successfully completes the mission. Upon return to earth, the vehicle undergoes safing (inspection for dangerous conditions). Unscheduled and scheduled maintenance are then performed on each of the vehicle's systems as needed.

The unscheduled and scheduled maintenance processes are diagrammed in figure 2. If a system had one or more failures during the mission, unscheduled maintenance followed by scheduled maintenance is performed on that system. The number of failures is determined by a Poisson distribution with a mean equal to the average number of failures per mission for that system (mission operating hours divided by MTBM from the Reliability and Maintainability Model).

An unscheduled maintenance action is initiated for each failure. Some of these maintenance actions results in the removal of a component. If a spare is not available, the removed component is repaired immediately and is installed back onto the vehicle. If a spare is available, the component is replaced with a spare. Repair of the removed component is done after scheduled maintenance as 'off-vehicle unscheduled maintenance'. Once all of the unscheduled maintenance actions are completed, scheduled maintenance begins. If no failures occurred during the mission, scheduled maintenance is performed directly.

Scheduled maintenance is done both on and off-vehicle. All of the on-vehicle maintenance is completed before the off-vehicle begins. As soon as the on-vehicle scheduled maintenance is complete, maintenance on another system can begin if the appropriate repair crew is available. The current repair crew will then finish the off-vehicle scheduled and unscheduled maintenance (repair of removed components) for the current system. The vehicle is ready for another mission when the on-vehicle maintenance for all of the systems has been completed.

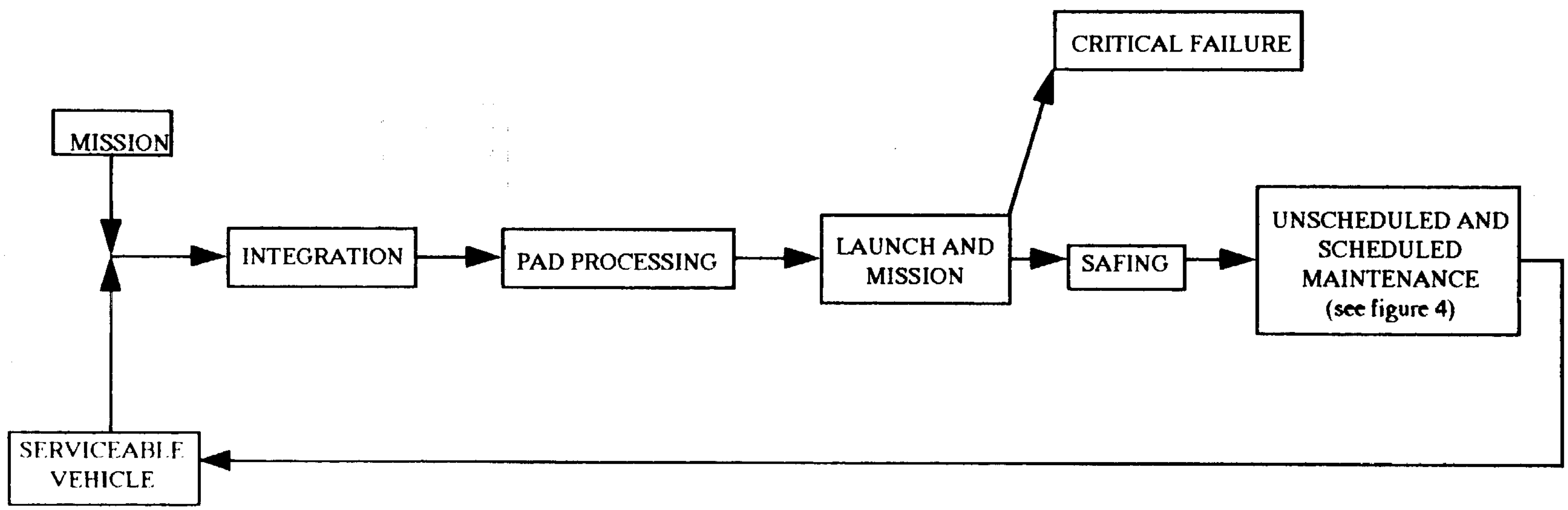

FIGURE 1: VEHICLE PROCESING AND MISSION OVERVIEW

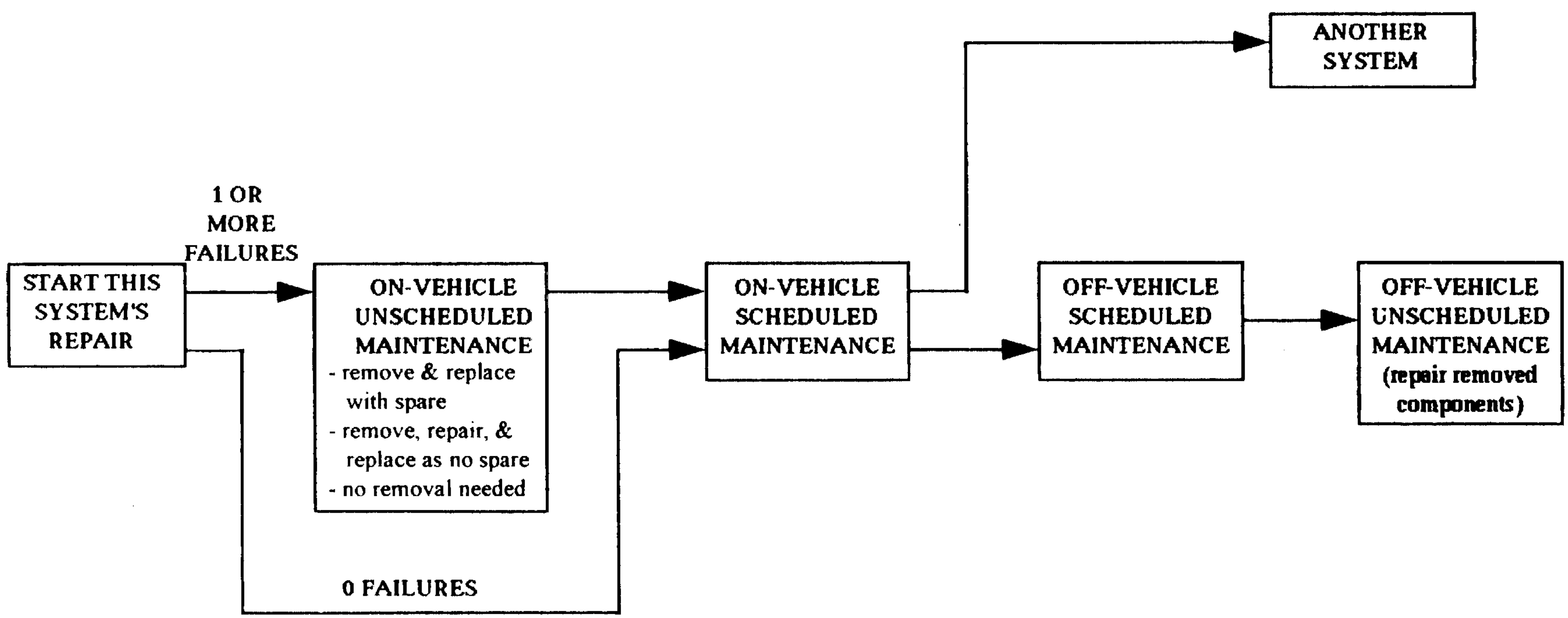

FIGURE 2: UNSCHEDULED AND SCHEDULED MAINTENANCE PROCESSES

B. Assumptions

The Reliability and Maintainability Model calculates reliability and maintainability parameters such as MTBM and MTTR values for up to thirty-three subsystems; the number of subsystems defining the proposed vehicle is user input. One simplifying assumption used in developing the simulation model was that the thirty-three subsystems could be aggregated into nine major systems for simulating maintenance. This aggregation was based upon assumed maintenance specialties. The necessary parameter values for a system were obtained from the values for the subsystems comprising that particular system. Figure 3 shows how the nine systems are defined. The numbers in parenthesis refer to the work breakdown structure (WBS) used in the Reliability and Maintainability Model for identifying the subsystems.

Assumptions were also made about the sequence in which the nine subsystems would be repaired. For example, it was assumed that the avionics system could not be repaired until after the power system was repaired. These two systems must be repaired in series. The structure and tanks systems must also be repaired before all other systems but the power system. Therefore, these three systems can be repaired in parallel. Figure 4 shows the sequence in which all nine systems are assumed to be repaired. The numbers preceding the system names correspond to attribute, global variable, and file indices used in the simulation model for those subsystems. For example, attribute 1 of each entity in the model representing a vehicle is the number of failures for the power system. Other sequences are possible. The simulation can be modified so that the sequence modeled represents the analyst's best estimate of how maintenance will actually be performed.

1. **POWER SYSTEMS** (9.10,9.20,9.30,&10.00): APU, BATTERY, FUEL CELL, & ELECTRICAL
2. **STRUCTURE** (1.00,2.00,&3.00): WING , TAIL , AND BODY GROUPS
3. **TANKS** (3.10&3.20): LOX TANKS AND LH2 TANKS
4. **AVIONICS** (13.10,13.20,13.30,13.40,13.50&13.60): GM & C, HEALTH MONITOR, COMM & TRACK, DISPLAYS & CONTR, INSTRUMENTS, AND DATA PROC
5. **THERMAL PROTECTION** (4.10,4.20&4.30): IEP-TILES,TCS, AND PVD
6. **AUXILIARY SYSTEMS** (16.30,16.40,16.50&16.60): REC & AUX-SEPARATION, CROSS FEED, DOCKING SUPPORT, AND MANIPULATOR
7. **LIFE SUPPORT** (14.10,14.40,15.00, 16.10&16.20): ENVIRONMENTAL CONTROL, ECS-LIFE SUPPORT, PERSONNEL PROVISION, REC & AUX-PARACHUTES, AND REC & AUX-ESCAPE SYSTEM
8. **MECHANICAL SYSTEMS** (5.00,11.00&12.00): LANDING GEAR, HYDRAULICS/ PNEUMATICS, AND AERO SURFACE ACTUATORS
9. **PROPULSION** (6.00,7.00&8.00): MAIN, RCS, & OMS

FIGURE 3: DEFINITION OF MODEL'S NINE SYSTEMS

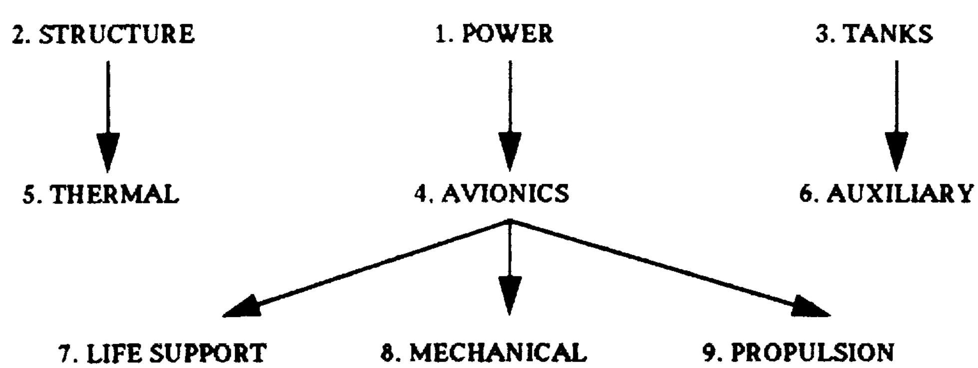

FIGURE 4: SEQUENCE OF SYSTEM REPAIRS

The assumption is made that each system has its own dedicated repair crew or crews, i.e.. there is at least one specialized repair crew for each system. The number of crews assigned to a particular subsystem can be modified within the model. The number of personnel assigned to a crew is the 'crew size' from the Reliability and Maintainability Model and is not explicitly considered within the simulation model.

Lastly, weather was not considered in the model. Weather certainly may delay the launch of a vehicle. These delays will affect the number of missions possible in a year. Also, a delayed landing due to a delayed launch or due to stormy weather will shorten the time between the landing of a vehicle and the scheduled start of its next mission. If maintenance cannot be completed in this time, its next mission will be delayed. Typically, the maintenance crews have idle time (crews finish one vehicle and then must wait for the next to land) that could be used to finish maintenance on a delayed vehicle so it is available on time for its next mission. Alternatively, overtime could be used to shorten the duration of maintenance. Overtime is also not explicitly considered in the model.

C. Model Description

The SLAM code is presented in Appendix A. It was written with SLAM SYSTEM on a personal computer. The program was designed so that a person with some knowledge of SLAM and SLAM SYSTEM could modify the code to model specific vehicles and applications. A full description of the code follows.

The program was written in three major sections: Primary Operation and Processing, System Maintenance, and User Input. The Primary Operation and Processing section simulates the vehicle processing and mission activities shown in figure 1. The System Maintenance section simulates the on-vehicle unscheduled, scheduled, and off-vehicle unscheduled maintenance processes shown in figure 2. The code for both of these sections is in the 'network file'. Nearly all of the necessary input values such as system MTBM and MTTR are entered into the 'control file' or User Input section of code. Each section is described separately below.

(1) Primary Operation and Processing

The model was designed to be simple, to use the least amount of code possible, and to be flexible. The most complicated aspect of the Primary Operation and Processing section to design and code was work shifts. The model had to be flexible so that simulations could be run with one, two, or three 8-hour shifts per day. For both one or two shifts per day, it would be possible that an activity would be started but not completed at the end of the last working shift on a particular day. That activity would then be completed at the start of the first working shift on the next day. The most common way to model work shifts is to remove the resources at the end of the last working shift so none are available during the off-shifts. The resources are then added back in at the start of the next working shift. However, code must also be added so that any activity which was not finished at the end of the last working shift is worked on at the start of the next working shift. Since each of the nine systems acquires and frees resources three times (for on-vehicle unscheduled, scheduled, and off-vehicle unscheduled maintenance), a significant amount of code would be needed to model shift changes in this way.

Alternatively, this model simulates all activities occurring continuously regardless of how many shifts are actually worked per day and then adjusts the primary outputs, maintenance duration and vehicle turnaround time, for one, two, or three 8-hour shifts. For example, if a system only has one resource (crew) available and three failures have occurred, the model simulates these three maintenance actions as occurring in series and continuously until complete. Assume that the three maintenance actions took 12 hours for this system. The maintenance duration in actual 24-hour days based on one 8-hour shift per day is calculated by dividing the continuous repair time of 12 hours by the number of hours worked in a day: 12/8=1.5 days. Therefore, if only one shift were worked per day, it would take one and a half days to complete the maintenance on this system. Similarly, if two or three shifts were worked per day, the maintenance duration would be 12/16=.75 or 12/24=.5 days respectively. Vehicle turnaround time in days is calculated the same way.

The Primary Operation and Processing section starts with two calculations needed because of the continuous working hours modeling approach described above (refer to figure 5). First, the time between missions must be calculated. In actual 24-hour days, if 28 missions are to be completed each year at regular intervals, one mission must occur every 1.86 weeks or 313 hours. However, since the model simulates all activities occurring continuously, the time between missions must be in continuous working hours which is based on the number of hours worked in a 24-hour day:

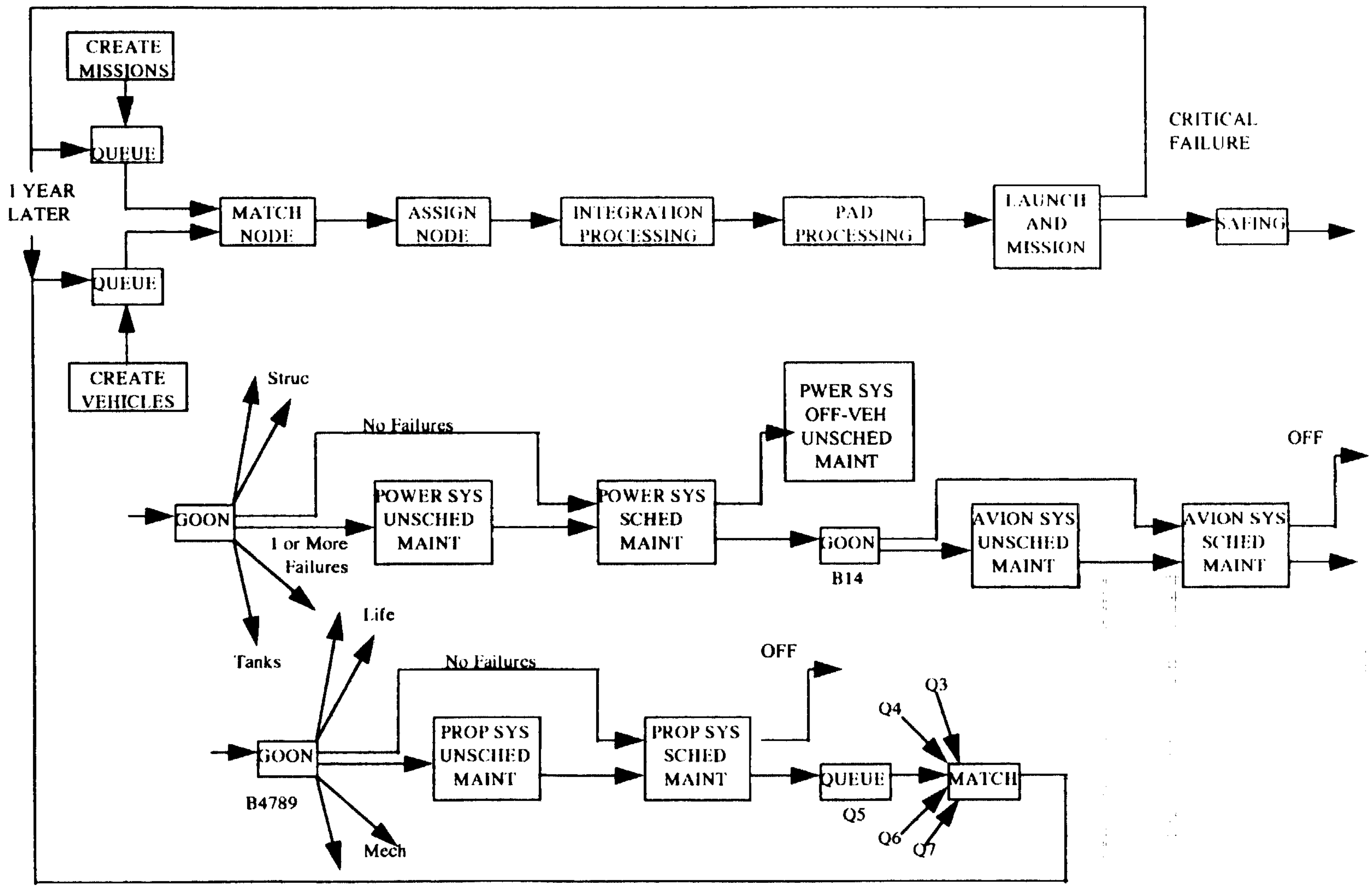

FIGURE 5: PRIMARY OPERATION AND PROCESSING SECTION

$$TimeBetweenMissions = \frac{52wks/yr * NbrDaysWorked/wk * NbrHrsWorked/day}{NbrMissions/yr}$$

If 24 hours (3 shifts) are worked each day for 7 days a week, the time between missions is 313 hours. However, if 28 missions are required each year, 5 days are worked each week, and only 8 hours are worked each day, then the time between missions is 52*XX(81)*XX(80)/XX(92)=74.3 hours where XX(81)=5, XX(80)=8, and XX(92)=28. A 'create node' at the beginning of the code creates an entity so that this value is calculated and assigned to global variable XX(84). Its use is described below. (The variables used in this and other calculations are entered as global variables in the control file as described in the User Input Section.)

The other required calculation is the duration of the simulation in working hours. It is calculated by:

$$SimDuration = NbrYrs * 52wks/yr * NbrDaysWorked/wk * NbrHrsWorked/day$$

This value is calculated and assigned to global variable XX(85) just after the time between missions node. Then an 'activity' with duration equal to the simulation duration routes the entity to a 'terminate node' with termination count set at one so that the arrival of the entity ends the simulation.

A create node with time between creations equal to the time between missions as calculated above creates one entity for each mission. The entity then waits in a 'queue' node until a vehicle is available. A create node creates one entity for each vehicle available at the beginning of the simulation. These 'vehicle entities' wait in a queue node until a mission is available. A 'match node' matches a mission to a vehicle as soon as each is available from their respective queues.

The vehicle entity then goes through a series of 'assign' nodes. The first node sets one of the entity's attributes equal to the current simulation time. This time will be subtracted from the time at which the vehicle's maintenance is completed to calculate the vehicle turnaround time. The remaining nodes assign the number of failures occurring for a system to a specific attribute. For example, the number of failures for the power system is assigned to the 1st attribute. Recall that the number of failures for a system is determined by a Poisson random variable with mean equal to the system's average number of failures per mission (calculated by the Reliability and Maintainability Model and input by the user).

The vehicle entity then passes through a series of activities representing integration processing, pad processing, the mission, and safing. The durations of these activities are entered in hours into the control file as global variables (described in User Input Section). The duration of the mission must be adjusted to account for the number of hours worked per day. In actuality, missions must occur continuously. For example, if a mission duration is 72 hours, the elapsed time from mission start to finish is 72 hours or three 24-hour days. In simulation time under the continuous working hours assumption, if one 8-hour shift is worked per day, an actual three day mission is also a simulated three day mission but **only 24 hours are worked during those three days**. Therefore, the duration of the mission must be 24 hours not 72. The simulation automatically changes the actual mission duration to the duration based on working hours with this formula:

$$\frac{ActualMissionDurationHrs}{24hrs / day} * NbrHrsWorked / day$$

Note that if three shifts are worked per day the mission duration stays at 72 hours. The other activity durations do not need to be modified as they are already in working hours. For example, if 12 hours are needed to complete pad processing, no matter whether one, two, or three shifts are worked a total of 12 hours will be worked to complete the pad processing. The number of days, however, will be 1.5, .75, or .5.

The Reliability and Maintainability Model calculates the probability that a vehicle successfully completes a mission (no critical failures). Therefore, there are actually two mission activities that the vehicle entity can take. It will take one with probability equal to one minus the successful completion probability (1-mission reliability), i.e., the vehicle has a critical failure resulting in mission abort and destruction of the vehicle. In this case the entity is routed to a 'goon node'; the entity is then duplicated so that an entity is immediately routed back to the mission queue as the mission will still need to be completed and an entity is routed with duration equal to one year back to the vehicle queue as a new vehicle will be manufactured to replace the destroyed one. The other mission activity will be taken with probability equal to the successful mission probability (mission reliability). If the entity flows through this activity, the mission is successfully completed and the entity continues on to the safing activity and then to a series of tests to determine which maintenance is to be performed.

The assign node at the end of the safing activity sets the entity's 11th attribute to the current time for calculation of the duration of all on-vehicle maintenance (i.e., the maintenance activities which delay the vehicle). It has six conditional branches emanating from it. The branches taken depend on which conditions are met. The power, structure, and tanks systems can all be worked on at the same time and must be worked on first according to the sequence in figure 4. A pair of branches is for each of these systems; the vehicle entity is duplicated so that the same vehicle entity takes one of the branches in each pair. Recall that the number of failures is stored as an attribute of the entity. The first branch in the pair routes a vehicle entity to the unscheduled maintenance repair subroutine if at least one failure has occurred (the entity is then routed to the scheduled maintenance subroutine). The second branch in the pair routes the entity directly to the scheduled maintenance subroutine if no failures have occurred. Recall that scheduled maintenance must always occur. The system maintenance subroutines are discussed later.

When a system's on-vehicle scheduled maintenance is complete, a vehicle entity is routed from the system's scheduled maintenance subroutine back to a goon node in the Primary Operation and Processing section. It is then routed to the maintenance subroutines for the next system in series with the current system. For example, when maintenance is done on the power system, an entity is routed to the goon node labeled B14 so maintenance can begin on the avionics system. (The labeling of the goon node indicates the system just finished with maintenance and the next to be started. For example, B14 means system 1 (power) is done and system 4 (avionics) must start.) Identical pairs of conditional branches as described in the paragraph above are used to route the entity to either unscheduled or scheduled maintenance. When the scheduled maintenance on the avionics system is done, the vehicle entity is routed back to another goon node for the same conditional branching to determine subsequent maintenance.

The life support, mechanical, propulsion, thermal, and auxiliary systems are the last systems in series (see figure 4). For each of these systems, a dummy entity is routed from its scheduled maintenance subroutine back to one of five queue nodes in the Primary Operation and Processing section when the scheduled maintenance is complete. This waiting entity signifies that all on-vehicle maintenance is done on all of the systems in that particular series. The vehicle is ready for another mission, i.e., on-vehicle maintenance is complete on all of the nine systems, when all five systems have an entity waiting in their respective queue node as confirmed by a match node.

Once a match is made, an entity goes to an assign node to calculate the duration of all of the on-vehicle maintenance activities (XX(95) = current time minus time just before maintenance starts). Recall that this time is in continuous working hours and is changed to days based on the number of hours (shifts) worked per day by dividing the duration by either 8, 16, or 24 hours for one, two, or three shifts respectively. The 'collect node' displays the mean value and a histogram of the duration times in days on the output report. Similarly the turnaround time, which is the elapsed time for a vehicle being assigned to one mission and then to being available for the next, is calculated and displayed. The entity is then routed back to the vehicle 'queue node' where it waits to be assigned to another mission.

(2) System Maintenance Subroutines

There are three maintenance subroutines for each system: on-vehicle unscheduled, scheduled, and off-vehicle unscheduled (refer to figure 6). Within each subroutine, maintenance actions are modeled by resources and activities. Modeling maintenance this way allows for multiple resources (crews) to be used.

If at least one failure occurs for a system during the mission, a vehicle entity is sent from the Primary Operation and Processing section to the system's on-vehicle unscheduled maintenance subroutine. The attribute storing the number of failures is decremented by one at an assign node. Three activities emanate from that node. The first activity is always taken by the entity; this activity sends one entity to wait for a resource (crew) at an await node. A duplicate entity takes one of the remaining two branches depending upon which condition is met. If there is one or more failures remaining (attribute value greater than 0), the entity is routed back to the assign node so that another entity is sent to the await node. This cycle continues until one entity for each failure (attribute value equals 0) has been sent to the await node. Now an entity takes the other branch to an await node in the scheduled maintenance subroutine so that scheduled maintenance is initiated after the on-vehicle unscheduled maintenance is complete.

The failure entities at the await node seize a resource as soon as one is available. The entity then takes one of two activities which simulate the on-vehicle maintenance. The first activity is a maintenance action which results in removal of a component when no spare is available. In this case, the removed component is repaired immediately and

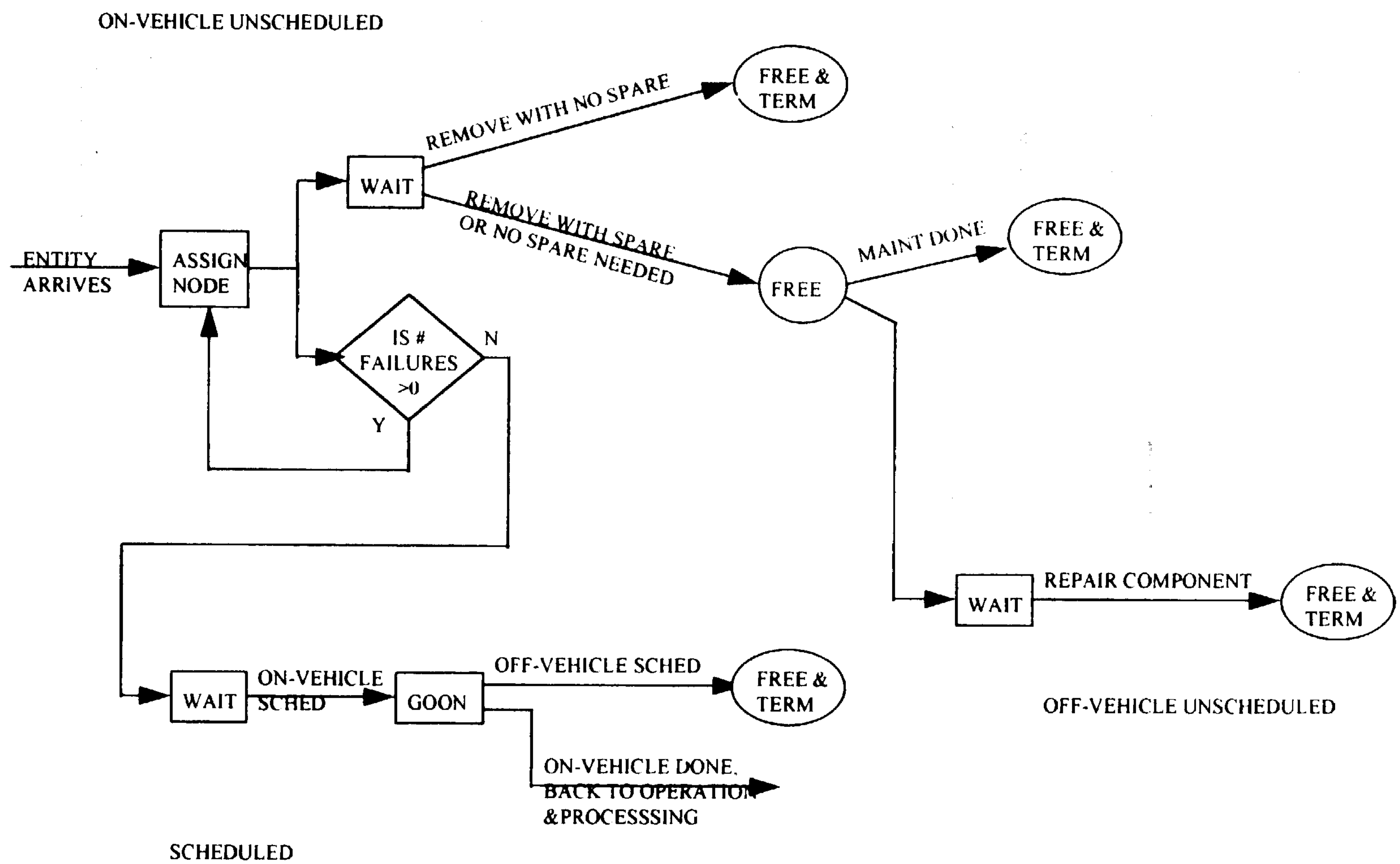

FIGURE 6: SYSTEM MAINTENANCE SUBROUTINES

reinstalled on the vehicle. The probability of this occurring is calculated by the Reliability and Maintainability Model and is user input. The duration of this activity is the sum of the times to remove, replace, and repair the component. Removing and replacing a component is considered a typical on-vehicle unscheduled maintenance action; its duration is lognormal with mean equal to the system's on-vehicle unscheduled MTTR value and variance equal to .29 times the mean (Lewellen, 18). Repair of the component is considered an unscheduled off-vehicle maintenance action; its duration is exponential with mean equal to the system's off-vehicle unscheduled MTTR. When this maintenance action is complete, the resources are freed and the entity is terminated.

The other activity represents all other possible maintenance actions, i.e., spare is available or not needed. These actions are typical on-vehicle unscheduled maintenance actions so their durations are lognormal as described above. The resources are freed at the completion of the activity. The entity then takes one of two branches. One branch represents a component that was removed, replaced with a spare, and needs to be repaired. It sends the entity to the off-vehicle unscheduled maintenance subroutine. The other branch represents a completed maintenance action so it sends the entity to a terminate node. The probabilities for taking these branches are calculated by the Reliability and Maintainability Model and are user input.

As soon as there are no entities waiting for on-vehicle unscheduled maintenance and the user specified number of resources are available, the entity that was sent by the unscheduled on-vehicle maintenance subroutine to the await node in the scheduled maintenance subroutine seizes the resources so that the on-vehicle scheduled maintenance is performed. The number of resources (crews) that perform scheduled maintenance is user input and is a critical variable in determining the minimum number of crews as will be described in Chapter 4. The total number of hours to complete the on-vehicle scheduled maintenance is calculated by the Reliability and Maintainability Model and is user input. The duration of the maintenance activity is calculated automatically by the model as the number of hours divided by the number of resources. For example if 15 hours (XX(21)) are required to complete scheduled maintenance and 3 resources (XX(71)) will perform the maintenance, the duration of the activity will be XX(21)/XX(71)=5 hours.

When the maintenance activity is complete, the entity is duplicated so there are two entities. One entity goes back to the Primary Operation and Processing section. It goes either to a goon node so maintenance of the next system is initiated or, if the current system is the last in the series, to a queue node to wait until all of the systems' maintenance is done. The other entity takes an activity with duration equal to .02 times the scheduled maintenance duration and then frees the resources. This activity represents the off-vehicle scheduled maintenance. Note that this activity only affects the resource utilization and not the vehicle turnaround time.

Lastly, the entities that are waiting at the off-vehicle unscheduled maintenance subroutine seize the resource(s). The off-vehicle unscheduled maintenance is performed on the removed components. The duration of the off-vehicle unscheduled maintenance is exponential with mean equal to the system's off-vehicle unscheduled MTTR. Once a maintenance action is complete, the resource is freed and the entity is terminated. Again, note that this activity only affects the resource utilization and not the vehicle turnaround time.

One important feature of the code is the definition of the resources. The number of resources available can be defined. Also the order in which the resources are to be allocated can be specified. Each await node has a unique numerically designated file associated with it that stores the entities waiting at the node. These file numbers must be specified in the resource definition statement. The order of the file numbers is the order that available resources will be allocated. For example, entities waiting at the unscheduled maintenance node for the power system (file 1) are allocated resources before entities waiting at the scheduled maintenance node (file 2). This feature assures that the proper maintenance sequence is followed.

(3) User Input

Most of the user input values will be input as global variables into the 'control file'. Global variables are variables that store values input by the user until they are specifically changed through reassignment within the 'network program'. The values for the global variables are obtained from the Reliability and Maintainability Model. The table on the next page lists the global variable names and the corresponding Reliability and Maintainability Model output values.

The other values a user will most likely input are the number of resources available and the number of vehicles created at the start of the simulation. Both of these values are entered into the Primary Operation and Processing section of the network file. The resource definition block at the beginning of the file lists the resources; the number

GLOBAL VARIABLES	RELIABILITY AND MAINTAINABILITY PROGRAM OUTPUT
XX(1)-XX(9)	System On-vehicle Unscheduled MTTR
XX(11)-XX(19)	System On-vehicle Unscheduled MTTR Variance*
XX(21)-XX(29)	System On-vehicle Scheduled MTTR
XX(31)-XX(39)	System Mean Maintenance Actions per Mission
XX(41)-XX(49)	System Off-vehicle Unscheduled MTTR
XX(51)-XX(59)	System Probability of Removal & No Spare Available
XX(61)-XX(69)	System Probability of Removal & Spare Available
XX(71)-XX(79)	Number of Crews for Scheduled Maintenance
NHRS	Number of Hours Worked per Day
NDAYS	Number of Days Worked per Week
NMISSION	Number of Missions Planned per Year
INTEGRATION	Integration Time in Hours
PADPROC	Pad Processing Time in Hours
MISSION	Mission Time in Hours
SAFING	Safing Time in Hours
MISRELIABILITY	Mission Redundant Reliability

* these values calculated by user as sqrt(.29*MTTR)

Table 1: Global Variable Definition

available is in parenthesis. Enter the number of vehicles in the last field of the vehicle create node.

Once all of the necessary input values have been entered. The simulation can be run. A detailed description of running the model and reading the output reports for a specific set of inputs is presented in Chapter 4.

CHAPTER IV

RUNNING THE SIMULATION MODEL

The minimum number of vehicles and maintenance crews needed to meet the required mission rate can be estimated by repeatedly running the Simulation Model. A discussion of the information available in the output reports, guidelines for running the model, the results of a case study in which the model was run with real data obtained from the Reliability and Maintainability Model, and simple user modifications and limitations of the model are presented in this chapter.

A. Output Reports

An output report is automatically produced for each simulation run (Appendix B). The output report provides very useful information for deciding what adjustments to the resources need to made.

The initial statistics at the top of the output report give the mean maintenance repair time and the mean turnaround time. Also listed is the number of observations used in calculating the mean times, i.e., the number of missions successfully completed. If the number of missions completed is less than expected, the number of 'available resources' for at least one resource was too low. For example, if 28 missions are required each year, then 140 missions would be expected in a five year period. Note that if the integration, pad processing, mission, and safing times are all deterministic, the turnaround times will be equal to a constant (the sum of the integration, pad processing, mission, and safing times) added to the maintenance repair times. The histograms of the maintenance repair and turnaround times at the end of the report will show this clearly.

The next output is a set of statistics for all of the await and queue nodes. The average wait times for these nodes provide very useful information. The average wait time for Q1 is the average time a mission had to wait for a vehicle. If there is a wait time (i.e., greater than zero), some missions were not started at their scheduled time. Likewise, if there is an average wait time for Q2, some vehicles were available before missions were scheduled. The queues labeled Q3-Q7 hold the entities routed to signify that on-vehicle maintenance for the last system in a series has been completed. A large average wait time for anyone of these nodes means that the systems in the corresponding series completed maintenance before other systems and can have resources removed. Similarly, a node that has a small average wait time indicates that the systems in that series took a long time to complete maintenance. These systems were the last to complete maintenance and therefore prolonged the vehicle's maintenance time. These systems may need to have resources added.

Utilization statistics and the entity counts for the on-vehicle unscheduled, scheduled, and off-vehicle unscheduled maintenance activities for each subsystem, for the successful missions, and for missions with critical failures are available. The number of critical failures is useful for assessing the appropriate number of resources given the user's tolerance of risk. For example, a given number of resources may be sufficient to meet the required missions as long as there are 2 or fewer critical failures. If the user feels that 3 or more critical failures will not happen, he or she may risk not meeting the mission requirement by using that level of resources even though 3 or more critical failures are probabalistically possible.

Resource utilization statistics are listed on the output report for each of the systems. The maximum utilization rate may be helpful during the initial stages of resource allocation. If an early run of the model is made with a large number of resources, not all of the resources will be used. The maximum utilization values can then be used for the initial resource (maintenance crews) capacities and then reduced.

B. Guidelines

The minimal number of vehicles and crews is determined by running the model with a set of inputs, reviewing the output report, adjusting the inputs, and then rerunning the model. Number of crews available for each system, number of vehicles, and number of crews assigned to scheduled maintenance are the inputs to the Simulation Model which are repeatedly changed. The number of critical failures has the biggest impact on the number of resources required and the ability to meet the needed mission rate. For a given crew capacity the destruction of one vehicle can greatly reduce the number of completed missions because the turnaround time is not fast enough to complete maintenance on the remaining vehicles in time to meet the scheduled mission dates. It is best to run the model with the NNRNS field of the GEN statement in the control file set at 5 or more so that replications with different random variable seeds (and, therefore, varying numbers of critical failures) are obtained each time the model is run.

First, the output from the Reliability and Maintainability Model is entered into the control file as described at the end of Chapter 3. The number of crews assigned to perform scheduled maintenance (the XX(7_) global variables) and the number of vehicles is set to one. The number of available resources for each system is set at 99. Setting the number at 99 assures that all requests for resources will be immediately met so that there is no waiting time. The resulting turnaround time will be the shortest possible with only one resource performing the scheduled maintenance.

Once all of the input has been entered, the model is run. Adjustments are then made to the inputs based on review of the output reports and user insight. In order to understand the affect input changes have on the output, only one of the inputs is changed at a time.

With the input described above, the maintenance turnaround times will be very short. Therefore, an estimate for the minimum number of vehicles (recall only one resource is assigned to scheduled maintenance) is obtained first. The number of vehicles is increased by one until the required mission rate is met for each of the replications. If the number of completed missions is too low or at least one missions had to wait for a vehicle (average wait time for Q1 not equal to 0) the required mission rate is not met. This criteria will be used to judge all changes to the inputs.

The number of available crews is then reduced. The objective is to reduce the total number of crews to as few as possible without missing or delaying any missions. The number by which to reduce is determined by trial and error, but the average wait times for queues labeled Q3-Q7 help identify which systems' crew availability can be reduced. The systems associated with queues with long average wait times completed maintenance before other systems; these systems' crews can be reduced. For example, if only Q3 has a long wait time, the number of Life crews can be reduced. If Q3, Q4, and Q5 have long wait times, the number of Power and Avionics crews can be reduced. In the former example, only the number of Life crews can be reduced because it is the last system in a series and its previous systems (Power and Avionics) are in series with other systems (Mech and Prop). Reducing the number of Power and Avionics crews will increase the times the Mech and Prop systems complete maintenance. In the latter example, the number of Power and Avionics crews are reduced because all the systems in series with these systems (Life, Mech, and Prop) completed maintenance early. Future runs would then indicate if any of the number of crews for the Life, Mech, and Prop systems can be reduced as in the first example.

The mean number of maintenance actions per mission and on-vehicle MTTR values can also indicate which systems' number of available crews can be reduced. Systems with few maintenance actions and short MTTR values will complete maintenance in less time than other systems. The number of available crews for these systems can be reduced. For example, if the Avionics system has .05 maintenance actions per mission, on-vehicle unscheduled MTTR equal to 2 hours, and on-vehicle scheduled MTTR equal to 1 hour, its maintenance time will be extremely short relative to the other systems so its number of available crews can be reduced. Again, the number of crews is determined by trial and error.

Once the minimum number of available crews has been determined, the number of crews assigned to perform scheduled maintenance is increased to reduce the scheduled maintenance duration. More than one crew should be assigned to the systems with the longest on-vehicle scheduled MTTR values. A heuristic method to estimate the number assigned is to divide the on-vehicle scheduled maintenance MTTR by the on-vehicle unscheduled MTTR. For example, if the Therm system's unscheduled MTTR is 15 hours and scheduled MTTR is 60 hours, 4 crews should be assigned (XX(75=4)) so that the scheduled maintenance duration is 15 hours (60/4). The rationale for why this method works is given on page 39.

If a system's scheduled maintenance duration is significantly reduced, it will complete maintenance before other systems. The crews of some of these systems may have to be **increased**. For example, it may be possible to reduce the number of Therm crews available by 3 as the number assigned to perform scheduled maintenance is increased from 1 to 4. The Aux system may then become the last system to complete maintenance (small average wait time for Q7). One crew may need to be added to the Aux system to shorten its maintenance duration so that the desired mission rate is met. However, there is still a net reduction of two crews. Again, making changes to the number of crews and the allocation of those crews by trial and error is necessary to establish the minimal number of crews.

Once it is determined that additional crew reductions cause the number of missions completed to be too low or missions to wait for a vehicle, the minimal number of crews for the current number of vehicles is established. The maintenance durations and turnaround times of the vehicle are also minimized. If the maintenance durations are short enough, it may be possible to reduce the number of vehicles. The model is run again with the number of vehicles reduced by one. If the mission rate is met for all of the replications, one less vehicle is needed. If the mission rate is met for all replications except those with a large number of failures, the user may accept the risk and decide to use one less vehicle knowing there is a real, although small, chance that the mission rate will not be met. Alternatively, the user may run the simulation more adding crews and changing the number assigned to scheduled maintenance until the mission rate is met for all replications. The user has to make tradeoff studies of the cost of one additional vehicle and the assurance the mission rate will be met versus the savings one vehicle and the cost of additional resources for the assurance that the mission rate will be met.

C. Case Study

The simulation model was used to determine the minimum number of crews and vehicles needed to meet the mission requirements for a vehicle named "SSTOW". The Reliability and Maintainability Model was run with the vehicle's design parameters to obtain the simulation input (figure 7). This input was entered into the control file (Appendix A). The number of working hours, days, and years were also entered into the control file. It was assumed that crews would work one 8-hour shift 5 days per week for 5 years. The input into the control file was NHRS=8, NDAYS=5, and NYRS=5.

The model was run initially with 99 crews available for each system, 1 crew assigned to perform scheduled maintenance, and 1 vehicle. The number of missions

SIMULATION INPUT REPORT

OUTPUT FROM RAM MODEL
VEHICLE IS SSTOW   DATE: 09-12-1994   TIME: 04:41:55

Subsys	Maint Actions Per Mission	On-Veh MTTR in hours	Off-veh MTTR in hours	Prob-Rem
Structural	2.65186	2.924435	.2723976	.2517892
Fuel/Oxid Tanks	5.348793	10.05298	0	.1845534
Thermal/Tiles	26.6948	13.59266	0	.1456551
Propulsion	84.22968	2.406619	6.276508	.2074564
Power/Electrical	2.240062	9.743523	.5522666	.5032578
Mechanical Sys	3.752104	.6054564	.2341774	.3130305
Avionics	3.100063E-02	1.840963	.6621949	.6565623
ECS/Life Support	3.197754	3.252513	.3342901	.4288046
Auxiliary Systems	2.67297	10.05298	0	.3230138

Subsys	Removal & No spare	On-Veh Sched MTTR	Off-Veh Sched MTTR	AVG CREW SIZE
Structural	.0105865	8.664279	.176822	2.122753
Fuel/Oxid Tanks	8.200002E-03	17.47582	.3566493	2.122753
Thermal/Tiles	6.69142E-03	41.14294	.8396518	4.5
Propulsion	9.042779E-03	240.4031	4.906185	2.43
Power/Electrical	.0176199	4.870956	9.940727E-02	3.547937
Mechanical Sys	1.254753E-02	12.25904	.2501846	2.122753
Avionics	2.086002E-02	9.862685E-02	2.012793E-03	2.18
ECS/Life Support	1.579549E-02	9.571705	.1953409	2.317058
Auxiliary Systems	.01285	8.733248	.1782295	2.122753

Launch Reliability	.9996665
Mission Redundant Reliability	.9896423
Integration Time - days	0
Pad Time - days	.5
Mission Time	72
Planned missions per Year	28
Fill rate objective	.95

Figure 7 : Case Study Input

completed was less than the required 28 missions per year. The number of available vehicles had to be increased to 4 to ensure that the required number of missions was met with no missions waiting for a vehicle (average wait time for Q1=0) for 7 replications (each with different random number seeds for varying numbers of critical failures). The mean turnaround time was 15.9 days. One of the output reports is in Appendix B.

The number of crews for each system was then reduced from 99 to the 'maximum number utilized' listed in the output. The number of crews was further reduced for the systems associated with the queue nodes labeled Q3-Q7 that had long average wait times. For example, queue nodes Q3 and Q4 had average wait times over 60 hours. The number of crews for the Life and Mech systems was reduced to 1 by repeatedly running the model with fewer crews for each run. Crews were removed from each system with long wait times in this manner.

Crews were also removed from systems with small average wait times for their associated queue node. It is important to note that incurring some wait time at nodes Q3-Q7 is not a problem as long as maintenance is completed quickly enough that no missions ever have to wait for a vehicle. In other words, reducing the number of crews may increase the turnaround time but that is acceptable if the mission rate is still met. The following table lists the minimum values for number of crews and the average wait times for queue nodes Q3-Q7 with 1 resource assigned to scheduled maintenance, and an output report is in Appendix C:

SYSTEM	NBR OF CREWS	AVG WAIT TIME
Power	1	
Structure	1	
Tanks	2	
Avionics	1	
Thermal	25	Q6: 22 hours
Aux	1	Q7: 2 hours
Life	1	Q3: 63 hours
Mech	1	Q4: 67 hours
Propulsion	16	Q5: 7 hours

Table 2: Minimum Crews with 4 Vehicles and 1 Scheduled Maintenance Crew

The turnaround time for this vehicle was 19.8 days, but the mission rate was met for each of 7 replications.

The number of crews assigned to perform scheduled maintenance on each system was then increased to reduce the scheduled maintenance duration. If a system's scheduled maintenance duration is significantly reduced, fewer crews are needed to keep that system's mean maintenance duration the same; the duration of the unscheduled maintenance can increase by the amount the scheduled maintenance is reduced. Only the Tanks, Therm, and Prop systems had more than 1 crew available. (These systems were the last to complete maintenance as they had the shortest wait times in the above table.) The first estimate for the number of crews to be assigned to perform scheduled maintenance was determined by dividing the scheduled maintenance MTTR by the unscheduled MTTR. The values for the Tanks, Therm, and Prop systems were calculated as 30/10=3, 70/13=5, and 83/2=40. Note that the resulting numbers for the Tanks, 3, and the Prop, 40, systems were greater than the number available. Therefore, the numbers assigned were the numbers available, 2 and 5. Adjusting the values for number assigned and number available for repeated runs of the model resulted in the following minimum resource values:

SYSTEM	NBR OF CREWS	NBR ASSIGNED
Power	1	1
Structure	1	1
Tanks	3	2
Avionics	1	1
Thermal	8	5
Aux	1	1
Life	1	1
Mech	1	1
Propulsion	5	5

Table 3: Minimum Crews with 4 Vehicles and Optimum Scheduled Maintenance Crews

The number of crews available for the Therm and Prop systems were greatly reduced. However, the number of crews available for the Tanks system had to be increased because for one replication it became the last system to complete maintenance (Q7=0) and caused mission waiting time (Q1>0). An output report for these inputs is in Appendix D.

Typically, the final values for number of crews available and assigned can be justified. The mean number of maintenance actions for the Therm system is 27. On average, 24 unscheduled maintenance actions are completed continuously by the 8 crews and then 3 crews complete the remaining unscheduled maintenance actions while 5 crews perform the scheduled maintenance. In this case, all 8 crews will finish maintenance at about the same time since the unscheduled MTTR and the scheduled maintenance duration with 5 crews are nearly equal. This observation led to the heuristic method for estimating the number of crews assigned described on page 34.

The turnaround time was reduced to 15.8 hours, nearly the same time for the first run with the crew availability set at 99, by assigning more than 1 crew to scheduled maintenance. Four vehicles had initially been needed to ensure that the mission rate was met; the mission rate had been met with 3 vehicles for all the replications except those with 3 critical failures. Therefore, crews were added back into the model and the values for the number assigned to scheduled maintenance were adjusted to see if the turnaround time could be reduced further so the mission rate could be met with only 3 vehicles. The following values for number of crews available and assigned to scheduled maintenance resulted from repeated runs of the model. The turnaround time was reduced to 9 days as seen in the output report in Appendix E.

SYSTEM	NBR OF CREWS	NBR ASSIGNED
Power	3	2
Structure	3	3
Tanks	6	5
Avionics	1	1
Thermal	22	10
Aux	3	2
Life	3	2
Mech	2	2
Propulsion	10	8

Table 4: Minimum Crews and Scheduled Maintenance Crews with 3 Vehicles

Once the minimal number crews and vehicles has been determined, decisions based on cost, risk tolerance, and practicality must be made. The outputs of the simulation model can be input into the Life Cycle Costing Model to determine if it is cheaper to have 3 vehicles and more crews or 4 vehicles and fewer crews. Fewer crews can be used if the user believes that there will not be a lot of critical failures even though probabalistically possible. The user must establish his or her risk tolerance by examining the consequences of not meeting the mission rate. Lastly, the number of crews that can actually work on the vehicle concurrently must be considered. For this example, if this vehicle is small, 22 Therm crews may not be able to work on the vehicle at the same time to perform unscheduled maintenance. Some adjustments to the model can be made to obtain additional data that may help the user make resource decisions.

D. Modifications and Limitations

The simulation was designed so that a user with some knowledge of SLAM could modify the code so that it more accurately models the real vehicle and its intended operation. The user may want to modify the times at which vehicles are available, the durations of the integration, pad processing, mission, and safing activities, and the statistics collected.

The model has been used to simulate the vehicle over a fixed life cycle with all of the vehicles available at the start of the simulation. If the model is to be used to simulate vehicles being introduced into service over a period of time, a value is entered into the time between creations field of the vehicle create node. For example, if 1 vehicle is to be manufactured each year until a total of 4 vehicles are available, the vehicle create node in the network file is changed to

CREATE,2080,0,,4.

Note that 1 year is calculated in working hours. If one 8-hour shift is worked 5 days each week, the number of working hours is

8 hours/day * 5 days/week * 52 weeks/year =2080 hours/year.

The duration times for the integration, pad processing, mission, and safing activities are deterministic. It may be more realistic to model the durations with a probability distribution. For example, the mission duration for the case study discussed above could be changed from 72 hours to a value determined from a normal distribution with mean equal to 72 and variance equal to .29 times the mean. The activity statement in the network file is changed to

ACT,RNORM(XX(80),XX(81)),MISRELIABILITY;

where the global variables XX(80) and XX(81) are the mean and standard deviation calculated by

XX(80)=MISSION/24*NHRS and XX(81)=SQRT(.29*XX(80)).

These global variables can be entered into the network file at an assign node prior to the activity or into the control file with an 'intlc' statement.

Modifications to the model can also be made to calculate additional statistics. If the maintenance duration of a specific system is needed, two assign nodes and a collect node are added. For example, the mean maintenance duration of the Therm system can be calculated by replacing the goon node labeled B25 with an assign node which assigns TNOW to an attribute. An assign node and collect node like the ones used to calculate the mean vehicle maintenance duration and turnaround time are added before the queue node labeled Q6; the label is moved to the assign node. After the scheduled maintenance is completed on the Therm system, the entity is routed to the assign node where the time stored in the attribute (the time maintenance on the system starts) is subtracted from the current time (the time maintenance on the system ends). The entity is then routed to the colct node for calculation of the mean Therm maintenance duration and to the queue node.

A limitation of the model is the wait time that is incurred while one or more crews wait for the required number of crews to become free so scheduled maintenance can start. Each system's scheduled maintenance await node has a global variable XX(7_) in the RES/UR field so that an entity at the node must wait until XX(7_) crews are free. In reality, if a crew is no longer needed for unscheduled maintenance, it would immediately start scheduled maintenance. It would not wait until XX(7_) crews are free. However, the inaccuracy introduced into the turnaround times and mission completion rate because of this limitation appears to be small and is on the conservative side. As discussed earlier, the minimum number of crews and the number assigned to scheduled maintenance for each system typically make sense. For example, 6 crews are needed with 5 assigned to scheduled maintenance for the Tanks system if only 3 vehicles are available. The mean number of unscheduled maintenance actions for the Tanks system is 5.3. On average, the 6 crews will be able to start working on all of the maintenance actions simultaneously and they will finish around the same time. Then 5 of the crews can start the scheduled maintenance. If for a particular run there were 7 unscheduled maintenance actions, the 6th crew will start the 7th maintenance action (while the other 5 crews start the scheduled maintenance). In this case not a lot of wait time was incurred while the entity at the scheduled maintenance node waited for 5 crews to become free. Similar justifications can be made for other systems' values for the number of crews available and assigned to scheduled maintenance.

CHAPTER V

CONCLUSION

A description of the SLAM II model designed to simulate the operation and processing of proposed space vehicles and a discussion of its use for determining vehicle and manpower requirements for a specific vehicle and mission plan has been presented. Remaining issues for discussion include model verification and validation and additional user insights for effective use of the model.

A. Model Verification and Validation

There are two methods to verify that the model operates properly. First, the mean turnaround time can be calculated by hand from the input table (figure 7). If only 1 crew is available for each system, all of a system's unscheduled maintenance will be completed in series before the scheduled maintenance. A system's mean unscheduled maintenance duration is calculated by multiplying its maintenance actions per mission by its on-vehicle unscheduled MTTR. The resulting values are then added for each sequence in figure 3. For example, the unscheduled maintenance duration of the Power, Avionics, and Life sequence for the data in figure 7 is 21.3 + .05 + 10.3 or 31.7 hours total. The scheduled maintenance durations are also added for each sequence. For example, the scheduled maintenance duration for the Tanks and Aux sequence is 29.7 + 14.8 or 44.5 hours total. Adding a sequence's unscheduled and scheduled maintenance durations results in the total maintenance duration for that sequence. The largest of the sequence maintenance durations is the time at which the vehicle completes maintenance. For example, the unscheduled and scheduled maintenance durations for the Struc and Therm sequence are 363 and 84.7 hours respectively. Therefore, the total maintenance duration for this sequence is 363 + 84.7 or 447.7 hours. This is the longest total maintenance duration for a sequence so the vehicle will complete maintenance, on average, in 447.7 hours. This time is compared to the mean maintenance duration calculated by the model with one vehicle, one crew for each system, and mission reliability of 1. For these inputs, the model computes a mean maintenance duration of 451 hours which is within 1 percent of 447.7 hours. Therefore, the model operates as expected.

Numerous statistics are calculated and available on the output reports. These statistics can also be used to verify that the model is operating properly. For example, the output report lists the number of failures as the entity count for the critical failure activity. If the critical failure rate is 1-.989 and 140 missions are scheduled, one or two critical failures are expected (140x(1-.989)=1.54). The number of failures for all runs during the case study analysis were always between 0 and 3 (reasonable values). As another example, the entity count for a system's scheduled maintenance activity should equal the number of missions successfully completed. This was true for all of the case study runs. Examining the statistics in this way can also help in determining if the model responds to user input changes as expected.

The model has not been validated. Validation of a simulation model compares the output of the model to actual 'output' data. Actual data was not available for this effort. Consequently, it would be very worthwhile to obtain space shuttle maintenance personnel data to perform validation.

B. Additional User Insights

The critical failure rate is the most significant factor in estimating the number of vehicles and crews required to met the planned mission rate. Therefore, it may be more insightful to run the model without critical failures (probability of successful mission equal to one). Contingency plans can be established to account for the real probability that one or more vehicles would have a catastrophic failure. These plans may include temporarily bringing in crews from other space vehicle or aircraft programs to shorten the maintenance duration or manufacturing an additional vehicle at some established future date as a potential replacement for a destroyed vehicle. The user can run the simulation to model these contingency plans to determine their effect on meeting the mission rate.

As discussed earlier, the weather has not been explicitly considered in the model. In some cases weather may significantly affect the number of resources required to meet the mission rate. Code can be added to the model to simulate the effects of weather. Weather can be considered as another resource that a vehicle must seize for both launch and landing. The availability of the weather resource can be determined by probability distribution and 'alter' nodes in a separate portion of code. As in the case of critical failures, the model can be run without the weather code to establish an ideal number of resources and then run with the weather code to establish contingency plans.

Lastly, it is important to remember that the simulation model is a tool to be used in conjunction with the Reliability and Maintainability Model and Life Cycle Costing Model to **estimate** maintainability and operational parameters. Since the output of the Reliability and Maintainability Model is input into the simulation model, it is important that the user understand the limitations and assumptions of the Reliability and Maintainability Model to avoid making inaccurate interpretations of the simulation output. Refer to "Enhanced Methods for Determining Operational Capabilities and Support Costs of Proposed Space Systems" (Ebeling) for a discussion of the Reliability and Maintainability Model.

Appendix A

```
;NETWORK FILE
;
;START OPERATION AND PROCESSING SECTION
;
        RESOURCE/POWER(3),1,2,3;     SYSTEM IDENTIFICATION NUMBER- 1
        RESOURCE/STRUC(3),4,5,6;                                   2
        RESOURCE/TANKS(6),22,23,24;                                3
        RESOURCE/AVION(1),10,11,12;                                4
        RESOURCE/THERM(22),7,8,9;                                  5
        RESOURCE/AUX(3),25,26,27;                                  6
        RESOURCE/LIFE(3),13,14,15;                                 7
        RESOURCE/MECH(2),16,17,18;                                 8
        RESOURCE/PROP(10),19,20,21;                                9
;
        CREATE;
        ASSIGN,XX(84)=52*NDAYS*NHRS/NMISSION; NBR WORK HRS B/N MISSIONS
        ASSIGN,XX(85)=NYRS*52*NDAYS*NHRS;     NBR WORK HRS FOR SIMULATION
        ACT,XX(85);                           SIMULATION DURATION
        TERM,1;                               STOP SIMULATION
;
        CREATE,XX(84);              CREATE MISSIONS EVERY XX(84) HRS
        ASSIGN,ATRIB(10)=1;
Q1      QUEUE(28),,,,M1;            (ENTITIES WAIT FOR VEHICLE)
        CREATE,0,,,3;               CREATE VEHICLES AT TIME=0
        ASSIGN,ATRIB(10)=1;
Q2      QUEUE(29),,,,M1;            (ENTITIES WAIT FOR MISSION)
M1      MATCH,10,Q1,Q2/A1;          ONLY CONTINUE IF VEHICLE AND MISSION
;
A1      ASSIGN,ATRIB(12)=TNOW;                SET START TIME FOR TURN CALC
        ASSIGN,ATRIB(1)=NPSSN(XX(31));        NBR FAILURES FOR POWER SYS
        ASSIGN,ATRIB(4)=NPSSN(XX(34));        NBR FAILURES FOR AVION SYS
        ASSIGN,ATRIB(7)=NPSSN(XX(37));        NBR FAILURES FOR LIFE SYS
        ASSIGN,ATRIB(8)=NPSSN(XX(38));        NBR FAILURES FOR MECH SYS
        ASSIGN,ATRIB(9)=NPSSN(XX(39));        NBR FAILURES FOR PROP SYS
        ASSIGN,ATRIB(2)=NPSSN(XX(32));        NBR FAILURES FOR STRUC SYS
        ASSIGN,ATRIB(5)=NPSSN(XX(35));        NBR FAILURES FOR THERMAL SYS
        ASSIGN,ATRIB(3)=NPSSN(XX(33));        NBR FAILURES FOR TANKS SYS
        ASSIGN,ATRIB(6)=NPSSN(XX(36));        NBR FAILURES FOR AUX SYS
;
        ACT,INTEGRATION;                      INTEGRATION PROCESSING HRS
        GOON;
        ACT,PADPROC;                          PAD PROCESSING HRS
        GOON;
        ACT/29,,1-MISRELIABILITY,C1;               CRIT FAIL GO TO C1
        ACT/28,MISSION/24*NHRS,MISRELIABILITY;     SUCCESSFUL MISSION
        GOON;
        ACT,SAFING;                           SAFING HRS
;
;           MAINTENANCE SEQUENCE FOR THE SYSTEMS:
;               1             2              3  (1,2&3 IN PARALLEL,ETC)
;               4             5              6
;           7   8   9                           (1,4&7 IN SERIES,ETC)
;
;START MAINT ON FIRST SYSTEMS (1,2&3)
        ASSIGN,ATRIB(11)=TNOW;      SET START FOR REPAIR TIME CALC
        ACT,,ATRIB(1).GE.1,REP1;    GO TO REP1 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(1).EQ.0,SCH1;     GO FOR SCH MAINT ONLY (POWER)
        ACT,,ATRIB(2).GE.1,REP2;    GO TO REP2 FOR REPAIR AND SCH MAINT
```

```
        ACT,,ATRIB(2).EQ.0,SCH2;     GO FOR SCH MAINT ONLY (STRUC)
        ACT,,ATRIB(3).GE.1,REP3;    GO TO REP6 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(3).EQ.0,SCH3;     GO FOR SCH MAINT ONLY (TANKS)
;
B14     GOON;                 MAINT ON SYSTEM 1 DONE, START SYSTEM 4
        ACT,,ATRIB(4).GE.1,REP4;    GO TO REP4 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(4).EQ.0,SCH4;     GO FOR SCH MAINT ONLY (AVION)
;
B25     GOON;                 MAINT ON SYSTEM 2 DONE, START SYSTEM 5
        ACT,,ATRIB(5).GE.1,REP5;    GO TO REP5 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(5).EQ.0,SCH5;     GO FOR SCH MAINT ONLY (THERMAL)
;
B36     GOON;                 MAINT ON SYSTEM 3 DONE, START SYSTEM 6
        ACT,,ATRIB(6).GE.1,REP6;    GO TO REP6 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(6).EQ.0,SCH6;     GO FOR SCH MAINT ONLY (AUX)
;
B4789   GOON;              MAINT ON SYSTEM 4 DONE, START SYSTEMS 7,8&9
        ACT,,ATRIB(7).GE.1,REP7;    GO TO REP7 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(7).EQ.0,SCH7;     GO FOR SCH MAINT ONLY (LIFE)
        ACT,,ATRIB(8).GE.1,REP8;    GO TO REP7 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(8).EQ.0,SCH8;     GO FOR SCH MAINT ONLY (MECH)
        ACT,,ATRIB(9).GE.1,REP9;    GO TO REP9 FOR REPAIR AND SCH MAINT
        ACT,,ATRIB(9).EQ.0,SCH9;     GO FOR SCH MAINT ONLY (PROP)
;
;ONE ENTITY FOR EACH LAST SYSTEM IN A SERIES (5,6,7,8&9) DONE WITH
;ON-VEHICLE MAINT IS SENT TO A QUEUE TO WAIT UNTIL ALL SYSTEMS DONE.
Q3      QUEUE(30),,,,M2;           LIFE MAINT ON-VEH COMPLETE
Q4      QUEUE(31),,,,M2;           MECH MAINT ON-VEH COMPLETE
Q5      QUEUE(32),,,,M2;           PROP MAINT ON-VEH COMPLETE
Q6      QUEUE(33),,,,M2;           THERM MAINT ON-VEH COMPLETE
Q7      QUEUE(34),,,,M2;           AUX MAINT ON-VEH COMPLETE
M2      MATCH,10,Q3,Q4,Q5,Q6,Q7/A2;   ALL VEHICLE MAINT DONE
;
;CALC. STATISTICS FOR ON-VEHICLE MAINT DURATION AND TURN TIME IN DAYS
;BY DIVIDING DURATION IN HOURS BY NHRS (NBR HRS WORKED/DAY).
A2      ASSIGN,XX(95)=TNOW-ATRIB(11),XX(95)=XX(95)/NHRS;
        COLCT,XX(95),MEAN MAINT TIME IN DAYS,10/6/2;
        ASSIGN,XX(96)=TNOW-ATRIB(12),XX(96)=XX(96)/NHRS;
        COLCT,XX(96),MEAN TURN TIME IN DAYS,10/10/2;
;
;VEHICLE READY FOR ANOTHER MISSION, ROUTE ENTITY BACK TO VEHICLE QUEUE
        ACT,,,Q2;
;
;FOR CRITICAL FAILURES, MISSION STILL NEEDED SO 1 ENTITY ROUTED TO
;MISSION QUEUE AND NEW VEHICLE MADE SO 1 ENTITY ROUTED TO VEHICLE
;QUEUE WITH DURATION OF 1 YEAR.
C1      GOON;
        ACT,,,Q1;
        ACT,52*NDAYS*NHRS,,Q2;
;
;END OPERATION AND PROCESSING SECTION
;
;
;
;START SYSTEM MAINTENANCE SECTION
;
;EACH OF THE 9 SYSTEMS HAS ITS OWN MAINTENANCE SUBROUTINES:
;  -ON-VEHICLE UNSCHEDULED MAINT
;  -ON-VEHICLE SCHEDULED MAINT
;  -OFF-VEHICLE UNSCHEDULED
;
```

```
;POWER ON-VEHICLE UNSCHEDULED MAINT
REP1    ASSIGN,ATRIB(1)=ATRIB(1)-1; REMAINING NBR OF FAILURES
        ACT,,,R1;                   1 ENTITY REPRESENTING A FAILURE TO R1
        ACT,,ATRIB(1).GE.1,REP1;    BACK TO REP1 IF MORE FAILURES REMAIN
        ACT,,ATRIB(1).EQ.0,SCH1;    - OR- 1 ENTITY TO SCHED AWAIT NODE
R1      AWAIT(1),POWER;      START MAINT WHEN RESOURCE AVAILABLE
        ACT/1,RLOG(XX(1),XX(11))+EXPON(XX(41)),XX(51),T1; NO SPARE AVAIL
        ACT/1,RLOG(XX(1),XX(11)),1-XX(51); ON-VEH UNSCHED1
        FREE,POWER;
        ACT,,XX(61),OFF1;    SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(61);       NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM;
T1      FREE,POWER;
        TERM;
;POWER ON-VEHICLE SCHEDULED MAINT
SCH1    AWAIT(2),POWER/XX(71);      START WHEN XX(71) CREWS AVAIL
        ACT/2,XX(21)/XX(71);        ON-VEH SCH1 MAINT
        GOON;
        ACT,,,B14;     POWER ON-VEHICLE MAINT DONE, START NEXT SYSTEM
        ACT,.02*XX(21);             OFF-VEH SCH1 MAINT
        FREE,POWER/XX(71);
        TERM;
;POWER OFF-VEHICLE UNSCHEDULED MAINT
OFF1    AWAIT(3),POWER;
        ACT/3,EXP(XX(41));          OFF-MAINT1
        FREE,POWER;
        TERM;
;
;AVIONICS ON-VEHICLE UNSCHEDULED MAINT
REP4    ASSIGN,ATRIB(4)=ATRIB(4)-1;
        ACT,,,R4;
        ACT,,ATRIB(4).GE.1,REP4;
        ACT,,ATRIB(4).EQ.0,SCH4;
R4      AWAIT(10),AVION;
        ACT/10,RLOG(XX(4),XX(14))+EXPON(XX(44)),XX(54),T4; NO SPARE AVAIL
        ACT/10,RLOG(XX(4),XX(14)),1-XX(54); ON-VEH UNSCHED4
        FREE,AVION;
        ACT,,XX(64),OFF4;     SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(64);        NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T4      FREE,AVION;
        TERM;
;AVIOICS ON-VEHICLE SCHEDULED MAINT
SCH4    AWAIT(11),AVION/XX(74);     START WHEN XX(74) CREWS AVAIL
        ACT/11,XX(24)/XX(74);       ON-VEH SCH4 MAINT
        GOON;
        ACT,,,B4789;    AVIONICS ON-VEHICLE MAINT DONE, START NEXT SYSTEM
        ACT,.02*XX(24);             OFF-VEH SCH4 MAINT
        FREE,AVION/XX(74);
        TERM;
;AVIONICS OFF-VEHICLE UNSCHEDULED MAINT
OFF4    AWAIT(12),AVION;
        ACT/12,EXP(XX(44));         OFF-MAINT4
        FREE,AVION;
        TERM;
;
;LIFE ON-VEHICLE UNSCHEDULED MAINT
REP7    ASSIGN,ATRIB(7)=ATRIB(7)-1;
        ACT,,,R7;
        ACT,,ATRIB(7).GE.1,REP7;
        ACT,,ATRIB(7).EQ.0,SCH7;
```

```
R7      AWAIT(13),LIFE;
        ACT/13,RLOG(XX(7),XX(17))+EXPON(XX(47)),XX(57),T7; NO SPARE
        ACT/13,RLOG(XX(7),XX(17)),1-XX(57); ON-VEH UNSCHED7
        FREE,LIFE;
        ACT,,XX(67),OFF7;      SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(67);         NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T7      FREE,LIFE;
        TERM;
;LIFE ON-VEHICLE SCHEDULED MAINT
SCH7    AWAIT(14),LIFE/XX(77);          START WHEN XX(77) CREWS AVAIL
        ACT/14,XX(27)/XX(77);           ON-VEH SCH7 MAINT
        GOON
        ACT,,,Q3;         LIFE SYSTEM & ALL ON-VEH MAINT IN THIS SERIES
DONE
        ACT,.02*XX(27);                 OFF-VEH SCH7 MAINT
        FREE,LIFE/XX(77);
        TERM;
;LIFE OFF-VEHICLE UNSCHEDULED MAINT
OFF7    AWAIT(15),LIFE;
        ACT/15,EXP(XX(47));             OFF-MAINT7
        FREE,LIFE;
        TERM;
;
;MECHANICAL ON-VEHICLE UNSCHEDULED MAINT
REP8    ASSIGN,ATRIB(8)=ATRIB(8)-1;
        ACT,,,R8;
        ACT,,ATRIB(8).GE.1,REP8;
        ACT,,ATRIB(8).EQ.0,SCH8;
R8      AWAIT(16),MECH;
        ACT/16,RLOG(XX(8),XX(18))+EXPON(XX(48)),XX(58),T8; NO SPARE
        ACT/1,RLOG(XX(8),XX(18)),1-XX(58); ON-VEH UNSCHED8
        FREE,MECH;
        ACT,,XX(68),OFF8;      SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(68);         NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T8      FREE,MECH;
        TERM;
;MECHANICAL ON-VEHICLE SCHEDULED MAINT
SCH8    AWAIT(17),MECH/XX(78);          START WHEN XX(78) CREWS AVAIL
        ACT/17,XX(28)/XX(78);           ON-VEH SCH8 MAINT
        GOON;
        ACT,,,Q4;         MECH SYSTEM & ALL ON-VEH MAINT IN THIS SERIES
DONE
        ACT,.02*XX(28);                 OFF-VEH SCH8 MAINT
        FREE,MECH/XX(78);
        TERM;
;
;OFF-VEHICLE UNSCHEDULED MAINT
OFF8    AWAIT(18),MECH;
        ACT/18,EXP(XX(48));             OFF-MAINT8
        FREE,MECH;
        TERM;
;
;PROPULSION ON-VEHICLE UNSCHEDULED MAINT
REP9    ASSIGN,ATRIB(9)=ATRIB(9)-1;
        ACT,,,R9;
        ACT,,ATRIB(9).GE.1,REP9;
        ACT,,ATRIB(9).EQ.0,SCH9;
R9      AWAIT(19),PROP;
        ACT/19,RLOG(XX(9),XX(19))+EXPON(XX(49)),XX(59),T9; NO SPARE
```

```
        ACT/19,RLOG(XX(9),XX(19)),1-XX(59); ON-VEH UNSCHED9
        FREE,PROP;
        ACT,,XX(69),OFF9;      SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(69);         NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T9      FREE,PROP;
        TERM;
;PROPULSION ON-VEHICLE SCHEDULED MAINT
SCH9    AWAIT(20),PROP/XX(79);          START WHEN XX(79) CREWS AVAIL
        ACT/20,XX(29)/XX(79);           ON-VEH SCH9 MAINT
        GOON;
        ACT,,,Q5;         PROP SYSTEM & ALL ON-VEH MAINT IN THIS SERIES
DONE
        ACT,.02*XX(29);                 OFF-VEH SCH9 MAINT
        FREE,PROP/XX(79);
        TERM;
;PROPULSION OFF-VEHICLE UNSCHEDULED MAINT
OFF9    AWAIT(21),PROP;
        ACT/21,EXP(XX(49));             OFF-MAINT9
        FREE,PROP;
        TERM;
;
;STRUCTURE ON-VEHICLE UNSCHEDULED MAINT
REP2    ASSIGN,ATRIB(2)=ATRIB(2)-1;
        ACT,,,R2;
        ACT,,ATRIB(2).GE.1,REP2;
        ACT,,ATRIB(2).EQ.0,SCH2;
R2      AWAIT(4),STRUC;
        ACT/4,RLOG(XX(2),XX(12))+EXPON(XX(42)),XX(52),T2; NO SPARE
        ACT/4,RLOG(XX(2),XX(12)),1-XX(52); ON-VEH UNSCHED2
        FREE,STRUC;
        ACT,,XX(62),OFF2;      SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(62);         NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T2      FREE,STRUC;
        TERM;
;STRUCTURE ON-VEHICLE SCHEDULED MAINT
SCH2    AWAIT(5),STRUC/XX(72);          START WHEN XX(72) CREWS AVAIL
        ACT/5,XX(22)/XX(72);            ON-VEH SCH2 MAINT
        GOON;
        ACT,,,B25;        STRUC ON-VEHICLE MAINT DONE, START NEXT SYSTEM
        ACT,.02*XX(22);                 OFF-VEH SCH2 MAINT
        FREE,STRUC/XX(72);
        TERM;
;
;STRUCTURE OFF-VEHICLE UNSCHEDULED MAINT
OFF2    AWAIT(6),STRUC;
        ACT/6,EXP(XX(42));              OFF-MAINT2
        FREE,STRUC;
        TERM;
;
;THERMAL/TILES ON-VEHICLE UNSCHEDULED MAINT
REP5    ASSIGN,ATRIB(5)=ATRIB(5)-1;
        ACT,,,R5;
        ACT,,ATRIB(5).GE.1,REP5;
        ACT,,ATRIB(5).EQ.0,SCH5;
R5      AWAIT(7),THERM;
        ACT/7,RLOG(XX(5),XX(15))+EXPON(XX(45)),XX(55),T5; NO SPARE
        ACT/7,RLOG(XX(5),XX(15)),1-XX(55); ON-VEH UNSCHED5
        FREE,THERM;
        ACT,,XX(65),OFF5;      SEND ENTITY FOR MAINT OF REMOVED COMPONENT
```

```
        ACT,,1-XX(65);          NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T5      FREE,THERM;
        TERM;
;THERMAL/TILES ON-VEHICLE SCHEDULED MAINT
SCH5    AWAIT(8),THERM/XX(75);             START WHEN XX(75) CREWS AVAIL
        ACT/8,XX(25)/XX(75);               ON-VEH SCH5 MAINT
        GOON;
        ACT,,,Q6;        THERM SYSTEM & ALL ON-VEH MAINT IN THIS SERIES
DONE
        ACT,.02*XX(25);                    OFF-VEH SCH5 MAINT
        FREE,THERM/XX(75);
        TERM;
;THERMAL/TILES OFF-VEHICLE UNSCHEDULED MAINT
OFF5    AWAIT(9),THERM;
        ACT/9,EXP(XX(45));                 OFF-MAINT5
        FREE,THERM;
        TERM;
;
;FUEL/OXIDE TANKS ON-VEHICLE UNSCHEDULED MAINT
REP3    ASSIGN,ATRIB(3)=ATRIB(3)-1;
        ACT,,,R3;
        ACT,,ATRIB(3).GE.1,REP3;
        ACT,,ATRIB(3).EQ.0,SCH3;
R3      AWAIT(22),TANKS;
        ACT/22,RLOG(XX(3),XX(13))+EXPON(XX(43)),XX(53),T3; NO SPARE
        ACT/22,RLOG(XX(3),XX(13)),1-XX(53); ON-VEH UNSCHED3
        FREE,TANKS;
        ACT,,XX(63),OFF3;       SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(63);          NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T3      FREE,TANKS;
        TERM;
;FUEL/OXIDE TANKS ON-VEHICLE SCHEDULED MAINT
SCH3    AWAIT(23),TANKS/XX(73);            START WHEN XX(73) CREWS AVAIL
        ACT/23,XX(23)/XX(73);              ON-VEH SCH3 MAINT
        GOON;
        ACT,,,B36;       TANKS ON-VEHICLE MAINT DONE, START NEXT SYSTEM
        ACT,.02*XX(23);                    OFF-VEH SCH3 MAINT
        FREE,TANKS/XX(73);
        TERM;
;
;FUEL/OXIDE TANKS OFF-VEHICLE UNSCHEDULED MAINT
OFF3    AWAIT(24),TANKS;
        ACT/24,EXP(XX(43));                OFF-MAINT3
        FREE,TANKS;
        TERM;
;
;AUXILIARY SYSTEMS ON-VEHICLE UNSCHEDULED MAINT
REP6    ASSIGN,ATRIB(6)=ATRIB(6)-1;
        ACT,,,R6;
        ACT,,ATRIB(6).GE.1,REP6;
        ACT,,ATRIB(6).EQ.0,SCH6;
R6      AWAIT(25),AUX;
        ACT/25,RLOG(XX(6),XX(16))+EXPON(XX(46)),XX(56),T6; NO SPARE
        ACT/25,RLOG(XX(6),XX(16)),1-XX(56); ON-VEH UNSCHED6
        FREE,AUX;
        ACT,,XX(66),OFF6;       SEND ENTITY FOR MAINT OF REMOVED COMPONENT
        ACT,,1-XX(66);          NO ADDITIONAL MAINT REQUIRED, TERM ENTITY
        TERM
T6      FREE,AUX;
```

```
        TERM;
;AUXILIARY SYSTEMS ON-VEHICLE SCHEDULED MAINT
SCH6    AWAIT(26),AUX/XX(76);          START WHEN XX(76) CREWS AVAIL
        ACT/26,XX(26)/XX(76);          ON-VEH SCH6 MAINT
        GOON;
        ACT,,,Q7;        THERM SYSTEM & ALL ON-VEH MAINT IN THIS SERIES
DONE
        ACT,.02*XX(26);                OFF-VEH SCH6 MAINT
        FREE,AUX/XX(76);
        TERM;
;AUXILIARY SYSTEMS OFF-VEHICLE UNSCHEDULED MAINT
OFF6    AWAIT(27),AUX;
        ACT/27,EXP(XX(46));            OFF-MAINT6
        FREE,AUX;
        TERM;
        ENDNETWORK;
;END SYSTEM MAINTENANCE SECTION
```

```
;CONTROL FILE (USER INPUT SECTION)
;
GEN,DONOHUE,NASASIM,8/29/1994,6,Y,Y,Y/Y,Y,Y/1,132;
LIMITS,34,13,650;
EQUIVALENCE/XX(80),NHRS/XX(81),NDAYS/XX(82),NYRS/XX(83),NMISSION;
EQUIVALENCE/XX(90),INTEGRATION/XX(91),PADPROC/XX(92),MISSION;
EQUIVALENCE/XX(93),SAFING/XX(94),MISRELIABILITY;
;
;FOR THE GLOBAL VARIABLES BELOW,
;THE LEAST SIGNIFICANT DIGIT IDENTIFIES THE SYSTEM:
; 1  POWER                 6  AUXILIARY
; 2  STRUCTURAL            7  ECS/LIFE SUPPORT
; 3  FUEL/OXID TANKS       8  MECHANICAL SYS
; 4  AVIONICS              9  PROPULSION
; 5  THERMAL/TILES
;
;THE MOST SIGNIFICANT DIGIT IDENTIFIES THE INPUT DATA TYPE:
; 0  ON-VEH MTTR
; 1  ON-VEH STD DEV
; 2  ON-VEH SCHED MTTR
; 3  MAINT ACTIONS PER MISSION
; 4  OFF-VEH MTTR
; 5  REMOVAL & NO SPARE
; 6  PROB-REM
;
;               ON-VEHICLE UNSCHEDULED MTTR
INTLC,XX(1)=9.743523,XX(2)=2.924435,XX(3)=10.05298;
INTLC,XX(4)=1.840963,XX(5)=13.59266,XX(6)=10.05298;
INTLC,XX(7)=3.252513,XX(8)=.6054564,XX(9)=1.683705;
;
;ON-VEHICLE MTTR STANDARD DEVIATION=SQRT(.29*MTTR)
INTLC,XX(11)=1.68096,XX(12)=.920916,XX(13)=1.70744;
INTLC,XX(14)=.73067,XX(15)=1.98541,XX(16)=1.70744;
INTLC,XX(17)=.971199,XX(18)=.419025,XX(19)=.698766;
;
;               ON-VEHICLE SCHEDULED MTTR
INTLC,XX(21)=8.280173,XX(22)=14.72847,XX(23)=29.70727;
INTLC,XX(24)=.1676565,XX(25)=69.93918,XX(26)=14.84571;
INTLC,XX(27)=16.27101,XX(28)=20.83924,XX(29)=82.83476;
;
;           MAINTENANCE ACTIONS PER MISSION
INTLC,XX(31)=2.240062,XX(32)=2.65186,XX(33)=5.348793;
INTLC,XX(34)=.0310006,XX(35)=26.6948,XX(36)=2.67297;
INTLC,XX(37)=3.197754,XX(38)=3.752104,XX(39)=17.0731;
;
;             OFF-VEHICLE UNSCHEDULED MTTR
INTLC,XX(41)=.5522666,XX(42)=.2723976,XX(43)=0;
INTLC,XX(44)=.6621949,XX(45)=0,XX(46)=0;
INTLC,XX(47)=.3342901,XX(48)=.2341774,XX(49)=4.102313;
;
;     REMOVAL RATE WITH NO SPARE AVAILABLE
INTLC,XX(51)=.0352398,XX(52)=.021173,XX(53)=.0164;
INTLC,XX(54)=.04172,XX(55)=.0133828,XX(56)=.0257;
INTLC,XX(57)=.031591,XX(58)=.0250951,XX(59)=.0274691;
;
;
;
;    PROBABILITY OF REMOVAL WITH SPARE AVAILABLE
INTLC,XX(61)=.464468,XX(62)=.2354174,XX(63)=.173158;
INTLC,XX(64)=.60123,XX(65)=.136939,XX(66)=.300898;
INTLC,XX(67)=.39727,XX(68)=.291749,XX(69)=.328412;
```

```
;
;    NUMBER OF CREWS FOR SCHEDULED MAINTENANCE
INTLC,XX(71)=2,XX(72)=3,XX(73)=5;
INTLC,XX(74)=1,XX(75)=10,XX(76)=2;
INTLC,XX(77)=2,XX(78)=2,XX(79)=8;
;
INTLC,NHRS=8,NDAYS=5,NYRS=5,NMISSION=28,INTEGRATION=0;
INTLC,PADPROC=12,MISSION=72,SAFING=0,MISRELIABILITY=.9896423;
;
NETWORK;
INITIALIZE,,,Y;
FIN;
```

The output report for the input as specified in this appendix is in Appendix E.

Appendix B

Output with 99 crews available for each system, 4 vehicles, and 1 crew assigned to scheduled maintenance for each system.

S L A M I I S U M M A R Y R E P O R T

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SIMULATION PROJECT NASASIM                        BY DONOHUE
DATE  8/29/1994                                   RUN NUMBER     1 OF     7
CURRENT TIME     .1040E+05
STATISTICAL ARRAYS CLEARED AT TIME     .0000E+00
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
MEAN MAINT TIME	.114E+02	.321E-04	.282E-05	.114E+02	.114E+02	139
MEAN TURN TIME I	.159E+02	.321E-04	.202E-05	.159E+02	.159E+02	139

FILE STATISTICS

FILE NUMBER	LABEL/TYPE		AVERAGE LENGTH	STANDARD DEVIATION	MAXIMUM LENGTH	CURRENT LENGTH	AVERAGE WAIT TIME
1	R1	AWAIT	.000	.000	1	0	.000
2	SCH1	AWAIT	.000	.000	1	0	.000
3	OFF1	AWAIT	.000	.000	1	0	.000
4	R2	AWAIT	.000	.000	1	0	.000
5	SCH2	AWAIT	.000	.000	1	0	.000
6	OFF2	AWAIT	.000	.000	1	0	.000
7	R5	AWAIT	.000	.000	1	0	.000
8	SCH5	AWAIT	.000	.000	1	0	.000
9	OFF5	AWAIT	.000	.000	1	0	.000
10	R4	AWAIT	.000	.000	1	0	.000
11	SCH4	AWAIT	.000	.000	1	0	.000
12	OFF4	AWAIT	.000	.000	1	0	.000
13	R7	AWAIT	.000	.000	1	0	.000
14	SCH7	AWAIT	.000	.000	1	0	.000
15	OFF7	AWAIT	.000	.000	1	0	.000
16	R8	AWAIT	.000	.000	1	0	.000
17	SCH8	AWAIT	.000	.000	1	0	.000
18	OFF8	AWAIT	.000	.000	1	0	.000
19	R9	AWAIT	.000	.000	1	0	.000
20	SCH9	AWAIT	.000	.000	1	0	.000
21	OFF9	AWAIT	.000	.000	1	0	.000
22	R3	AWAIT	.000	.000	1	0	.000
23	SCH3	AWAIT	.000	.000	1	0	.000
24	OFF3	AWAIT	.000	.000	1	0	.000
25	R6	AWAIT	.000	.000	1	0	.000
26	SCH6	AWAIT	.000	.000	1	0	.000
27	OFF6	AWAIT	.000	.000	1	0	.000
28	Q1	QUEUE	.000	.000	1	0	.000
29	Q2	QUEUE	2.091	.608	3	3	150.982
30	Q3	QUEUE	.891	.313	2	1	66.185
31	Q4	QUEUE	.829	.376	1	1	61.617
32	Q5	QUEUE	.000	.000	1	0	.000
33	Q6	QUEUE	.088	.284	1	0	6.615
34	Q7	QUEUE	.625	.484	1	0	46.730
35		CALENDAR	13.489	11.275	55	6	2.037

REGULAR ACTIVITY STATISTICS

ACTIVITY INDEX/LABEL	AVERAGE UTILIZATION	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL	ENTITY COUNT
1 ON-VEH UNSCH	.3237	.9638	13	0	844
2 ON-VEH SCH1	.1115	.3147	1	0	140
3 OFF-MAINT1	.0069	.0849	2	0	149
4 ON-VEH UNSCH	.0998	.5490	8	0	352
5 ON-VEH SCH2	.1983	.3987	1	0	140
6 OFF-MAINT2	.0019	.0453	2	0	70
7 ON-VEH UNSCH	4.8888	10.0694	41	0	3747
8 ON-VEH SCH5	.9370	.2459	2	1	139
9 OFF-MAINT5	.0000	.0000	1	0	532
10 ON-VEH UNSCH	.0015	.0392	1	0	6
11 ON-VEH SCH4	.0023	.0475	1	0	140
12 OFF-MAINT4	.0005	.0222	1	0	4
13 ON-VEH UNSCH	.1359	.6929	9	0	442
14 ON-VEH SCH7	.2190	.4136	1	0	140
15 OFF-MAINT7	.0047	.0720	3	0	164
16 NO SPARE	.0005	.0233	2	0	7
17 ON-VEH SCH8	.2805	.4493	1	0	140
18 OFF-MAINT8	.0036	.0658	3	0	160
19 ON-VEH UNSCH	.4196	2.4065	30	0	2468
20 ON-VEH SCH9	1.1100	.3273	2	1	139
21 OFF-MAINT9	.3200	1.0082	10	0	831
22 ON-VEH UNSCH	.6983	1.8777	12	0	735
23 ON-VEH SCH3	.3999	.4899	1	0	140
24 OFF-MAINT3	.0000	.0000	1	0	130
25 ON-VEH UNSCH	.3703	1.0583	7	2	381
26 ON-VEH SCH6	.1992	.3994	1	1	139
27 OFF-MAINT6	.0000	.0000	1	0	108
28 SUCCESSFUL M	.3231	.4677	1	0	140
29 CRIT FAIL GO	.0000	.0000	1	0	1

RESOURCE STATISTICS

RESOURCE NUMBER	RESOURCE LABEL	CURRENT CAPACITY	AVERAGE UTIL	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL
1	POWER	99	.41	1.141	9	0
2	STRUC	99	.30	.795	9	0
3	TANKS	99	1.11	2.143	13	0
4	AVION	99	.00	.067	2	0
5	THERM	99	5.84	10.095	42	1
6	AUX	99	.57	1.368	8	3
7	LIFE	99	.36	.943	10	0
8	MECH	99	.32	.608	12	0
9	PROP	99	1.87	2.978	32	1

RESOURCE NUMBER	RESOURCE LABEL	CURRENT AVAILABLE	AVERAGE AVAILABLE	MINIMUM AVAILABLE	MAXIMUM AVAILABLE
1	POWER	99	98.5864	90	99
2	STRUC	99	98.6960	90	99
3	TANKS	99	97.8938	86	99
4	AVION	99	98.9957	97	99
5	THERM	98	93.1554	57	99
6	AUX	96	98.4264	91	99
7	LIFE	99	98.6359	89	99
8	MECH	99	98.6791	87	99
9	PROP	98	97.1283	67	99

```
1                                  **HISTOGRAM NUMBER 1**
                                      MEAN MAINT TIME
 OBS  RELA    UPPER
 FREQ FREQ   CELL LIM 0         20        40        60        80        100
                      +    +    +    +    +    +    +    +    +    +    +
   0  .000  .600E+01  +                                                  +
   0  .000  .800E+01  +                                                  +
   0  .000  .100E+02  +                                                  +
 139 1.000  .120E+02  +***************************************************
   0  .000  .140E+02  +                                                  C
   0  .000  .160E+02  +                                                  C
   0  .000  .180E+02  +                                                  C
   0  .000  .200E+02  +                                                  C
   0  .000  .220E+02  +                                                  C
   0  .000  .240E+02  +                                                  C
   0  .000  .260E+02  +                                                  C
   0  .000    INF     +                                                  C
 ---                  +    +    +    +    +    +    +    +    +    +    +
 139                  0         20        40        60        80        100
1                                  **HISTOGRAM NUMBER 2**
                                      MEAN TURN TIME I

 OBS  RELA    UPPER
 FREQ FREQ   CELL LIM 0         20        40        60        80        100
                      +    +    +    +    +    +    +    +    +    +    +
   0  .000  .100E+02  +                                                  +
   0  .000  .120E+02  +                                                  +
   0  .000  .140E+02  +                                                  +
 139 1.000  .160E+02  +***************************************************
   0  .000  .180E+02  +                                                  C
   0  .000  .200E+02  +                                                  C
   0  .000  .220E+02  +                                                  C
   0  .000  .240E+02  +                                                  C
   0  .000  .260E+02  +                                                  C
   0  .000  .280E+02  +                                                  C
   0  .000  .300E+02  +                                                  C
   0  .000    INF     +                                                  C
 ---                  +    +    +    +    +    +    +    +    +    +    +
 139                  0         20        40        60        80        100
```

Appendix C

Output with minimum number of crews available for each system, 4 vehicles, and 1 crew assigned to scheduled maintenance for each system. The output report has been edited.

S L A M I I S U M M A R Y R E P O R T

SIMULATION PROJECT NASASIM BY DONOHUE
DATE 8/29/1994 RUN NUMBER 1 OF 5
CURRENT TIME .1040E+05
STATISTICAL ARRAYS CLEARED AT TIME .0000E+00

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
MEAN MAINT TIME	.153E+02	.238E+01	.156E+00	.123E+02	.264E+02	138
MEAN TURN TIME	.198E+02	.238E+01	.120E+00	.168E+02	.309E+02	138

FILE STATISTICS

FILE NUMBER	LABEL/TYPE		AVERAGE LENGTH	STANDARD DEVIATION	MAXIMUM LENGTH	CURRENT LENGTH	AVERAGE WAIT TIME
28	Q1	QUEUE	.000	.000	1	0	.000
29	Q2	QUEUE	1.658	.605	3	1	120.547
30	Q3	QUEUE	.847	.502	3	1	63.394
31	Q4	QUEUE	.897	.487	3	1	67.130
32	Q5	QUEUE	.090	.289	2	1	6.730
33	Q6	QUEUE	.266	.466	2	1	19.877
34	Q7	QUEUE	.293	.473	2	0	22.112
35		CALENDAR	13.594	9.577	53	8	2.058

REGULAR ACTIVITY STATISTICS

ACTIVITY INDEX/LABEL	AVERAGE UTILIZATION	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL	ENTITY COUNT
28 SUCCESSFUL M	.3231	.4677	1	0	140
29 CRIT FAIL GO	.0000	.0000	1	0	2

RESOURCE STATISTICS

RESOURCE NUMBER	RESOURCE LABEL	CURRENT CAPACITY	AVERAGE UTIL	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL
1	POWER	1	.42	.494	1	0
2	STRUC	1	.32	.468	1	0
3	TANKS	2	1.13	.810	2	1
4	AVION	1	.00	.060	1	0
5	THERM	25	5.90	8.824	25	1
6	AUX	1	.59	.492	1	1
7	LIFE	1	.37	.482	1	1
8	MECH	1	.32	.466	1	1
9	PROP	16	1.83	2.580	16	1

Appendix D

Output with minimum number of crews available for each system, 4 vehicles, and optimum number of crews assigned to scheduled maintenance for each system. The output report has been edited.

```
                 S L A M   I I   S U M M A R Y   R E P O R T
SIMULATION PROJECT NASASIM                     BY DONOHUE
DATE   8/29/1994                               RUN NUMBER    1 OF    7
CURRENT TIME    .1040E+05
STATISTICAL ARRAYS CLEARED AT TIME    .0000E+00
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
MEAN MAINT TIME	.106E+02	.133E+01	.126E+00	.748E+01	.183E+02	139
MEAN TURN TIME I	.151E+02	.133E+01	.882E-01	.120E+02	.228E+02	139

FILE STATISTICS

FILE NUMBER	LABEL/TYPE		AVERAGE LENGTH	STANDARD DEVIATION	MAXIMUM LENGTH	CURRENT LENGTH	AVERAGE WAIT TIME
28	Q1	QUEUE	.000	.000	1	0	.000
29	Q2	QUEUE	1.779	.756	3	3	126.697
30	Q3	QUEUE	.370	.485	2	0	27.717
31	Q4	QUEUE	.420	.495	2	0	31.432
32	Q5	QUEUE	.356	.479	2	0	26.610
33	Q6	QUEUE	.008	.090	1	0	.616
34	Q7	QUEUE	.376	.489	2	0	28.151
35		CALENDAR	11.802	3.942	25	13	1.830

REGULAR ACTIVITY STATISTICS

ACTIVITY INDEX/LABEL	AVERAGE UTILIZATION	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL	ENTITY COUNT
28 SUCCESSFUL M	.3231	.4677	1	0	140
29 CRIT FAIL GO	.0000	.0000	1	0	3

RESOURCE STATISTICS

RESOURCE NUMBER	RESOURCE LABEL	CURRENT CAPACITY	AVERAGE UTIL	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL
1	POWER	1	.41	.492	1	0
2	STRUC	1	.32	.465	1	0
3	TANKS	3	1.13	1.303	3	0
4	AVION	1	.00	.056	1	0
5	THERM	8	5.90	3.002	8	8
6	AUX	1	.32	.467	1	1
7	LIFE	1	.37	.483	1	1
8	MECH	1	.32	.466	1	1
9	PROP	5	1.94	2.255	5	5

Appenxdix E

Output with minimum number of crews available for each system, 3 vehicles, and optimum number of crews assigned to scheduled maintenance for each system.

```
                    S L A M   I I   S U M M A R Y   R E P O R T
SIMULATION PROJECT NASASIM                        BY DONOHUE
DATE  8/29/1994                                   RUN NUMBER    1 OF    7
CURRENT TIME    .1040E+05
STATISTICAL ARRAYS CLEARED AT TIME    .0000E+00
```

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
MEAN MAINT TIME	.429E+01	.500E+00	.117E+00	.311E+01	.570E+01	140
MEAN TURN TIME I	.879E+01	.500E+00	.569E-01	.761E+01	.102E+02	140

FILE STATISTICS

FILE NUMBER	LABEL/TYPE		AVERAGE LENGTH	STANDARD DEVIATION	MAXIMUM LENGTH	CURRENT LENGTH	AVERAGE WAIT TIME
1	R1	AWAIT	.034	.240	3	0	1.098
2	SCH1	AWAIT	.096	.294	1	0	7.106
3	OFF1	AWAIT	.023	.184	3	0	1.721
4	R2	AWAIT	.019	.224	6	0	.533
5	SCH2	AWAIT	.054	.225	1	0	3.976
6	OFF2	AWAIT	.028	.211	3	0	3.287
7	R5	AWAIT	.777	2.400	20	0	2.185
8	SCH5	AWAIT	.194	.395	1	0	14.378
9	OFF5	AWAIT	.049	.308	6	0	.969
10	R4	AWAIT	.000	.000	0	0	.000
11	SCH4	AWAIT	.000	.000	1	0	.000
12	OFF4	AWAIT	.000	.000	0	0	.000
13	R7	AWAIT	.034	.290	6	0	.758
14	SCH7	AWAIT	.047	.212	1	0	3.507
15	OFF7	AWAIT	.027	.219	5	0	1.537
16	R8	AWAIT	.023	.278	8	0	.426
17	SCH8	AWAIT	.019	.136	1	0	1.396
18	OFF8	AWAIT	.140	.499	4	0	9.029
19	R9	AWAIT	.145	1.080	17	0	.634
20	SCH9	AWAIT	.067	.249	1	0	4.945
21	OFF9	AWAIT	.257	.888	9	0	3.452
22	R3	AWAIT	.090	.500	6	0	1.165
23	SCH3	AWAIT	.166	.372	1	0	12.313
24	OFF3	AWAIT	.027	.185	3	0	2.073
25	R6	AWAIT	27.724	15.007	53	53	858.116
26	SCH6	AWAIT	.087	.282	1	0	6.488
27	OFF6	AWAIT	.004	.059	1	0	.455
28	Q1	QUEUE	.000	.000	1	0	.000
29	Q2	QUEUE	1.852	.476	3	3	133.785
30	Q3	QUEUE	.151	.358	1	0	11.251
31	Q4	QUEUE	.149	.356	1	0	11.077
32	Q5	QUEUE	.102	.303	1	0	7.594
33	Q6	QUEUE	.055	.227	1	0	4.049
34	Q7	QUEUE	.029	.167	1	0	2.141
35		CALENDAR	10.708	10.694	51	1	1.635

REGULAR ACTIVITY STATISTICS

ACTIVITY INDEX/LABEL	AVERAGE UTILIZATION	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL	ENTITY COUNT
1 ON-VEH UNSCH	.3342	.8181	3	0	855
2 ON-VEH SCH1	.0557	.2294	1	0	140
3 OFF-MAINT1	.0068	.0869	2	0	142
4 ON-VEH UNSCH	.1080	.4946	3	0	380
5 ON-VEH SCH2	.0661	.2484	1	0	140
6 OFF-MAINT2	.0023	.0503	3	0	88
7 ON-VEH UNSCH	4.8106	8.1994	22	0	3697
8 ON-VEH SCH5	.0942	.2920	1	0	140
9 OFF-MAINT5	.0000	.0000	1	0	525
10 ON-VEH UNSCH	.0000	.0000	0	0	0
11 ON-VEH SCH4	.0023	.0475	1	0	140
12 OFF-MAINT4	.0000	.0000	0	0	0
13 ON-VEH UNSCH	.1452	.5855	3	0	464
14 ON-VEH SCH7	.1095	.3123	1	0	140
15 OFF-MAINT7	.0057	.0757	2	0	182
16 NO SPARE	.0016	.0394	1	0	19
17 ON-VEH SCH8	.1403	.3473	1	0	140
18 OFF-MAINT8	.0036	.0697	2	0	161
19 ON-VEH UNSCH	.4021	1.7978	10	0	2376
20 ON-VEH SCH9	.1394	.3463	1	0	140
21 OFF-MAINT9	.3011	.7414	6	0	773
22 ON-VEH UNSCH	.7724	1.7607	6	0	799
23 ON-VEH SCH3	.0800	.2713	1	0	140
24 OFF-MAINT3	.0000	.0000	1	0	136
25 ON-VEH UNSCH	.2717	.7555	3	0	283
26 ON-VEH SCH6	.0999	.2999	1	0	140
27 OFF-MAINT6	.0000	.0000	1	0	81
28 SUCCESSFUL M	.3231	.4677	1	0	140
29 CRIT FAIL GO	.0000	.0000	1	0	1

RESOURCE STATISTICS

RESOURCE NUMBER	RESOURCE LABEL	CURRENT CAPACITY	AVERAGE UTIL	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL
1	POWER	3	.43	.959	3	0
2	STRUC	3	.32	.888	3	0
3	TANKS	6	1.21	2.173	6	0
4	AVION	1	.00	.048	1	0
5	THERM	22	5.94	8.934	22	0
6	AUX	3	.48	.998	3	0
7	LIFE	3	.38	.885	3	0
8	MECH	2	.33	.735	2	0
9	PROP	10	2.00	3.714	10	0

RESOURCE NUMBER	RESOURCE LABEL	CURRENT AVAILABLE	AVERAGE AVAILABLE	MINIMUM AVAILABLE	MAXIMUM AVAILABLE
1	POWER	3	2.5730	0	3
2	STRUC	3	2.6796	0	3
3	TANKS	6	4.7877	0	6
4	AVION	1	.9977	0	1
5	THERM	22	16.0596	0	22
6	AUX	3	2.5205	0	3
7	LIFE	3	2.6213	0	3
8	MECH	2	1.6732	0	2
9	PROP	10	8.0034	0	10

```
1                                  **HISTOGRAM NUMBER 1**
                                      MEAN MAINT TIME
 OBS  RELA   UPPER
 FREQ FREQ  CELL LIM 0         20         40         60         80         100
                     -    +    +    +    +    +    +    +    +    +    +
   0  .000  .200E+01 +                                                  +
   0  .000  .300E+01 +                                                  +
  34  .243  .400E+01 +*************                                     +
  91  .650  .500E+01 +********************************              C   +
  15  .107  .600E+01 +*****                                             C
   0  .000  .700E+01 +                                                  C
   0  .000  .800E+01 +                                                  C
   0  .000  .900E+01 +                                                  C
   0  .000  .100E+02 +                                                  C
   0  .000  .110E+02 +                                                  C
   0  .000  .120E+02 +                                                  C
   0  .000    INF    +                                                  C
 ---                 +    +    +    +    +    +    +    +    +    +    +
 140                 0         20         40         60         80         100

1                                  **HISTOGRAM NUMBER 2**
                                      MEAN TURN TIME I
 OBS  RELA   UPPER
 FREQ FREQ  CELL LIM 0         20         40         60         80         100
                     +    +    +    +    +    +    +    +    +    +    +
   0  .000  .200E+01 +                                                  +
   0  .000  .300E+01 +                                                  +
   0  .000  .400E+01 +                                                  +
   0  .000  .500E+01 +                                                  +
   0  .000  .600E+01 +                                                  +
   0  .000  .700E+01 +                                                  +
   6  .043  .800E+01 +**                                                +
 102  .729  .900E+01 +************************************   C          +
  30  .214  .100E+02 +***********                                      C+
   2  .014  .110E+02 +*                                                 C
   0  .000  .120E+02 +                                                  C
   0  .000    INF    +                                                  C
 ---                 +    +    +    +    +    +    +    +    +    +    +
 140                 0         20         40         60         80         100
```

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