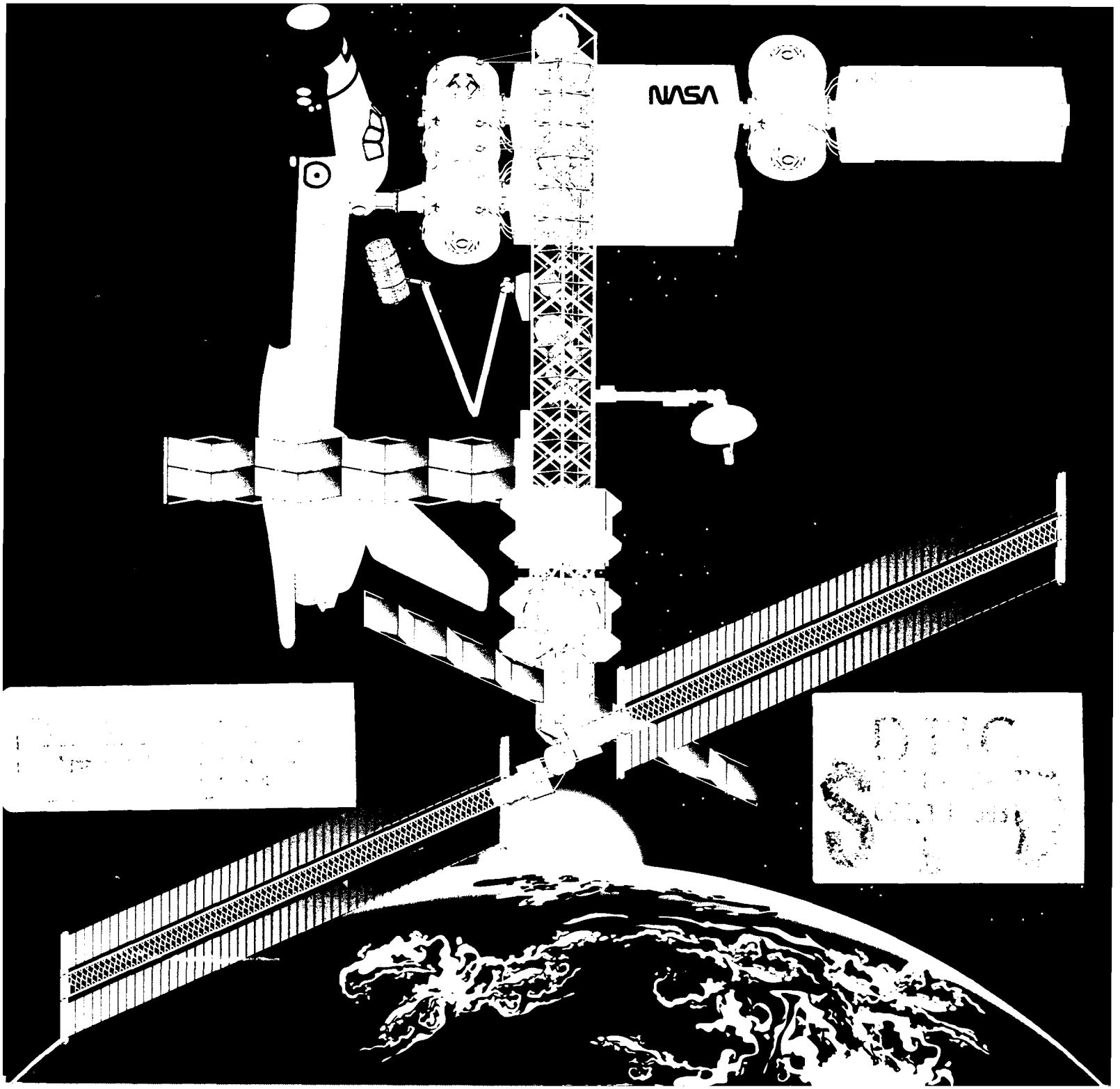
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Estimating Spares Requirements for Space Station Freedom

Using the M-SPARE Model

July 1993

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PREFACE

This document includes the minor enhancements the Logistics Management Institute has made to M-SPARE since the previous model documentation in August 1992. The enhancements fall into two basic categories: first, those that expand the M-SPARE forecasting capability include repair budgets, ground-storage packing requirements, and preventive maintenance spares estimates; second, those that make M-SPARE more responsive to user needs and let the user limit the output reports M-SPARE generates, use either current or constant year dollars, select spares based upon the orbital replacement unit's procurement lead time, or use two types of probability-of-sufficiency estimates.

Executive Summary

ESTIMATING SPARES REQUIREMENTS FOR SPACE STATION FREEDOM

Using the M-SPARE Model

Space Station Freedom (SSF) will be a manned research laboratory designed by NASA to orbit 200 miles above the Earth for 30 years. To ensure the safety of its crew and the success of its missions, the station will need additional parts (spares) to replace failed equipment. Because spares are expensive and SSF budgets constrained, NASA needed a method to determine the optimal spares inventory for a specified cost.

The Multiple Spares Prioritization and Availability to Resource Evaluation (M-SPARE) model provides NASA that capability. M-SPARE implements a method that considers the unique characteristics of SSF, applies across all SSF organizational levels, and ensures the best station performance for any specified level of investment. M-SPARE has evolved significantly over its 4-year life and now addresses most SSF spares issues. NASA is currently using M-SPARE to answer three basic questions concerning SSF:

- What spares does it need?
- When does it need them?
- How much will they cost?

This guide describes the M-SPARE methodology, products, capabilities, and operations necessary to answer those questions.

Methodology – The core of M-SPARE is its selection methodology that links station performance to spares resource requirements. Station performance (we term it *availability*) is defined as the probability that no critical system becomes inoperative over the resupply cycle (time interval between shuttle flights) for lack of an orbital replaceable unit (ORU) spare. The annual spares resource requirement can be a single resource such as budget dollars, weight the shuttle can carry, station storage volume, or it can be a combination of resources. M-SPARE is based on a

marginal-analysis approach. Spares are ranked in order of decreasing benefit per cost (essentially the improvement provided to station availability per unit resource) and added, in that order, to the inventory until a target resource expenditure or station availability is reached. Besides resources, the model also considers the ORU's failure rate, frequency of shuttle resupply, repair time, procurement lead time, and assembly sequence.

Products – M-SPARE develops three key products over a specified period of the station's life. First, it specifies the entire range (a plotted curve) of how SSF's availability changes as annual spares resource expenditures change. Every point on the curve corresponds to an optimal spares mix that maximizes station availability. Second, the model develops a list of required spares by year based upon a user-specified station availability target or resource constraints. Finally, the model converts spares requirements over a period of station life to current funding estimates for the next 9 fiscal years.

Other Capabilities – To conserve weight and volume, the model optimizes the spares storage location so that only the most vital spares are stored on orbit. To resolve conflicting resource constraints, the model develops a range of tradeoff options enabling users to determine a balanced solution. To help produce complete budget estimates, the model estimates spares requirements for all types of ORUs (critical and noncritical). To address additional spares-related costs, the model also estimates ORU repair budgets.

Operations – M-SPARE operates on a personal computer, making the model accessible to SSF users. It contains a menu-driven interface so that users can easily prepare inputs, run the model, and analyze results. The model's data requirements are based upon existing user data base information so that the model is responsive to current conditions. It is an analytic model that generates solutions in minutes.

With the use of M-SPARE, NASA obtains three important benefits:

- A comprehensive approach that helps to ensure station spares are available when needed
- A consistent approach for the many organizations that are involved with SSF
- A defensible approach that links spares budgets to station availability, the ultimate program goal.

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CHAPTER 1

INTRODUCTION

Space Station Freedom (SSF) will be a manned orbital research laboratory with a planned life cycle of 30 years. The station will orbit 200 miles above Earth, and its only life line to the planet will be a few shuttle resupply flights each year. Although the original station components are highly reliable, spares are necessary to replace the possible component failures that astronauts cannot repair. Thus, spares are necessary to ensure maximum station performance and minimal crew risk. NASA asked LMI to develop a model to answer three basic questions about SSF:

- What spares are needed?
- When are they needed?
- How much will they cost?

In this guide, we present a methodology that prioritizes spares selection as the station is assembled and operated. Optimal spares requirements are converted into funding requirements, which drive NASA spares budgets.

Over the past 4 years, we developed a model to address most of SSF's reparable spares issues. It is called the Multiple Spares Prioritization and Availability to Resource Evaluation (M-SPARE) model. The core of the model is its spares selection methodology that links station performance to spares resource requirements. Station performance (what we term *availability*) is defined as the probability that no critical system becomes inoperative over the resupply *logistics cycle* (the interval between shuttle resupply launches) for lack of an orbital replaceable unit (ORU) spare. The spares resource requirement can be a single resource (such as budget dollars, weight the shuttle can carry, or station storage volume) or a combination of resources.

The M-SPARE model is based on a marginal-analysis approach. Spares are ranked in order of decreasing benefit per cost (essentially the improvement provided to station availability per unit resource)[1] and added, in the same order, to the

[1]For technical reasons, M-SPAREs actually considers the logarithm of the increase in availability. See Appendix A.

inventory until a target resource expenditure or station availability is reached. Besides resources, the model also considers the ORU's failure rate, frequency of shuttle resupply, repair time, procurement time, and assembly sequence.

The M-SPARE model develops three key products. First, it specifies how SSF availability changes as resource expenditures change (Figure 1-1). Every point on the plotted curve corresponds to an optimal spares mix that maximizes availability for a given resource level. Second, the model develops a list of required spares by year based upon a user-specified station availability target or resource target. Finally, the model converts spares requirements over a period of station life to current funding estimates that shape NASA spares budgets for the next 9 fiscal years.

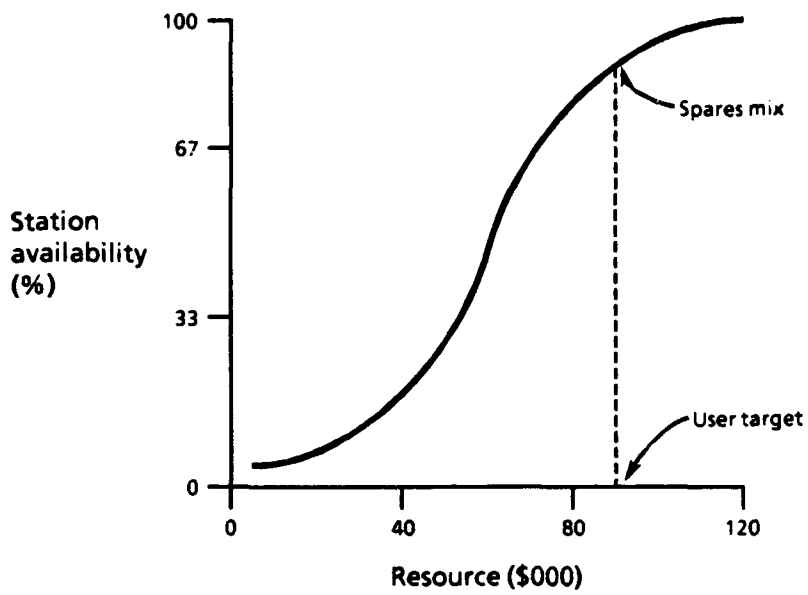

FIG. 1-1. RESOURCE-VERSUS-STATION-AVAILABILITY CURVE
(Critical on-orbit ORUs)

Model operations start with two basic inputs – annual station configurations and annual station targets (see Figure 1-2). The SSF configuration specifies the ORU criticality type, population, and characteristics such as failure rates and ground repair times. The SSF targets help specify the size of the required spares inventory. Users can specify availability, price, weight, or volume targets or any target combination. Given those inputs, M-SPARE automatically determines the *gross spares requirement* for successive years of the station's life – the total number of spares of each item needed in the inventory to reach the specified target. Next, the

model estimates the annual difference, by item, between gross requirements and available assets (spares procured in previous years). That difference is the *net spares requirement.* The accumulation of each item's net spares requirement times the unit price then drives the estimates for the budgets in the fiscal years a procurement lead time earlier. We chose that fiscal year format so that M-SPARE outputs are consistent with the SSF general budget process. [*Note:* When we refer to budgets, we really mean outlays that accrue in a specific fiscal year as opposed to obligations that can be spent over several years.]

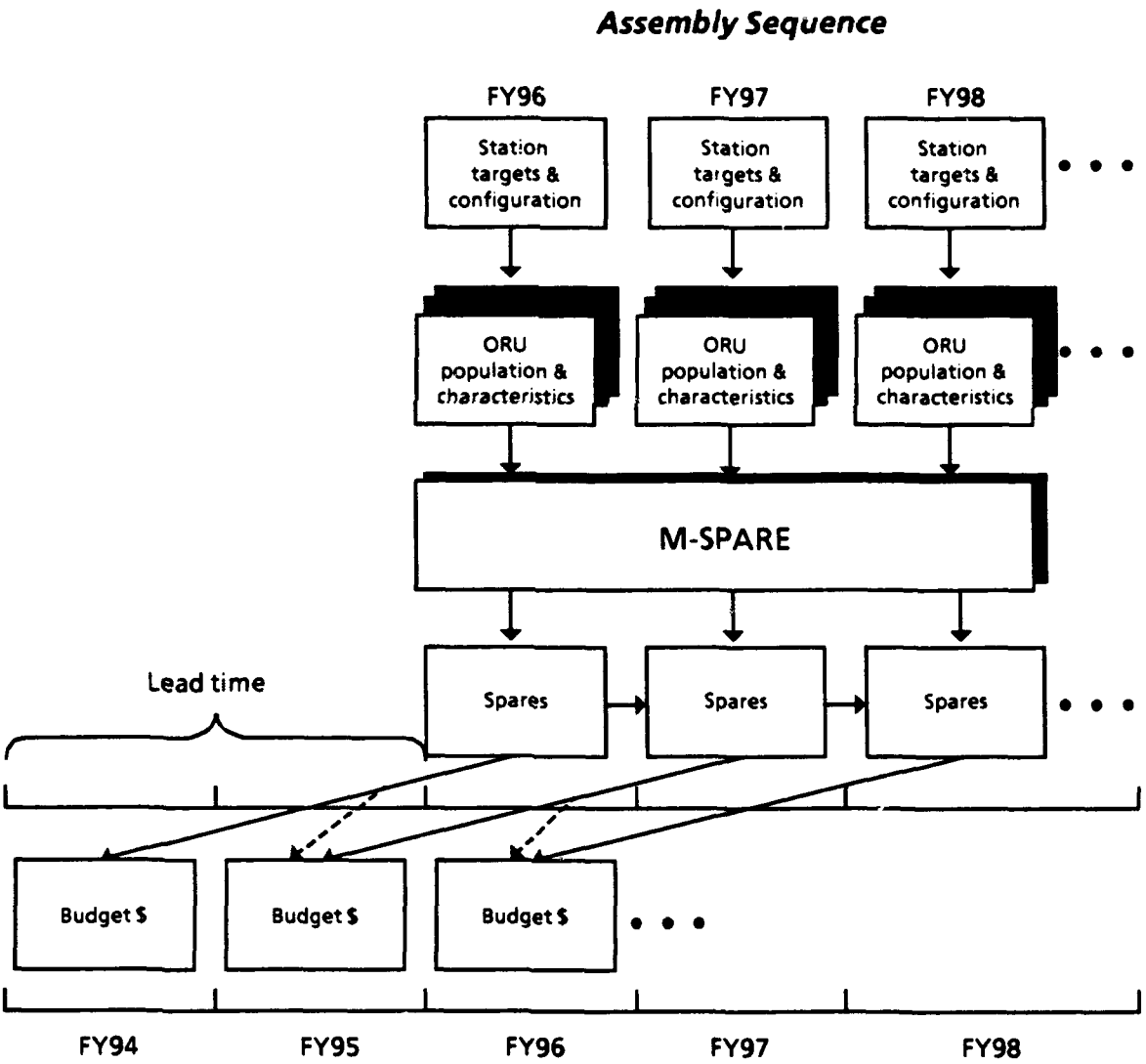

FIG. 1-2. OVERVIEW OF CREATING BUDGET REQUIREMENTS

In addition, M-SPARE has the following capabilities:

- It determines the optimal storage location (on orbit or ground) for each type of spare. If on-orbit storage is not available, users can override that optimization and specify ground storage only.
- It balances conflicting resource constraints such as spares budget dollars and shuttle weight limitations.
- It estimates spares weight and volume projections to resupply all failures throughout each year.
- It produces a combined budget for all types of ORUs (e.g., Criticality Codes 1, 2, and 3).
- It constrains spares levels to a specified annual budget.
- It estimates reparable spares requirements, including condemnations (a broken spare that can no longer be fixed).
- It produces supplementary estimates of annual repair budgets and ground packing requirements.
- It estimates spares based upon ORU failures from random and time-dependent processes (e.g., wear-related failures or preventive maintenance actions that usually occur when an ORU is a certain age).
- It estimates the benefit (availability improvement or the cost savings) of changing the resupply frequency or using common ORUs for more than one application.
- It generates most solutions within minutes on IBM-compatible personal computers (PCs).

USERS GUIDE ORGANIZATION

In this guide, we describe the M-SPARE model methodology, why that methodology is used, and the algorithms within the computer code. We offer further guidance to the user to install and operate the model, describe the model's data inputs and how to modify them, and present sample data outputs and what they mean. In addition, we describe how to modify model assumptions to perform various types of analyses. The remainder of this Chapter and Chapter 2 present an overview of the model methodology and operation. Chapters 3 and 4 concentrate on the technical details of the methodology. The remaining chapters present details on how to use the model. The following paragraphs describe each chapter in more detail:

- *Chapter 1 – Introduction.* In the rest of this chapter, we discuss why the station needs spares and present simple examples to illustrate why the M-SPARE methodology outperforms a more traditional sparing approach. We also outline the overall model methodology.

- *Chapter 2 – Installation and Demonstration.* In this chapter, we discuss how to install the model on a PC and guide the user through a test drive. That whole process takes about 10 minutes and gives an overview of the model's operation and capability. We also discuss the model user interface that helps users prepare input, operate the model, and analyze results.

- *Chapter 3 – Spares Prioritization Overview.* In this chapter, we provide an overview of the spares optimization methodology and capabilities. Specifically, we discuss station availability, the optimal spares selection process, and resource tradeoff analyses.

- *Chapter 4 – Detailed ORU Multi-Echelon Methodology.* In this chapter, we present the details of the ORU multi-echelon tradeoff, the basic building block of the spares selection process. That tradeoff considers a host of factors such as on-orbit failure rates, times required to repair or replace ORUs, and shuttle flight frequency. The final result is an optimal tradeoff that decides the mix of spares to be stored on orbit and on the ground and the resulting station availability.

- *Chapter 5 – Model ORU Input Data.* This chapter discusses the input data required for the model and how to create or modify those data.

- *Chapter 6 – Model Options.* This chapter discusses the procedure for setting basic model options that change infrequently such as the element launch schedule or the budget time horizon.

- *Chapter 7 – Model Operation and Analysis.* In this chapter, we discuss the steps required to run the model and the different modes of operation. We also discuss the types of analyses – estimating spares mixes, using multiple resources, developing resource tradeoffs, and examining alternative solutions.

- *Chapter 8 – Model Outputs.* This chapter presents model outputs and describes how to interpret them. The model produces two files. One is a budget file that summarizes spares and funding requirements over time; the other is a detailed output file that focuses on displaying pertinent input, intermediate results, and output data used in the model.

- *Chapter 9 – M-SPARE Use for the Program Operating Plan* (POP). In this chapter, we discuss how to use M-SPARE for its major purpose: to produce spares and funding requirements for a POP cycle (part of NASA's overall budget process).

- *Chapter 10 – The Wear Preprocessor.* In this chapter, we discuss how the model deals with ORUs that wear out. Besides the standard random failures, ORUs may also exhibit a failure mode after being in operation for a specific period of time. M-SPARE uses a preprocessor that simulates wear-out and random failures over 15 years of the station's life. The preprocessor then produces a time-dependent, aggregate failure rate that M-SPARE uses in the spares prioritization.

- *Appendix A – Spares Optimization Proof.* This appendix presents a mathematical proof for the model's optimization methodology.

- *Appendix B – Repair Budget: Methods, Assumptions, and Data.* The repair budget starts where the spares budget leaves off. That is, once you procure a spare, you incur additional costs if the spare breaks and requires repair. In this appendix, we describe how we converted historic repair data from existing NASA systems to serve as the foundation of the M-SPARE repair method for Space Station Freedom.

- *Appendix C – Glossary.* This glossary defines the acronyms used throughout this guide.

WHY DOES THE STATION NEED SPARES?

A basic question is why does a station whose components fail every 30 years or more on average need spares? That is especially true when you consider that even if an item fails, the station has redundant backup systems that will work in its place. The question seems reasonable until you start examining the numbers.

Suppose individual ORUs last, on average, for 30 years. That means some will operate longer and, more importantly, some will operate less. If we assume a standard failure rate probability distribution (Poisson), there is a 6 percent chance that any given item will fail in the first 2 years. When you then consider that an ORU is installed in five separate locations on the station, the chance of a failure in 2 years increases to 30 percent. Add to that failures caused by accidents or the harsh space environment and the chance of failure may increase to 60 percent. Next, consider that if the station does have a failure, it could wait 2 to 5 years before the failed item can be returned to Earth, repaired or replaced, and then delivered back to the station. (Astronauts will have limited repair capability.) Even with redundant

systems, that is a long time to wait with only a backup between you and an emergency evacuation. Finally, if the chance that one ORU fails is 60 percent, then the chance of a failure among SSF's hundreds of ORUs is certain. In fact, the question, "Do you need a spare?" quickly changes to "How many spares do you need?"

Estimating how many spares the station requires becomes even more complicated when you consider many spares are extremely expensive (in the $100,000 to $1 million dollar range) and that spares budgets are very limited. You also must decide what spares can be brought and stored in the station and what spares must stay on the ground because shuttle weight and station storage volume is also severely constrained. All those considerations went into developing the M-SPARE methodology.

WHY THIS APPROACH?

Another question is, "What does this method do that other approaches fail to do?" The answer is illustrated in Table 1-1. That table compares two ways of selecting spares for a hypothetical station that contains only two critical ORUs. The traditional approach treats all ORUs the same. It selects spares so that each ORU has a 95 percent chance of having at least as many spares as demands (see top of Table 1-1). Space station availability is the probability that no ORU is inoperative for lack of a spare, which is the product of the two probabilities (90 percent). That means both ORUs are operating 90 percent of the time. The station resource expenditure is $13: $3 for three spares of ORU A at $1 each, and $10 for two spares of ORU B at $5 each.

However, there is a better way to determine a spares mix. The approach focuses on how well the station as a system of ORUs is performing as opposed to how well each ORU is performing. Thus, the system approach does not treat all ORUs the same but considers that their failure rates and costs are different. Table 1-1 (bottom section) demonstrates that by slightly changing the spares mix for ORUs A and B to 4 and 1, respectively, you can improve the station availability (from 90 percent to 91 percent) and reduce cost (from $13 to $9). This example is a simplification of how the M-SPARE model forecasts spares requirements. Basically, M-SPARE sets priorities for spares and selects the spares that will improve the station availability the most per unit cost.

TABLE 1-1

COMPARISON OF TWO SPARES' SELECTION APPROACHES

Traditional Targets: 0.95			
Parameter	**ORU A Cost = $1**	**ORU B Cost = $5**	**Space station**
Performance probability	0.95	0.95	90%
Number of spares	3	2	—
Cost ($)	3	10	13
Optimal: A Better Way			
Performance probability	0.98	0.93	91%
Number of spares	4	1	—
Cost ($)	4	5	9

To prove our point, we evaluated a data base with 50 ORUs using the first approach and selected spares so that each ORU's performance probability would be 0.95 or more. This procedure resulted in an expenditure of $106,840 and station availability of approximately 25 percent. For the same $106,840, M-SPARE selected an optimal spares list that produced a station availability of 73 percent, almost three times greater than the traditional approach. In Chapter 7, we discuss how that analysis can be duplicated.

A DETERMINISTIC EXAMPLE

To help define and explain the M-SPARE methodology, let's discuss the spares and funding estimates for a simple example with a deterministic, constant ORU failure rate. Consider one ORU with a 180-day logistics cycle, one resupply flight at the beginning of the year and one in the middle, four failures every logistics cycle, a launch date of October 1995 (the beginning of FY96), and a constant failure rate.

If this ORU is not reparable, then our spares requirement model is simple. For FY96, the ORU needs 4 spares pre-positioned on orbit on Day 1 of the year to replace the 4 failures over the course of the first logistics cycle and then 4 more ready for the

mid-year launch to cover the second logistics cycle. That sums to a spares requirement of 8 for the entire year. The cumulative spares requirements increases to 12 in the beginning of FY97 and then 16 in the middle of FY97. Thus, for the nonreparable example item, the "gross" spares requirement at launch equals the cumulative failures (previous failures plus the expected failures in the next cycle) shown in Row 2 of Table 1-2a.

TABLE 1-2a

SPARES REQUIREMENTS (DETERMINISTIC FAILURES)

Logistics cycle	Row	FY96		FY97		FY98		FY99	
		1	2	3	4	5	6	7	8
Failures	1	4	4	4	4	4	4	4	4
Cumulative failures	2	4	8	12	16	20	24	28	32

However, if we assume that the broken ORU is reparable 75 percent of the time, the generated repairs eventually produce serviceable spares to replace some of the failed ORUs and slow the growth of the gross requirement. In our example, ORUs do not start entering the repair process until the second shuttle flight returns with broken ORUs from the first logistics cycle. We assume the original equipment manufacturer (OEM) requires 145 days to repair them so they are available by the end of the year. Thus, the OEM repairs three ORUs (75 percent repair rate times four broken ORUs) in time for the third shuttle launch. From then on, the OEM generates an additional three repairs each logistics cycle (Row 3 of Table 1-2b).

We can now calculate spares requirements for this reparable ORU by subtracting cumulative repairs from cumulative failures (i.e., Row 2 − Row 3 = Row 4 in Table 1-2b). To calculate the maximum *gross spares requirements* in the year, we use the requirements for the second logistics cycle (see Row 5 of Table 1-2b). The *net spares requirements* for any year is the increase in requirements from the previous year (see Row 6 of Table 1-2b). After the transition year, FY96, the net spares equals the condemnations per year.

TABLE 1-2b

SPARES REQUIREMENTS (DETERMINISTIC FAILURES)

Logistics cycle	Row	FY96		FY97		FY98		FY99	
		1	2	3	4	5	6	7	8
Failures	1	4	4	4	4	4	4	4	4
Cumulative failures	2	4	8	12	16	20	24	28	32
Cumulative repairs	3	0	0	3	6	9	12	15	18
Requirements	4	4	8	9	10	11	12	13	14
Gross requirements/year	5		8		10		12		14
Net requirements/year	6		8		2		2		2

We next spread the spares price (net spares times unit price) across the procurement lead time (PLT), assumed to be the 2 previous years. We also assume we incur 60 percent of our costs in the first year and 40 percent of our costs in the second year of the PLT. (The user can specify those percentages as input.) Thus, if we need eight spares in FY96 with a unit price of $125,000, we spend $600,000 (eight times $125,000 times 60 percent) in FY94 and $400,000 in FY95 (see bottom of Table 1-2c). We repeat that cost spread for the other net spares requirements in the next 3 years. We develop ORU funding requirements (*annual budget estimates*) by summing up the dollars for each fiscal year. If we follow this process for all ORUs and for all criticalities, we have our spares and funding requirements by year.

With this simple example as background, we can now discuss the basic assumptions of the model. Later, we will expand upon our example and discuss the more complicated probabilistic processes and changing failure rate implemented in M-SPARE. In such cases, M-SPARE adds "safety" margins of spares to the requirements so that the station can meet unexpected increases in demand.

BASIC MODEL ASSUMPTIONS

To estimate funding requirements, we must make some basic assumptions. Those assumptions are intended to accurately reflect possible future conditions while keeping the M-SPARE model simple and understandable. Figure 1-3 summarizes those assumptions for a single model year – FY98.

TABLE 1-2c

SPARES REQUIREMENTS (DETERMINISTIC FAILURES)

Logistics cycle	Row	FY96		FY97		FY98		FY99	
		1	2	3	4	5	6	7	8
Failures	1	4	4	4	4	4	4	4	4
Cumulative failures	2	4	8	12	16	20	24	28	32
Cumulative repairs	3	0	0	3	6	9	12	15	18
Requirements	4	4	8	9	10	11	12	13	14
Gross requirements/year	5		8		10		12		14
	6		8		2		2		2

Outlays ($000)	FY94	FY95	FY96	FY97	FY98
For SSF FY96	600	400			
For SSF FY97		150	100		
For SSF FY98			150	100	
For SSF FY99				150	100
Annual budget estimate	600	550	250	250	100

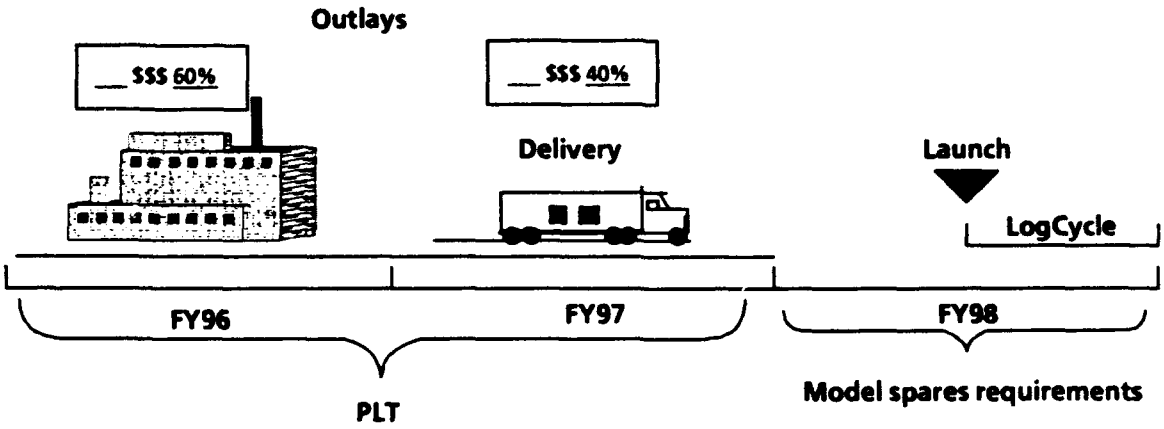

FIG. 1-3. OUTLAYS MEET FUTURE SPARES REQUIREMENTS FOR FY98

Since the SSF budget process uses annual estimates, we need to develop spares requirements on an annual basis. In addition, we need sufficient spares to satisfy the year's most demanding requirement. For the growing SSF, the greatest number of failures should occur at the end of the year when SSF is at its largest configuration. Since M-SPARE generates spares requirements for a specific logistics cycle, we run M-SPARE for the last logistics cycle in the fiscal year. In that way, M-SPARE requirements are based upon the point when the station growth is the largest. [In exceptional cases, ORU quantity may decline over time (e.g., phasing out an ORU) so that the timeframe also ensures that we do not buy a spare we later will not need.] We assume that all ORU logistic cycles end at the end of the fiscal year and start a logistics cycle earlier. For instance, if an ORU has a 180-day logistics cycle, we assume the last logistics cycle starts on the seventh month of the fiscal year; if an ORU has a 135-day logistics cycle, we assume the last logistics cycle starts on the eighth month of the fiscal year. Eventually, NASA might want to input actual logistics resupply flight schedules into M-SPARE, but for now and for a budget model, we believe this level of detail is adequate.

Next, we assume that spares deliveries arrive at the beginning of each fiscal year. That assumption forces all orders to be placed a PLT earlier (in Figure 1-3, that is at the beginning of FY96). We also assume that outlays for the procurement occur over the entire lead time (e.g., a 2-year PLT: FY96 and FY97). The percent of unit price that occurs each PLT year (e.g., 60 percent in FY96 and 40 percent in FY97) is determined by a user-specified *spread vector*.

For two reasons we assume the station receives all orders at the beginning of a fiscal year. One reason is to simplify the budget outlay calculations. The outlays now fall in the same number of fiscal years as the PLT, and we can easily apply and track the spread vector percentages. The more important reason is to ensure dollars are budgeted and spares delivered in time to meet all requirements. In practice, the station does not need all spares on Day 1 of the year. However, the station does need many spares early in the year to be loaded for the first shuttle launch, which is assumed to occur at the beginning of the year. Also, all spares must be delivered by the last shuttle launch of the year, which occurs near the middle of the year. The same Figure 1-3 process repeats itself for each requirement year thereafter.

Finally, we assume that the PLT includes the time from when the broken ORU is brought down to the ground to the time a new one is procured and is ready to be loaded on the shuttle. That means the PLT includes production time, administrative time, shuttle launch processing time, order and shipping time, and all other delays that may occur. Users can specify the PLT for each ORU (from 1 to 5 years) and the corresponding spread vector for each year.

Eventually, NASA might want to modify those assumptions. For instance, when NASA actually orders spares, they will probably place orders throughout the year and run M-SPARE at more frequent intervals, perhaps even before every procurement. That may cause the spares requirements to fall in to more than one fiscal year. We believe that at this early stage of station development and for the aggregate projections of a budget model, more complex assumptions are unnecessary.

In summary, M-SPARE includes a number of key assumptions:

- Gross spares requirements are calculated on an annual basis and represent the maximum requirements for the fiscal year.
- Net spares requirements (gross requirements minus assets) are delivered at the beginning of the fiscal year and are ordered a PLT earlier.
- Budgets are outlays that accrue over a specific fiscal year of the PLT.
- Those outlays are distributed to each PLT year based upon a spread vector that defines what percentage of the ORU unit price is accrued in each of the PLT years.
- The PLT includes the time from when the broken ORU is returned to Earth until the time a new ORU is procured and loaded on the shuttle.
- All costs are assumed to be in constant dollars with the baseline year equaling the year of the ORU unit price unless otherwise specified.
- All time units for spares and funding requirements are fiscal years unless otherwise specified.

USERS AND USES

The M-SPARE model is being used at all NASA SSF project offices and their prime contractors and at the Canadian Space Agency to estimate SSF spares requirements (the other international partners have also received copies of the model). Specifically, M-SPARE is used at project offices in the POP cycle to produce two basic products. The first POP product presents the spares and funding

requirements or what the station ideally would like to have. The user inputs yearly availability targets, and M-SPARE generates spares requirements for the first years of the station's life (e.g., FY96 to FY04) and the corresponding funding requirements for the next 9 fiscal years (FY94 to FY02) that meet those specified targets. That method is described in the Basic Model Assumptions section of this chapter and is what we term the *spares requirements product.*

For the second POP product, the user inputs the expected annual budgets for the next 9 fiscal years, and M-SPARE determines how many spares NASA can buy with these funds. We will refer to those input budgets as *annual POP marks* and the output as the spares *constrained budget product.* It is more difficult to produce the constrained product. As we will discuss in Chapter 9, M-SPARE does produce spares estimates based upon the POP marks.

CHAPTER 2

INSTALLATION AND DEMONSTRATION

In this chapter, we explain how to install the model, how to operate the user interface, and how to take the model on a quick test drive. This version of M-SPARE is self-contained so that the user can edit input files, set options, operate the wear preprocessor (see Chapter 10), and run the model all within the M-SPARE interface.

INSTALLATION

To install the M-SPARE model, log on to your computer. Insert our floppy disk into your drive (our example assumes this will be the A drive but any high-density 5.5 inch floppy drive works). The commands listed below make a new directory called SPARE on your hard disk drive (our example assumes this will be the C drive, but again any hard drive works) and copy the required files from our floppy disk to the new SPARE directory. [*Note:* All characters enclosed in double quotations are the commands you enter or select from your PC keyboard usually followed by pressing the "Enter" key. You do not need to enter the quotation marks themselves.]

- Enter "A:" – the drive where our floppy disk is.
- Enter "INSTALL C" to install the model on your C drive.
- Press any key to complete installation.

When the installation is finished, you will see a Disk Operating System (DOS) prompt on your screen. At that point, M-SPARE and its accompanying interface are installed and you are ready to run the model.

INTERFACE OPERATION

Now that the model is installed, we will discuss what is necessary to run the model.

- If your system is not already in the SPARE directory, type "CD\SPARE" to move there.
- Type "START" to enter the M-SPARE interface.

Your computer screen now resembles Exhibit 2-1, and you can choose one of five choices displayed in the menu bar at the top. [*Note:* All exhibits (figures in a box) in this report represent information that may appear on your computer monitor.] The user can select a menu choice in three ways. (1) use the left or right arrow keys to move the highlight bar to the menu option and then press the "Enter" key, (2) press the highlighted red letter in each menu choice, or (3) click on the option with your mouse. The bottom line of the interface reminds you to press the function key "F1" to access the menu or press the "ALT-X" key combination to terminate M-SPARE after executing the model. Each of the following menu choices corresponds to one of the steps required to run M-SPARE and analyze its results.

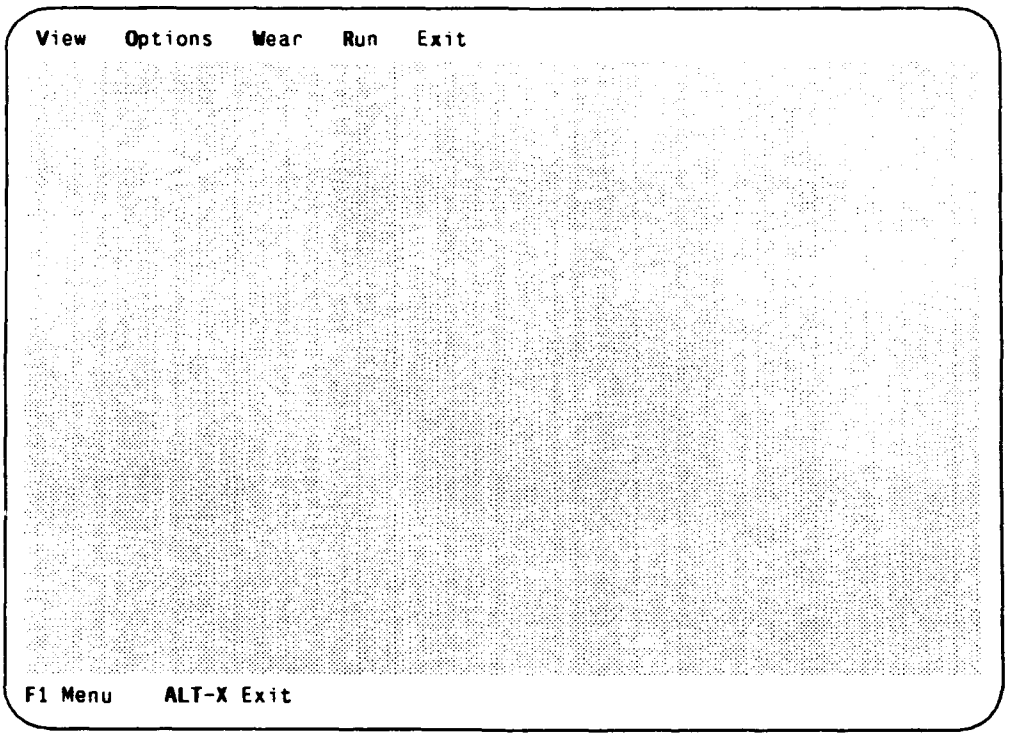

EXHIBIT 2-1. INTERFACE MENU

View

If you select the "View" choice, a menu box appears (see Exhibit 2-2) and the user can select various options to view M-SPARE ORU inputs (see Chapter 5) and outputs (see Chapter 8). The first step in running the model is to examine the ORU data base, MSPAREIN.RPT, to make sure the appropriate data exists. From this point, you can also examine the summary and detail output report files

(BUDGET.RPT and OUT.RPT, respectively) once you run the model. The computer automatically stores the output reports from your previous run (OLDOUT.RPT and OLDBUD.RPT). In general, the "View" choice allows the user to access a powerful commercial text editor called Vedit. Vedit can view and edit large files, examine several files at once, and perform a host of other functions described in the accompanying *Vedit User's Manual.* Once in the editor, press the "F1" key to display its menu choices. To access only the editor, select the "Editor" option. If you then change your mind while in the "View" menu box, and want to step back to the previous menu, just press the "Esc" key. [*Note:* If your package does not contain a text editor or you want to use your own, copy your editor into the SPARE subdirectory and name it Vedit (i.e., Vedit.exe or Vedit.com). MS-DOS 5.0 now has an editor that allows you to access large files so you may want to use that editor.]

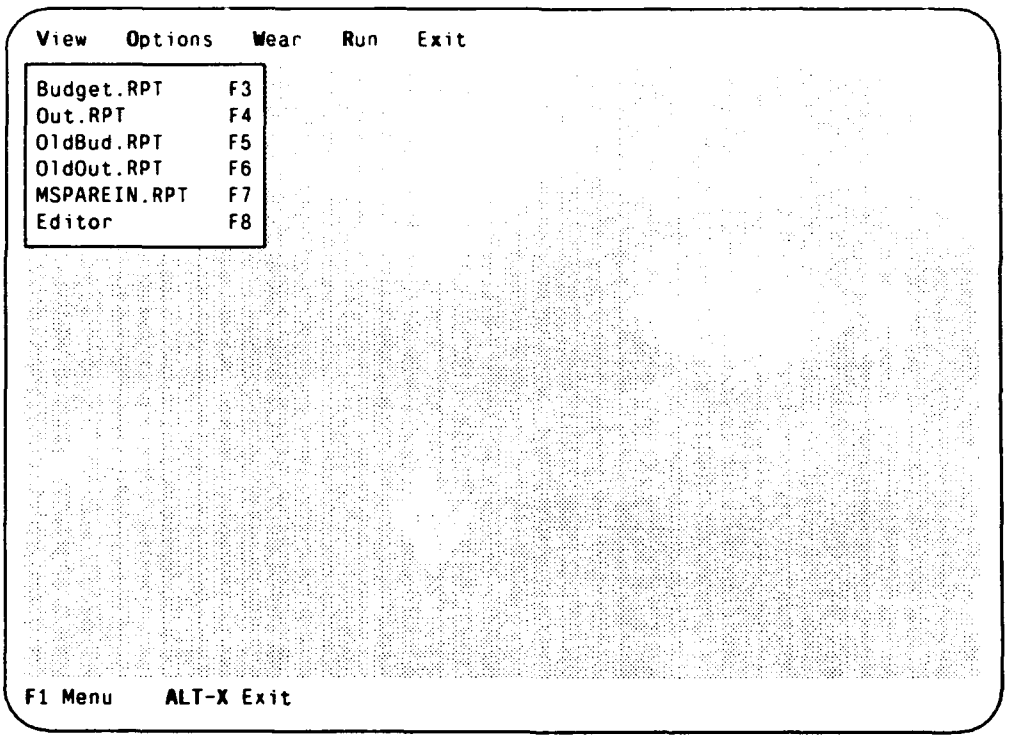

EXHIBIT 2-2. VIEW MENU

Options

The second step in running the model is to set the basic model options. The "Options" menu choice opens the options file that provide a set of key parameters that

usually do not vary from one model run to the next. Chapter 6 describes how to change options and what each options does.

Wear

The third step in running the model is to set up and run the wear preprocessor. This step is required only if the MSPAREIN.RPT file under the "View" menu contains ORUs that may wear out during the model time horizon. If that is the case, the wear preprocessor only needs to be run once or whenever a demand factor changes in the MSPAREIN.RPT file or the launch schedule changes in the OPTIONS.RPT file. The preprocessor simulates an ORU's wear rate and random failure rate and then estimates an aggregate failure rate (i.e., mean demand). That rate is automatically used in the spares calculation. For more information on the operations of the preprocessor, see Chapter 10.

Run

Once you view the input, check the options, and execute the wear preprocessor (if necessary), then select the menu choice "Run" to execute the model and calculate spares and budget estimates. Chapter 7 describes the user queries required for M-SPARE operation. After each M-SPARE run, the user is returned to the initial interface screen to examine the results using the "View" choice or rerun the model using the "Run" choice.

Exit

When you are finished with M-SPARE and the interface, select the "Exit" choice to exit the interface and return to DOS.

QUICK TEST DRIVE

To present an overview of the M-SPARE operations and capabilities, we will take you on a test drive. We have already set the options and a sample data base for you. You will need to take about 10 minutes to enter the inputs we specify. Our goal is to determine spares requirements for the first 8 years. The sample station is a single system, the electric power system (EPS) with only Criticality Code 1 ORUs. In Chapter 7, we discuss in detail the meaning of the queries and model plots. For now, we merely present an overview of the model operation.

To begin, make sure you are in the model interface. If you have questions, see the interface operation section near the beginning of this chapter. Enter "R" to run the M-SPARE model. The model flashes the M-SPARE title page and then asks you to select a criticality code. Enter "1" for Criticality Code 1. Next, the model will ask you to enter information year by year.

First Model Year: FY98

Enter "R" to run the first model year and "G" to select the Ground-Stock-Only option from the Run menu. This reflects the fact that there will be no on-orbit spares storage. Once in the Ground-Stock-Only Mode Dialog, press the "Tab" key, then press the down arrow to select a ground availability target. Press the "Tab" key again to move to the next query and enter a "95". Then, press the "Enter" key to run M-SPARE for FY98. In less than a minute, the resource-versus-ground availability curve (see Exhibit 2-3) appears on the screen. Ground availability estimates the performance only of the ground inventory, our current assumption. That is the probability the ground inventory supplies all spares needed to replace the on-orbit failures from the previous cycle. As we discuss in Chapter 4, it is similar to measuring station availability used when both on-orbit and ground inventories are available.

The curve presents all possible ground availabilities under varying investments. The solid area corresponds to the 95 percent availability target you entered and defines the initial spares list. It shows that to reach 95 percent availability, we require a spares investment of about $95 million. The spares list associated with that point is stored in the output file that we discuss in Chapter 8. Press the "Enter" key to remove the plot and continue.

Model Year 2: FY99

To run the next model year, FY99, for the same availability target, press "Enter" to run the model and "G" to select the Ground-Stock-Only option from the run menu. Press "Tab", then press "Enter" (no additional selection is required because the model defaults are the inputs from the previous year). In less than a minute, the resource-versus-ground-availability curve (see Exhibit 2-4) appears on the screen. The new curve is different from the previous curve. The straight line part of the curve, from 0 investment to $95 million, displays the systems performance with only last year's spares investment (the starting asset position for FY99). The curve

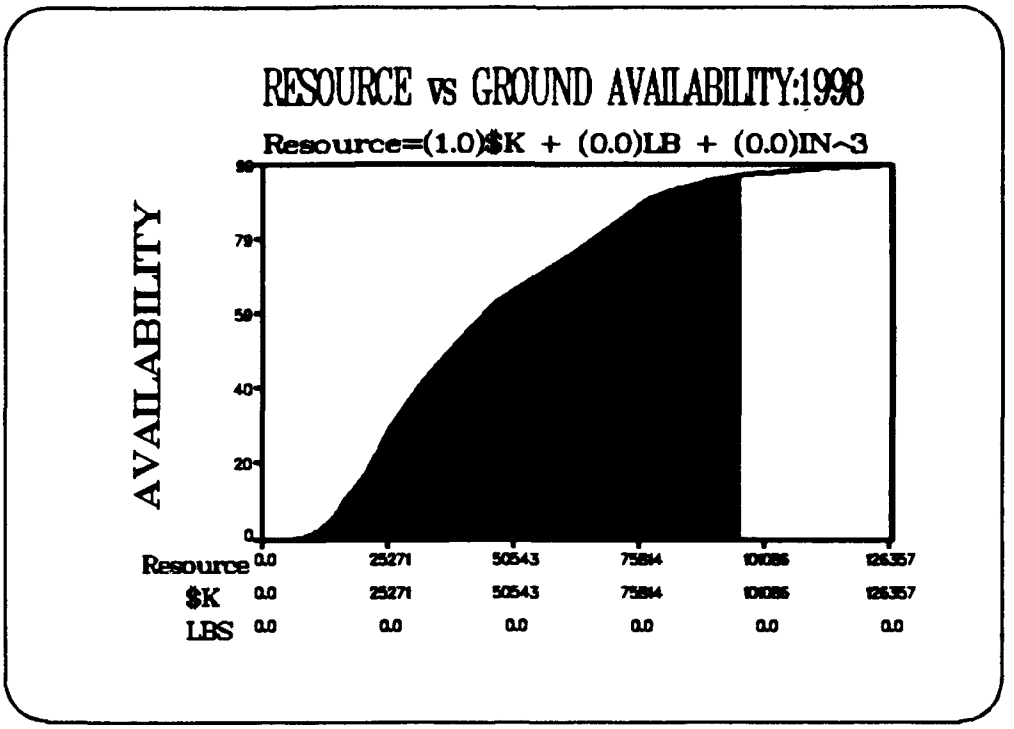

EXHIBIT 2-3. RESOURCE-VERSUS-GROUND AVAILABILITY CURVE: FY98

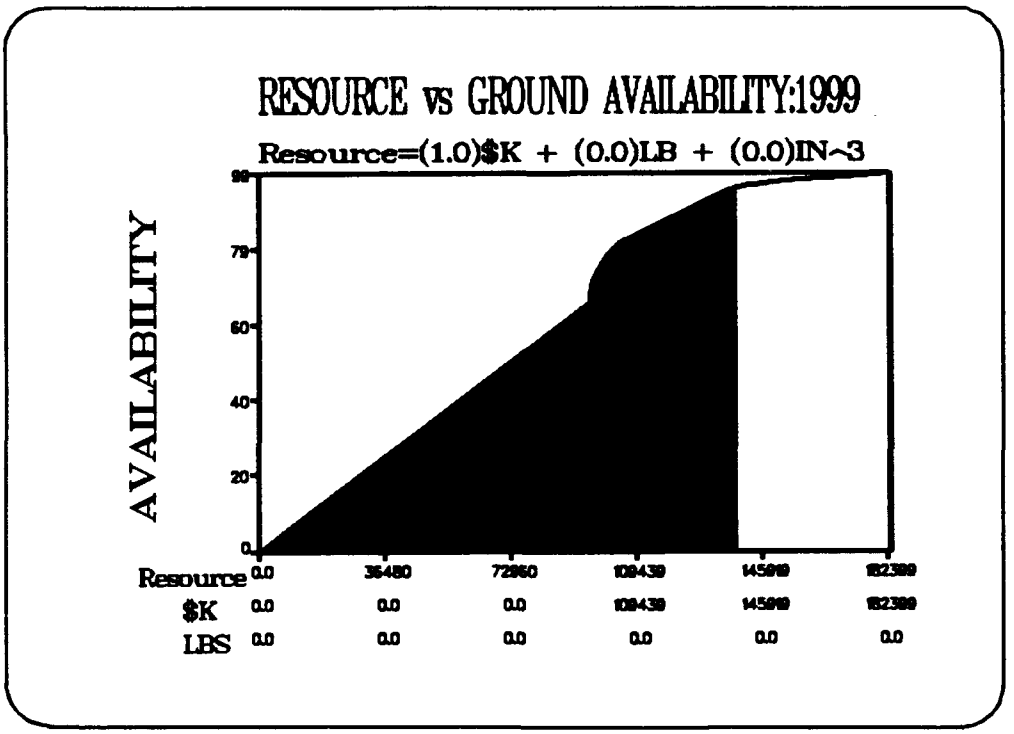

EXHIBIT 2-4. RESOURCE-VERSUS-GROUND AVAILABILITY CURVE: FY99

from $95 million to $140 million displays the net requirements needed to reach a 95 percent availability. In other words, the curve illustrates that with the growth of the EPS in the current fiscal year, the previous spares inventory only brings the predicted system availability up to 60 percent. The system requires a total investment of about $140 million to reach a 95 percent availability in FY99.

Model Year 3: FY00

In the next model year, we suppose that on-orbit storage is available. Price and weight of each ORU is also considered. You press "R" to run the model year and "Enter" to select the Multiple-Pass: Orbit & Ground option (i.e., assumes levels of orbit and ground storage). Once in the Multiple-Pass-Mode Dialog, keep pressing "Tab" until you highlight the last query, enter an Availability Target from 0 to 100 percent, and then type "95" and press "Enter" to start the model run for model year 3. The model runs a number of tradeoff passes between price and weight (the tradeoff you selected). Each pass reduces the total weight of the on-orbit spares at a related price penalty (see Chapter 3 for more information).

After a couple of minutes, a resource-versus availability curve such as Exhibit 2-4 appears on the screen. It shows that to reach 95 percent availability, we need resources of about $195 million and 14,000 pounds (see the exhibit's second and third X-axes, respectively).

Press "Enter" to display possible price-versus-weight tradeoff solutions for all passes at a 95 percent availability (see Exhibit 2-5). The plot's top left point is the minimum price solution. As you move to the right, total weight is reduced but at a price penalty. The solution M-SPARE automatically selects is near the elbow of the curve. We discuss how you can select other solution points in Chapter 7. Thus, M-SPARE calculates spares requirements based upon price and weight and also presents a range of possible solutions. Press "Enter" to remove the plot and continue.

Model Years 4 to 7: FY01 to FY05

The next 5 model years also assume on-orbit storage and a 95 percent availability. For each year, enter the following sequence of inputs. Press "R" to run the model. Press "Enter" to select the Multiple-Pass: Orbit & Ground option. Once in the Multiple-Pass-Mode Dialog, press "Tab" and then "Enter". The model does not

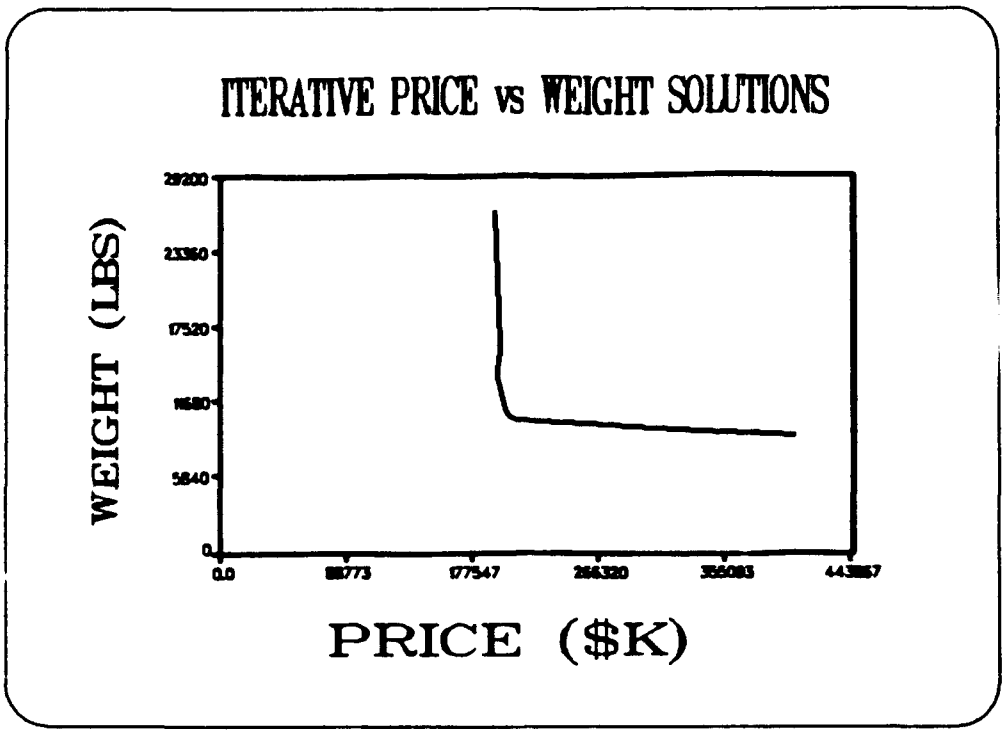

EXHIBIT 2-5. ITERATIVE-PRICE-VERSUS-WEIGHT TRADEOFF SOLUTIONS: FY00

require you to enter a 95 percent availability because that input did not change from the previous year.

As in the analysis of FY00, the model displays the resource-versus-availability curve and the iterative-price-versus-weight solutions curve. When you are finished examining a curve, press "Enter" to continue.

Notice that in FY02, the resource-versus-availability curve takes an unusual shape. This is because the ORU batteries in the data base are estimated to last approximately 5 years before they wear out. FY02 is the fifth year of their life and many will need to be replaced. The previous year's spares bring the station availability up to only 15 percent. However, once the system adds batteries, the availability shoots up.

After you enter variables for FY05, your work is over. The model then calculates the estimates for the budgets along with other information and stores them in the appropriate files (see Chapter 8). The model also produces a summary plot for spares weight (sometimes referred to as upweight or upmass) estimates (see Exhibit 2-6). The model produces a host of other summary tables stored in output

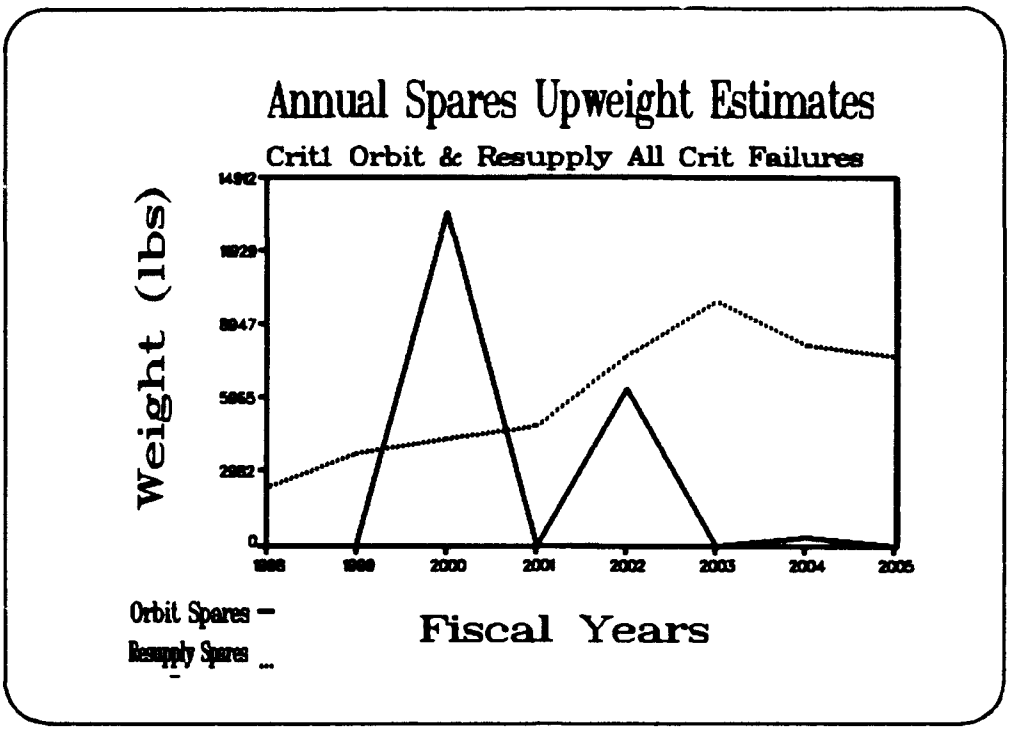

EXHIBIT 2-6. ANNUAL SPARES UPWEIGHT ESTIMATES

files, but displays weight information because it presents a glimpse of M-SPARE's additional capabilities.

Exhibit 2-6 summarizes two types of spares weight for all model years. The solid line displays the spares weight for all shuttle launches in a particular year. Those launches allow astronauts to pre-position spares in space to replace anticipated failures. M-SPARE estimates that launches to pre-position spares occur mostly in 2 specific years: in FY00 (the first time on-orbit storage volume becomes available) and in FY02 (in order to replace worn out batteries). Otherwise, the on-orbit inventory levels remain relatively constant. The other weight resource type in Exhibit 2-6 (dotted line) is the resupply weight of the spares. The resupply weight estimates the movement of spares from the ground to the station. M-SPARE assumes that shuttles resupply SSF with spares that replenish on-orbit inventory or replace failed ORUs if no inventory is available. To estimate the resupply weight, M-SPARE multiplies an ORU's average number of failures in a year times its unit weight and then sums across all ORUs for all criticalities. We display resource types to present the complete picture of spares weight requirements (the combination of on-orbit and

resupply weight). As with budget constraints, SSF must eventually meet weight and volume constraints so M-SPARE must also estimate those requirements.

When you are finished examining the upweight estimates press "Enter" and you return to the user interface discussed at the beginning of this chapter. You can now "View" the outputs or wait until we discuss outputs in Chapter 8.

PC REQUIREMENTS

The model operates on IBM-compatible PCs with about two megabyte of hard disk storage and about 250 kilobytes of memory to run 50 ORUs. A rough rule of thumb is that every ORU above the 50 will require an additional half of a kilobyte of memory. A PC with a math coprocessor runs the model about 10 times faster than one without a coprocessor.

The model input and output data are text or ASCII (American Standard Code for Information Interchange) files so that you can browse them with your editor or word processor. You can avoid using the interface if you prefer to view the text files this way. Just type "MSPARE" to run the model from the C:\SPARE DOS prompt.

The key M-SPARE input and output files in your C:\SPARE subdirectory are the following:

- *MSPARE.EXE* – the M-SPARE model in an executable form.
- *MSPAREIN.RPT* – a text file that now contains sample input data from three station subsystems and about 50 ORUs and eventually will contain your ORU data base.
- *OPTIONS.RPT* – the options text file that allows you to change detailed model options without recompiling a new executable file.
- *BUDGET.RPT* – a text file that contains the summary estimates of gross and net spares and funding requirements.
- *OUT.RPT* – the text output file in which the detailed spares results that generate the summary results of the BUDGET.RPT file are stored.

We describe the pertinent user files in more detail in the subsequent chapters of this guide.

CHAPTER 3

SPARES PRIORITIZATION OVERVIEW

The heart of the model is the process that sets priorities for spares. That process builds a prioritized "shopping list" for spares based upon each spare's benefit-to-cost ratio. At the top of the shopping list is the spare that has the greatest marginal benefit to station availability per resource expenditure, or the biggest "bang for buck." Selecting in the order indicated on the list yields the maximum availability rate for the resource expended. The optimization process assures that no other combination of spares will give a higher availability for the same resource expenditure or the same availability for a lower resource expenditure. As one moves down the priority list and adds spares to those already selected, the station availability and resource expenditure increases, always yielding an optimum mix. The entire selection process creates the resource-versus availability curve (see Exhibit 2-3), and each spare selected creates a point on that curve.

Significantly, the model can work on any "physical system" or set of ORUs. For this chapter, we will define the set as the critical ORUs on the station. However, the same discussion can apply to the set of critical ORUs at any level: distributed system, subsystem, or sub-subsystem.

Another significant point is that the M-SPARE model uses the benefit-to-cost ratio and assumes that all ORUs are of equal importance – if any ORU fails, it will create the same detrimental impact on the station as any other ORU. For instance, the model does not consider that critical life support ORUs are more important than noncritical lighting ORUs in the spares selection process. That means the model can only handle one classification of ORUs at a time. Thus, the user has at least three sets of ORUs (Criticality Codes 1, 2, and 3). The model handles each set separately. Another reason for separating ORU types is that Criticality Code 1 spares are stored on orbit and on the ground while other spares are stored only on the ground. We initially assume spares can be stored at either location and then we discuss how the model handles a case in which spares are stored on the ground only.

In the remainder of this chapter, we present an overview of model methodology in three sections:

- *Station Availability.* We define availability as the probability that no system is inoperative for lack of a spare ORU over the logistics cycle.
- *Spares Prioritization Across ORUs.* We define the process for prioritizing the ORU spare that yields the greatest bang for buck (highest station availability per resource expended).
- *Multiple Resource Optimization.* We discuss how the model manages several resources separately and in combination, a feature that allows the user to balance conflicting resource expenditures.

STATION AVAILABILITY

A major advantage of the M-SPARE methodology is that it links the spares mix directly to station availability. To understand the spares selection process, one must first understand how M-SPARE derives station availability.

We assume the station starts each logistics cycle after the shuttle has resupplied it with a complement of spares. Those spares are intended to satisfy demands (replace failures) over the logistics cycle (i.e., until the next shuttle provides resupply). For the station to be available over the entire logistics cycle, each ORU must either experience no failures or have at least one on-orbit spare replacement for every failure. We term the likelihood of that condition as the ORU "probability of a spare when needed" (PSN). Thus, assuming independence of failures across ORUs:

$$\textit{station availability} = \prod_i PSN_i\left(s_i\right), \qquad \text{[Eq. 3-1]}$$

where

s_i = number of spares for ORU_i

i = ORU index.

The ORU PSN used in M-SPARE is related to the standard ORU probability of sufficiency (POS) measure, but additional factors are considered. Both consider the length of time a broken ORU spends in the maintenance process, the length of the logistics cycle, and the number of on-orbit ORU failures during that cycle. However, in M-SPARE, the ORU PSN includes the possibility of starting the logistics cycle with fewer than the desired number of on-orbit spares because the ground stock is not

available at shuttle launch. Further, M-SPARE accounts for the different benefits of spares stored on orbit and on the ground – it performs an optimal multi-echelon tradeoff. An on-orbit spare has a greater benefit to station availability because it is more accessible; a ground spare has lower resource expenditure because it imposes no penalties for weight at shuttle launch or on-orbit-storage-volume. We present a detailed discussion of the calculation of ORU PSN and the multi-echelon tradeoff in Chapter 4. For now, we assume that information is available.

Thus, station availability is an indication of how well the entire space station performs its mission, given a certain spares mix. We do not imply that the model produces an all-inclusive view of station availability; rather, it merely considers hardware (ORU) failures. However, the station may not be available for other reasons such as lack of fuel or lack of crew time to replace a failed ORU even if a spare is at hand. Nevertheless, the model does capture the most important factors required to estimate spares. [M-SPARE may be linked with other models such as Simulation of Manned Space Station Logistics Support (SIMSYLS) or Reliability and Maintainability Assessment Tool (RMAT) to estimate impacts of those other factors.]

SPARES PRIORITIZATION ACROSS ORUs

Marginal Benefit-to-Cost Ratio

The first step required to develop our shopping list of spares is to determine the bang-for-buck measure (i.e., the marginal benefit-to-station availability divided by unit resource expenditure) for each ORU spare. Let us now discuss the steps necessary to develop the methodology. Appendix A provides mathematical proof that our methodology produces an optimum solution.

The methodology objective is to maximize the availability in Equation 3-1 subject to a constraint on spares investment. Note that Equation 3-1 is a product of the item decisions, whereas spares investment is the sum of costs on each item.

We need to convert the optimization problem into a sum of terms, so that the availability contribution and spares cost are additive across items. This can be done

by taking the logarithm of availability in Equation 3-1 since a function and its logarithm achieve their maximum at the same point (see Equation 3-2).

$$ln\,(station\ availability) = \sum_i ln\left[PSN_i(s_i)\right]. \qquad \text{[Eq. 3-2]}$$

Let s_i designate the optimal policy for each ORU_i that produces the largest availability for some total investment in spares (e.g., $s_i=0$ for all items i when the investment is 0). Then, the next item to buy is that item which gives the maximum increase in the logarithm of availability per unit resource. This is called marginal analysis and is generalized with the following equation:

$$\frac{marginal\ benefit_i}{unit\ resource_i} = \frac{ln\left[PSN_i(s_i+1)\right] - ln\left[PSN_i(s_i)\right]}{unit\ resource_i}. \qquad \text{[Eq. 3-3]}$$

Example of the Prioritization Process

To explain the prioritization process, we use a simple example for a few ORUs and assume price (dollars) is the resource type. We start the process by solving Equation 3-2 for the station availability with no resource expenditures (e.g., $s_i=0$ for all items). In the example given in Table 3-1, that value is equal to 22.8 percent.

TABLE 3-1

EXAMPLE OF SPACE STATION AVAILABILITY COST CURVE

Curve		ORU spares prioritized (shopping list)	*Bang for buck:* marginal benefit / cost	*Unit resource* (dollars)
Total resource (dollars)	Space station availability (percent)			
0	22.8	----	----	----
1	39.6	Filter	0.554	1
2	45.8	Filter	0.146	1
7	79.8	Valve	0.111	5
10	82.4	Sensor	0.033	3
⋮				

Next, the model checks all ORUs and chooses the one with the largest marginal benefit-to-cost ratio (i.e., the filter with a ratio of 0.554). It then increases the station availability by the marginal benefit to 39.6 percent and increases the total resource expenditure by the $1 unit cost of the filter. The selection of the filter creates the second point on our curve (first two columns of Table 3-1). Next, the model calculates a new benefit-to-cost ratio for the filter using Equation 3-3. Now the marginal benefit is the difference between obtaining the second and the first spare (i.e., 0.146). At that point, the process is repeated. The model selects the spare with the next biggest benefit-to-cost ratio (again, the filter); increments the resource expenditure and station availability to $2 and 45.8 percent, respectively; and recalculates a new benefit-to-cost ratio for the third filter. The model continues to repeat that process until the space station availability is close to 100 percent.

A final feature of the model is its ability to generate the spares mix for a user-specified resource or availability target. The model uses the resource target as the maximum resource expenditure and the availability target as the minimum station performance. To generate the spares mix, the model checks each point as it processes the curve. When it reaches the point at which the curve value first becomes greater than the target value, it stops. If the user selected an availability target, the model stores the spares level for each ORU. If a resource target is given, the model goes to the next to last spare so that it will not exceed the resource target. The model then stores the spares list.

In our example, if we want a spares mix for an availability of 82.4 percent, the model solution is to select two filters, one valve, and one sensor. If we want the spares mix for a resource target of $8, the model solution is to select two filters and one valve. Notice that the resource target ($8) is always greater than or equal to the model resource expenditure ($7) because the model buys complete spares. In general, the model expenditure is at worst a few percent less than the target. The resolution is accurate enough given the range of uncertainties for the budgets and spare costs. In the next section, we expand the model resources from dollars to include weight at shuttle launch and on-orbit storage volume.

MULTIPLE RESOURCE OPTIMIZATION

So far in our examples, the resource is the unit price of the ORU. However, the model can handle unit weight, unit volume, or a combination of individual resources

to establish the limiting resource. When a combination of resources is used, the model performs a multiple-criteria optimization and can balance possible conflicting resource utilization of spares.

The value for the unit resource in Equation 3-3 is estimated with the linear combination shown in Equation 3-4 for on-orbit spares. Equation 3-4 assumes that the user is interested in price and weight for shuttle launching.

$$unit\ resource_i = \left(coefficient \times price_i \right) + \left[(1 - coefficient) \times weight_i \right]. \qquad \text{[Eq. 3-4]}$$

If the user wishes to produce a spares mix for the minimal total cost (dollars), the model sets the coefficient to 1 and ignores the weight of the ORU. Conversely, if the user wishes to produce a spares mix for a minimal total weight, the model sets the coefficient to 0 and ignores the cost of the ORU. If a combination of the two resources is desired, the model uses a coefficient between 0 and 1. As the coefficient value changes over this range, the relative importance of price to weight changes proportionately. Each spares mix produced in this way is optimal in the sense that no other mix with the same or lesser total cost and the same or lesser total weight achieves the same or greater availability. (A modification of the reasoning in Appendix A can be used to establish this.) By using the coefficient, the user can perform multi-criteria optimization for two resources.

To demonstrate the multi-criteria optimization, we run the model (in the multiple-pass mode) for 11 different passes using our test drive data base and results. The example is for Criticality Code 1 ORU only. The model automatically changes the coefficients after each pass, producing a range of coefficients (1.0, 0.9, . . . 0.2, 0.1, 0). For each pass, the user-specified target is set to a 95 percent availability. Exhibit 3-1 displays the plot for the 11 passes. The plot is really composed of 11 points connected by a smooth line.

Similar to the resource-versus-availability curve, the plot in Exhibit 3-1 describes the range of tradeoffs between cost and weight. The user then can determine which tradeoff is most appropriate. For instance, we can attain a fairly low-cost solution without totally sacrificing station weight. The point near the elbow of the curve in Exhibit 3-1 offers that balance and is the point the model selected for the spares solution. Increasing the minimal total cost of the spares mix by 1 percent (from $193,306 with a coefficient of 1.0 to $195,230 with a coefficient of 0.5) improves

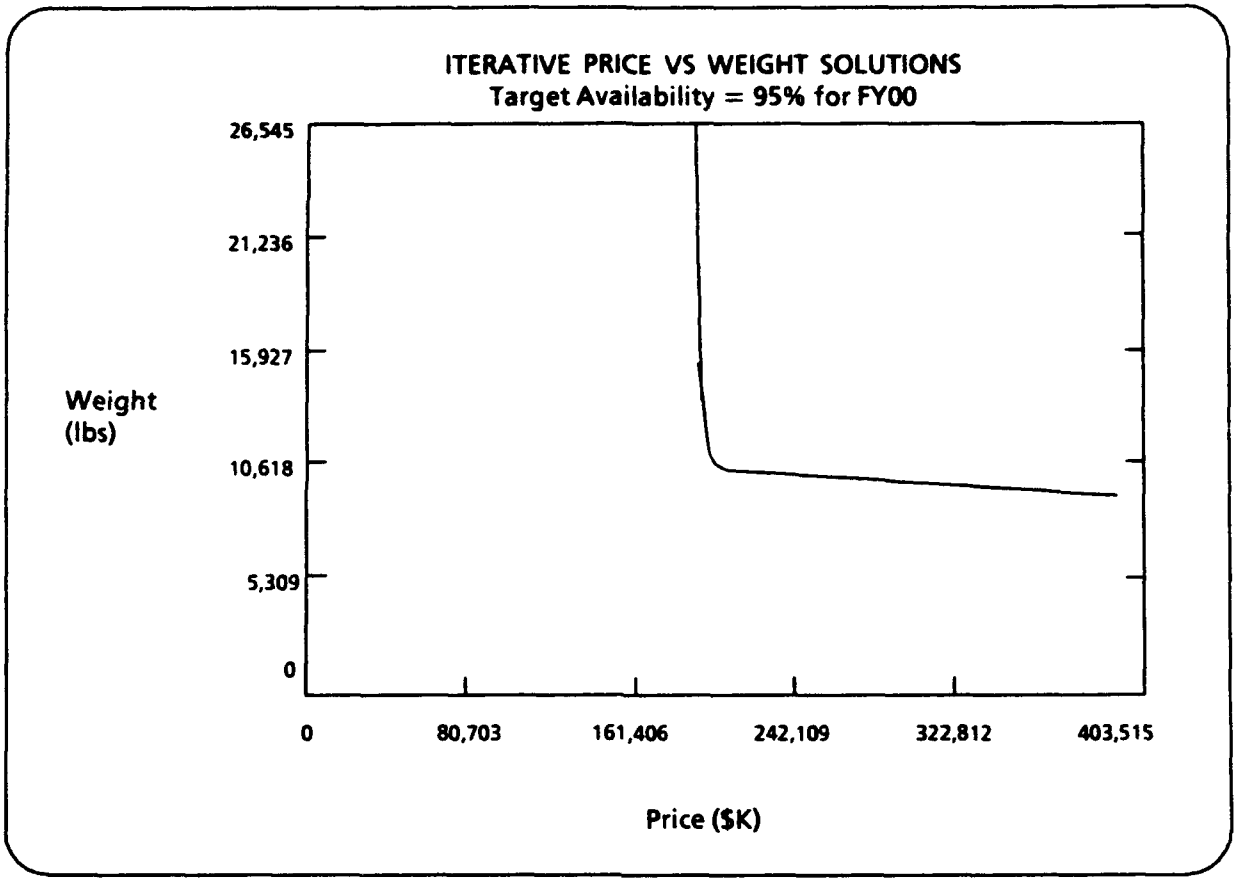

EXHIBIT 3-1. RESOURCE TRADEOFF POSSIBILITIES AT 95 PERCENT AVAILABILITY

the total weight of the initial spares 49 percent (from 26,545 pounds down to 13,556 pounds). [The Pass Solutions Table (see Chapter 8) presents the actual numbers that generated Exhibit 3-1.]

The model is actually performing two types of tradeoffs in Exhibit 3-1. One tradeoff is across ORUs. As the relative importance of weight increases, the model moves from selecting ORUs with the greatest bang for buck to selecting ORUs with the greatest bang for pound. The other tradeoff is between on-orbit and ground stock for a specific ORU. When price is the only resource of concern, on-orbit spares are selected because they offer a greater improvement in availability than ground spares. As weight becomes more important, more ground spares are selected because they carry no weight penalty.

As we said earlier, each point in Exhibit 3-1 is an undominated solution, meaning that for a point's total cost and weight, no other spares mix will produce a

higher station availability. Any mix with higher station availability will have higher cost, higher weight, or both.

In Exhibit 3-1, we showed a possible model scenario using price and weight in the ORU tradeoff and a user availability target of 95 percent. The model can also consider, in the linear combination for unit resource (Equation 3-4), the addition of a third resource – volume. (With modification, the model could include many more resources such as pressurized or nonpressurized weight and volume.) Also, if the user has a ceiling for station on-orbit storage volume, shuttle lift weight, and spares investment, the user can constrain the spares mix to those limits. Chapter 7 discusses how that expansion and the multiple-pass mode in general are implemented.

CHAPTER 4

DETAILED ORU MULTI-ECHELON METHODOLOGY

In this chapter, we discuss the model methodology at the lowest level, the ORU. We start by discussing the multi-echelon tradeoff for each successive spare (specifically, the ORU PSN and unit resource used in Equation 3-4). That tradeoff determines the number and storage location of the spares the model selects. We then discuss some M-SPARE ORU extensions in order to estimate most types of station spares requirements. Specifically, we discuss how M-SPARE estimates spares for various conditions or types of ORUs on the station.

The first section of this chapter, The ORU Multi-Echelon Tradeoff, is divided into the following subsections:

- *An Example of the Maintenance Process.* We present a deterministic example of the maintenance process and how the process affects the spares on the station.
- *Probability Distribution of Unserviceable Spares.* We move away from the deterministic example and discuss how to calculate the probability distribution for the number of unserviceable (broken) units in the maintenance process at the start of a cycle.
- *Multi-Echelon ORU PSN.* We describe how the model estimates the ORU PSN given any combination of on-orbit and ground stock.
- *Multi-Echelon Tradeoff.* We discuss the spares selection process between on-orbit and ground stock. The multi-echelon tradeoff is similar to the marginal analysis technique used across ORUs.

The second section, ORU Extensions, is divided into the following chapter subsections:

- *Replaced Condemnations.* We describe how M-SPARE selects spares to replace past condemnations.
- *Element Launch and Assembly Impacts.* We discuss how the model incorporates a growing station as elements are added and ORUs and quantities increase.

- *Alternative ORU Failure Patterns.* We describe how we approximate different failure patterns such as wear-related failures.
- *ORUs with Ground Spares Only.* We discuss ORUs whose spares are stored on the ground only and not on orbit.

THE ORU MULTI-ECHELON TRADEOFF

The initial focus of the multi-echelon tradeoff is the maintenance process that determines the time to replace or repair broken units. From there, the model determines the number of broken units before each shuttle launch, given a total spares level. Next, the model determines the ORUs available (total minus broken) to the station. Then, the model determines if the available units are adequate to cover the ORU failures in the next logistics cycle (the ORU PSN). Finally, M-SPARE determines the best location (ground or on orbit) for each successive spares level. This is the multi-echelon tradeoff.

An Example of the Maintenance Process

In this subsection, we describe the maintenance process and how it affects the spares for the station. We provide an example of an ORU with a deterministic, constant failure rate for each logistics cycle.

The maintenance process starts when an ORU fails on the station. The model assumes that the ORU is removed and replaced (if there is a spare) and the failed unit is brought back to Earth on the next shuttle. Once the ORU is on the ground, the model assumes it will face one of the three alternative maintenance levels: (1) the Kennedy Space Center (KSC) will repair the ORU; (2) the prime contractor or OEM will repair the ORU; or (3) maintenance engineers will condemn the ORU and a new one will be procured. If the repaired ORU or the replacement unit is needed, it is then ready to be returned to the station on the next shuttle. [*Note:* M-SPARE does not consider delays from on-orbit maintenance in its availability calculation because its impacts on spares selection are minimal.]

Figure 4-1 illustrates the deterministic maintenance process over time (logistics cycles of 180 days) for a hypothetical ORU. Four failures of the ORU initially occur on orbit during a cycle. The failed units are brought down to Earth where none are repaired at KSC, three spares (three quarters of the failures) are repaired at the OEM in 145 days (less than one logistics cycle), and one spare (a quarter of the failures) is condemned and a new spare procured in 26 months (less than five logistics

cycles). The user inputs the fraction of failures distributed to each maintenance level and the time required for maintenance at each level, and the M-SPARE model calculates the number of cycles required for maintenance (the number of days divided by logistics cycle length). The number of maintenance days at each level is the length of time a spare is on the ground before it is ready to be returned to orbit on the shuttle. The number of maintenance days includes time for testing, fault isolation, administration, transportation, and other times associated with the maintenance process or shuttle requirements.

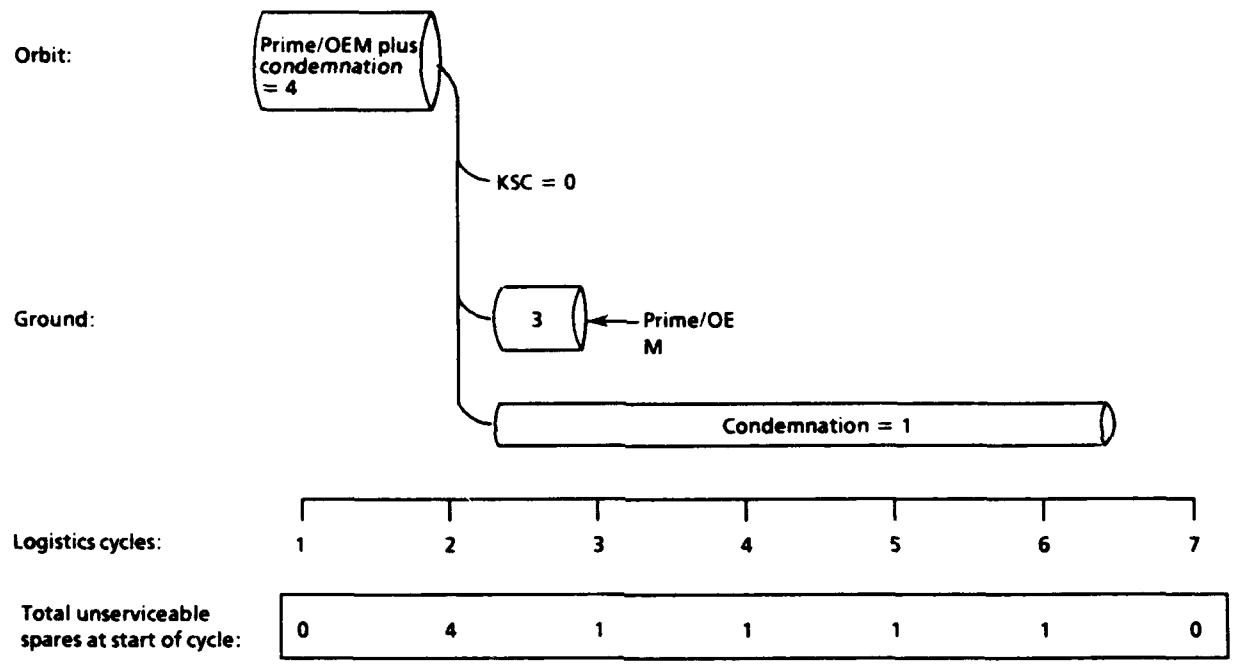

FIG. 4-1. MAINTENANCE PROCESS

(Estimating unserviceable ORU spares over time)

Most inventory models assume continuous repair and resupply of spares, but an on-orbit inventory is different. When an ORU fails on orbit, it must wait for a shuttle to return it to the ground, and after it is repaired or replaced on the ground, the unit must wait for a shuttle to return it to the station. The maintenance plan must include those waiting times. That is why our example includes the time a broken spare spends on-orbit in the first logistics cycle. Furthermore, whether the OEM can fix a spare in 45 days or 145 days, the number of logistics cycles for maintenance remains the same. Thus, the key reference for the model is not days, like other inventories, but conditions on the ground at the beginning of each cycle before the

shuttle launch. (To simplify the model, we assume that shuttle launching and landing occurs within a day. The actual interval is longer than one day, but it is relatively short when compared with the entire length of the logistics cycle.)

For our example, the number of unserviceable (broken) ORUs for Cycles 1 through 7 are 0, 4, 1, 1, 1, 1, and 0, respectively (see bottom row in Figure 4-1). However, that example only traces the unserviceable spares generated from one logistics cycle. Figure 4-2 depicts that same example with failures generated from many logistics cycles overlaid on one another. Each horizontal row above the logistics cycle line shows the number of unserviceable units generated from the same logistics cycle. To estimate the total number of unserviceable spares before any shuttle launch, we add the column of numbers in Figure 4-2 to obtain the bottom horizontal box. After a few cycles (start of cycle 6), we reach steady-state conditions. In steady state, the unserviceable units have arisen from five different cycles: the four failures from the last logistics cycle (three will eventually enter repair and one will be replaced) and then one condemnation from two, three, four, and five cycles earlier (the other failures from these cycle were repaired at the OEM).

							4
						4	1
					4	1	1
				4	1	1	1
			4	1	1	1	1
	0	4	1	1	1	1	0
Logistics cycles:	1	2	3	4	5	6	7
Total unserviceable spares at start of cycle:	0	4	5	6	7	8	8

FIG. 4-2. UNSERVICEABLE ORU SPARES AT SHUTTLE LAUNCH

Once we know the number of unserviceable spares at the beginning of each cycle, we then know the optimal spares mix: the total spares we need and their storage location. For the sixth logistics cycle (the sixth shuttle launch), we know that eight units are unserviceable. We also know that for the next cycle, the station will experience four failures so it needs the shuttle to lift an additional four spares. Thus, the station requires a total of 12 spares (8 plus 4) and 4 of the spares stored on orbit.

As discussed in Chapter 1, the model estimates net spares requirements once a year at a shuttle launch occurring one logistics cycle prior to the end of the year. For our example with a logistics cycle of 180 days, the shuttle launch month (LM) is the seventh month of each fiscal year.

Probability Distribution of Unserviceable Spares

Station ORUs do not behave in a deterministic fashion as portrayed in our example. Each part of the process just described has some uncertainty that we approximate with a probability distribution. For now, we assume the on-orbit failures process is random for each ORU so that the number of failures in a logistics cycle is described by a Poisson distribution. (Later, we will discuss how to handle ORUs that are not characterized by that random process such as items with wear-related failures.) The Poisson distribution that estimates the probability of variable on-orbit failures for an ORU in the next logistics cycle is

$$p(x|MO) = \frac{MO^x \times exp(-MO)}{x!}, \qquad \text{[Eq. 4-1]}$$

where

x = 0, 1, 2, . . . failures

MO = mean number of orbit failures for the next logistics cycle

= $\lambda \times T \times QPA$

λ = mean failure rate [1/MTBF (days)] × duty cycle

$MTBF$ = mean time between failures

T = length of the logistics cycle (days)

QPA = quantity per application.

The model calculates that probability once each fiscal year at the launch month. In this case, the mean number of orbit failures from our previous example equals four.

Each on-orbit failure from the original Poisson distribution pattern with mean MO has a probability distribution for the number of periods that will be required for the maintenance process. The mean of that distribution is based upon the user's estimate of the actual length of time the unit will spend in each maintenance level considering all conditions of the maintenance process. Those user estimates are

independent of the number or type of ORUs in maintenance. Given that, we compute the probability distribution for the total number of unserviceable or broken, b, units in maintenance on the ground or "just failed" on orbit.

At shuttle launch, there are failures from the previous logistics cycle, there are the failures from two cycles ago that are still in maintenance, there are failures from three cycles ago that are still in maintenance, etc. Each of those cycles has a Poisson distribution for unserviceable units. Since the failures occur in different cycles and the maintenance times are independent, their probability distributions are independent.[1] The sum of Poisson variables is Poisson with a mean equal to the sum of the individual cycle means. (That mean is what we termed the total unserviceable spares at launch in our deterministic example.) Equation 4-2 gives the probability distribution for the number of unserviceable units in maintenance.

$$probability\,(b\ unserviceables) = p(b \mid MB), \qquad \text{[Eq. 4-2]}$$

where

b = 0, 1, 2, . . . unserviceable spares

MB = mean number of unserviceable units at shuttle launch.

Multi-Echelon ORU PSN

Once the model estimates the probability distribution for unserviceable spares for a particular ORU, it then estimates the working spares available for the station and the ORU PSN (probability of a spare when needed). At a particular launch, the model looks back to determine the number of unserviceables and forward to determine what will fail on the station in the next cycle. When that is established, the model then calculates the PSN for each spares stock level, s, where s equals 0, 1, 2, 3, etc. The level, s, for the ORU is composed of the orbital echelon s_o and the ground echelon s_g (this is what we mean by a multi-echelon stock policy). The model first determines which is the best multi-echelon stock policy (i.e., produces the highest

[1]Palm's Theorem establishes the fact that if failures arise from a Poisson process and under certain other conditions satisfied here, the number of units in resupply is also Poisson with a mean equal to the product of the failure rate and the mean resupply time. For example, see Hadley and Whitin, *Analysis of Inventory Systems*, Englewood Cliffs, N.J.: Prentice-Hall, 1963, p.204.

PSN) for each stock level. In other words, for a spares level of 3, it decides whether the best policy would be to store 0, 1, 2, or 3 spares on orbit.

Table 4-1 presents a multi-echelon example of the model's evaluation process for which s equals 3 and s_o equals 2. We assume we send up enough stock on each shuttle to restore the orbital spares stock to s_o, if possible. Of course, on some occasions we may not be able to restore the orbital spare stock to s_o because of the number of broken units of the ORU. In order to estimate the PSN for this stockage policy, the model must consider several possible combinations. If 0 or 1 spare is broken, the station can have two spares on orbit. Thus, enough spares are available to cover 0, 1, or 2 additional on-orbit failures. If the ORU has 2 broken spares, it can have only 1 spare on orbit and can cover only 0 or 1 additional failure. If all 3 spares are broken on the ground, no spares are on orbit and that ORU can only operate through the entire logistics cycle if it experiences no failures.

TABLE 4-1

MULTI-ECHELON EVALUATION

Current status	Next cycle on orbit	
Possible broken ORUs	Spares on orbit	Failures covered
0	2	2, 1, 0
1	2	2, 1, 0
2	1	1, 0
3	0	0

Note: $s_O=2$; $s=3$.

If we take each combination just described and apply the appropriate probabilities, the result equals the ORU's PSN for a given s_o and s_g ($s_g = s - s_o$) (see Equation 4-3). The PSN is the sum of the conditional probabilities. Each conditional probability equals $p(b|MB)$, the probability an ORU is in a specific state, times $p(x|MO)$, the probability an ORU has adequate spares. Those three conditional probability terms in Equation 4-3 are depicted by the rows of Table 4-1. In that table,

the first two horizontal rows depict the first term in Equation 4-3; the next row, the next term; and the last row, the last term.

$$PSN(s_o, s_g) = \left[p(b \le s_g \mid MB) \times p(x \le s_o \mid MO)\right] \qquad \text{[Eq. 4-3]}$$

$$+ \left[p(b = s_g + 1 \mid MB) \times p(x \le s_o - 1 \mid MO)\right] \ldots$$

$$+ \left[p(b = s_g + s_o \mid MB) \times p(x = 0 \mid MO)\right] .$$

Using Equation 4-3, the model can estimate an ORU PSN for any combination of on-orbit and ground stock for the next logistics cycle. Table 4-2 lists the PSN for different spares stock combinations using our previous example – with one modification. We assume a lower, more realistic average of 0.4 instead of 4 on-orbit failures per cycle. The maintenance fractions and maintenance days remain the same so the mean number of unserviceable units equals 0.8. In general, an on-orbit spare offers a higher level of protection (a greater PSN) than a ground spare because only an on-orbit spare can replace a broken ORU and keep a system operating. However, the differences between the PSNs diminish as the number of on-orbit and on-ground spares increases.

TABLE 4-2

ORU PSN FOR COMBINATIONS OF ON-ORBIT AND GROUND SPARES

s_o – Orbital stock	s_g – Ground stock				
	0	1	2	3	...
0	30.1	54.2	63.8	66.4	
1	66.2	85.5	91.9	93.5	
2	87.9	96.3	98.6	99.1	
3	96.6	99.1	99.7	99.9	
4	99.2	99.8	99.9	99.9	
⋮					

Multi-Echelon Tradeoff

With the capability to estimate the ORU PSN for any combination of spares, the model can then calculate the best allocation of on-orbit and ground spares for each spares level. Before we discuss that prioritization, we have to define the various resources.

Unit price is a basic resource and does not change if the ORU is stored on orbit or on the ground. Station storage volume is another resource but is only consumed when spares are stored on orbit. The next resource is the weight capacity of the shuttle flights that transport the pre-positioned spares. Again, only spares stored on orbit consume that resource. Though on-orbit and needed ground spares require a lift into space, the on-orbit spare actually requires an additional lift. The on-orbit spares require a shuttle lift to pre-position them on orbit and a lift to replenish the inventory after a failure. Ground spares only require one lift to replace a failure.

The model starts the multi-echelon tradeoff process by developing a benefit-to-unit resource ratio in order to choose the spare location with the largest ratio. The process is similar to the method discussed earlier for setting priorities for spares across all ORUs. The next two equations extend the general ratio equation (Equation 3-3) to treat on-orbit and ground spares:

On-orbit spares:

$$\frac{marginal\ benefit}{unit\ resource} = \frac{ln\left[PSN(s_o+1, s_g)\right] - ln\left[PSN(s_o, s_g)\right]}{(coefficient \times price) + \left[(1-coefficient) \times weight\right]}. \qquad \text{[Eq. 4-4]}$$

Ground spares:

$$\frac{marginal\ benefit}{unit\ resource} = \frac{ln\left[PSN(s_o, s_g+1)\right] - ln\left[PSN(s_o, s_g)\right]}{(coefficient \times price)}. \qquad \text{[Eq. 4-5]}$$

Thus, if the user ignores an ORU's weight (i.e., makes the coefficient equal 1 for all ORUs), the model will select an on-orbit spare over a ground spare. That effect is illustrated in Table 4-2, in which the on-orbit spare always produces a higher PSN than the ground spare for the same unit cost. In Table 4-3, we take the same example, but consider cost and weight equally (coefficient = 0.5) and assume the ORU costs $1.00 and weighs one pound. The multi-echelon tradeoff selection process

starts by choosing a ground spare (highest ratio) and ends up selecting four out of seven on-orbit spares. If weight is given a greater importance (i.e., the coefficient decreases) the model selects the ground spares with more frequency.

TABLE 4-3

ORU MULTI-ECHELON TRADEOFFS

Spares selection			Resource ($0.5 + 0.5 lb)	PSN	Benefit/ resource ratio
Total	On orbit	Ground			
0	0	0	0	30.1	----
1	0	1	0.5	54.2	1.17562
2	1	1	1.5	85.5	0.45604
3	1	2	2.0	91.9	0.14487
4	2	2	3.0	98.6	0.06982
5	3	2	4.0	99.7	0.01184
6	3	3	4.5	99.9	0.00225
7	4	3	5.5	99.9	0.00088

The model implements its methodology by first producing the last column in Table 4-3 for every ORU. Then, at each stage of the selection process, it looks across all ORUs and picks the ORU whose top spare has the greatest benefit/resource ratio. The model then moves on down the ratio column of the selected ORU and repeats the process. The unit resource part of Equations 4-4 and 4-5 can be further extended to handle more resources (e.g., on-orbit volume).

ORU EXTENSIONS

In this section, we will discuss some of the model extensions that enable M-SPARE to estimate most of the station's spares requirements, including the following:

- Modeling future replacement of condemnations
- Station growth as elements are launched and assembled

- Alternative ORU failure patterns
- An alternative spares storage strategy.

Replaced Condemnations

The M-SPARE methodology mentioned above uses a repair philosophy to estimate unserviceables. The model assumes that after a specified time, maintenance generates a serviceable ORU. A condemnation also undergoes a maintenance time, but unlike a repair, its "maintenance" is actually the procurement of a new ORU. In this subsection, we discuss how M-SPARE incorporates a procurement for a replaced condemnation into its general repair philosophy.

To illustrate that point, we return to our general example in Chapter 1 and compare it to our example in the previous section depicting the M-SPARE methodology (both examples use identical deterministic failures rates and maintenance times and are displayed in Table 4-4). The general approach estimates spares requirements by subtracting cumulative repairs from cumulative failures. The difference equals the spares required to cover the number of failures that remain broken at the beginning of a logistics cycle (top of Table 4-4). That is similar to our example in the previous section (bottom of Table 4-4). For that example, we directly estimated the number of unserviceables (items that remain broken) at the beginning of a cycle and add that to the orbit failures for the next cycle to estimate spares requirements. Notice that the requirements/LC for the general approach is identical to the gross requirements/LC in our M-SPARE methodology, except for FY99. That difference is because M-SPARE thinks that maintenance process has had enough time to replace the earlier condemnations. In Table 4-4, those replaced condemnations equals cumulative condemnations minus ORUs in procurement.

The M-SPARE model incorporates replaced condemnations by decreasing assets from the previous year by the amount equal to the replaced condemnations. To calculate the assets for FY99 (bottom of Table 4-4), M-SPARE takes the previous year's requirements (12) minus the replaced condemnations in FY99 (2) to obtain a current asset level (10). Now, when the reduced assets are subtracted from gross requirements/year, the net requirement equals 2 (12 − 10). Thus, the net requirement for the M-SPARE implementation and the general approach are equal (two shaded rows). In that way, the net and gross requirements reflect the desired spares

TABLE 4-4

SPARES REQUIREMENTS
(DETERMINISTIC FAILURES)

Conditions	Spares							
	FY96		FY97		FY98		FY99	
	1	2	3	4	5	6	7	8
General approach:								
Failures/LogCycle	4	4	4	4	4	4	4	4
Cumulative failures	4	8	12	16	20	24	28	32
Cumulative repaired	0	0	3	6	9	12	15	18
Requirements/LogCycle	4	8	9	10	11	12	13	14
Requirements/year		8		10		12		14
Previous assets		0		8		10		12
Net requirements		8		2		2		2
M-SPARE methodology:								
Next orbit failures	4	4	4	4	4	4	4	4
Broken ORUs	0	4	5	6	7	8	8	8
Gross requirements/LogCycle	4	8	9	10	11	12	12	12
Broken ORUs								
ORUs in repair	0	3	3	3	3	3	3	3
ORUs in procurement	0	1	2	3	4	5	5	5
Cumulative condemnation	0	1	2	3	4	5	6	7
Replaced condemnations	0	0	0	0	0	0	1	2
Gross Requirements/year		8		10		12		12
Previous assets		0		8		10		12
Replaced condemnations		0		0		0		2
Net requirements		8		2		2		2

quantities. The net spares requirements include replacements for condemnations so that NASA can order and budget for the proper number of spares.

Another point is that when the model reduces assets by the number of replaced condemnations, it does not reduce M-SPARE dollar values. For instance, the accumulated spares investment used for the resource-versus-availability curve still includes the cost to replace condemnations. In that way, spares investment and the budget estimates are consistent.

Element Launch and Assembly Impacts

The M-SPARE model methodology also incorporates failure rates that vary over time due to element launches or "mission builds" (the construction phases of the space station). At any point in time, the M-SPARE failure rate equals the ORU's duty cycle, multiplied by the quantity per application (QPA), multiplied by the logistics cycle, and divided by the mean time between failures (MTBF). A particular ORU may have applications that are launched at different times. With the increase in the number of applications on the station, the ORUs total failure rate should increase (the model holds duty cycle, logistics cycle, and MTBF constant over time). M-SPARE uses a monthly QPA profile to estimate changing failure rates. The model generates a profile from the element launch schedule (see Chapter 6, Model Options) and from the number of ORU applications on each element (see Chapter 5, Model ORU Input Data).

Exhibit 4-1 displays the key variables the model uses to determine spares requirements and expands on our earlier example (the tables in that exhibit constitute the reports M-SPARE generates – see Chapter 8, Model Outputs). The example assumes the MTBF is 2,160 hours, the duty cycle is 1, and the QPA is 2 for each of 3 elements. The element launches are in Month 1 of FY96, Month 1 of FY00, and Month 7 of FY01 (the top part of the exhibit). Next, the exhibit presents the total QPA profile by month for 10 years. Notice how the total QPA increases at each element launch month. The middle part of Exhibit 4-1 displays the QPA for each element and lists the element launch schedule in calendar and fiscal months and years.

****** Element Launch Schedule *********

Element #	Calendar:Mth	Year	Fiscal:Mth	FY
1 LabA	10	1995	1	1996
2 HabA	10	1999	1	2000
3 PLM3	4	2001	7	2001

ORU# 1 EXAMPLE STATION ORU LogCycle= 180 NOT a wear item

QPA BY MONTH (COL), YEARS (ROW)

	1	2	3	4	5	6	7	8	9	10	11	12
1996	2	2	2	2	2	2	2	2	2	2	2	2
1997	2	2	2	2	2	2	2	2	2	2	2	2
1998	2	2	2	2	2	2	2	2	2	2	2	2
1999	2	2	2	2	2	2	2	2	2	2	2	2
2000	4	4	4	4	4	4	4	4	4	4	4	4
2001	4	4	4	4	4	4	6	6	6	6	6	6
2002	6	6	6	6	6	6	6	6	6	6	6	6
2003	6	6	6	6	6	6	6	6	6	6	6	6
2004	6	6	6	6	6	6	6	6	6	6	6	6
2005	6	6	6	6	6	6	6	6	6	6	6	6

Element #	1	2	3
Element QPA	2	2	2

AT ORU 1 EXAMPLE STATION ORU

Model YR	Mean Orbit	Mean Broken	Replace Condemn.	VMR
1996	4.00	4.00	0.00	1.00
1997	4.00	6.00	0.00	1.00
1998	4.00	8.00	0.00	1.00
1999	4.00	8.00	2.00	1.00
2000	8.00	12.00	2.00	1.00
2001	12.00	14.00	2.00	1.00
2002	12.00	21.00	2.00	1.00
2003	12.00	23.00	4.00	1.00
2004	12.00	24.00	5.00	1.00
2005	12.00	24.00	6.00	1.00

EXHIBIT 4-1. EXAMPLE STATION ORU

In FY96 to FY99, the entries for the mean on orbit, mean broken, and replaced condemnations at the bottom of Exhibit 4-1 matches our previous example in Table 4-4. In FY00, the QPA increases causing expected failures and other variables to increase as well.

As discussed in Chapter 1, the model estimates net spares requirements once each year at a shuttle launch. That launch occurs a logistics cycle from the end of the year. For our example, with a logistics cycle of 180 days, the shuttle launch month (LM) is the seventh month each fiscal year. At that time, the model looks back to determine the number of unserviceables units and forward to determine what is

expected to fail on the station in the next cycle. The bottom part of Exhibit 4-1 presents the key M-SPARE variables at the yearly launch month for mean orbit failures, mean broken ORUs, and replaced condemnations. We will now present the equations for each of these variables and then present the equation variable definitions.

In Equation 4-6, the model estimates mean broken (MB), ORUs for each model year by summing the fraction of the total failures that occurred for each component (KSC, prime/OEM, and condemnations) one maintenance time earlier (see Equation 4-7). Maintenance time equals a logistics cycle for broken ORUs still on-orbit plus the number of complete logistics cycles in the repair/procurement time.

$$MB(yr) = \sum_{l=1}^{3} B_l , \qquad \text{[Eq. 4-6]}$$

$$B_l(yr) = \lambda \times F_l \times \sum_{m=LM(yr)-MM_l}^{LM(yr)-1} QPA(m) . \qquad \text{[Eq. 4-7]}$$

The equation to estimate mean orbit, *MO*, failures for the next logistic cycle (i.e., from the launch month to the end of the fiscal year) for a given model year is the following:

$$MO(yr) = \lambda \times \sum_{m=LM(yr)}^{LM(yr)+MLC-1} QPA(m). \qquad \text{[Eq. 4-8]}$$

As discussed in Table 4-4, the model estimates the number of replaced condemnations by first subtracting the condemnation component of the mean number of broken ORUs [$B_3(yr)$] from the total condemnations since the first month of the first model year. That integer value is the cumulative number of replaced condemnations [$CRC(yr)$] (see Equation 4-9). Next, the model takes the projected difference in CRC for successive years to obtain the incremental number of replaced condemnations [$RC(yr)$] for a specific model year (see Equation 4-10).

$$CRC(yr) = \left[\left[\lambda \times F_3 \times \sum_{m=1}^{LM(yr)-1} QPA(m) \right] - B_3(yr) \right] \qquad \text{[Eq. 4-9]}$$

$$RC(yr) = CRC(yr) - CRC(yr - 1), \qquad \text{[Eq. 4-10]}$$

where

λ = mean orbit failures per month

$$= \frac{duty\ cycle \times 720\ (hours/months)}{MTBF(hours)}$$

m = 1, 2 . . . (year × 12) where the year is the number of model years the user specifies (see Chapter 6)

$QPA(m)$ = sum of all elements QPA launched by month m

l = maintenance levels (1 = KSC, 2 = prime/OEM, 3 = condemnations)

F = fraction of total failures entering each maintenance level

MM = maintenance months = $NLC \times MLC$

NLC = number of logistics cycles in the entire maintenance time

$$= \left[\frac{LogCycle\ (days) + repair\ or\ replace\ (days)}{LogCycle\ (days)} \right]$$

[ ] = for value in brackets, take the largest integer value, i.e., truncate real number into a integer value

MLC = months in a LogCycle

$$= \frac{LogCycle\ (days)}{30\ (days/month)}$$

$LM(yr)$ = launch month, calculation point of spares requirements, assumes that it is one LogCycle from end of fiscal year

= (yr × 12) − MLC + 1

yr = model year

RC = replaced condemnations

CRC = cumulative replaced condemnations.

Alternative ORU Failure Patterns

Typically, component failures are assumed to follow a Poisson distribution pattern. However, certain ORUs may exhibit different failure (demand) patterns that are not typical. M-SPARE uses two additional probability distributions to approximate the range of possible demand patterns. The actual distribution used by the model is determined on the basis of the variance-to-mean ratio (VMR) of the demand for ORUs and is an input to the model (see Chapter 5) or determined by the simulation (see Chapter 10). The ORU VMR is a measure of demand uncertainty. Larger VMRs translate into higher spares requirements. In most cases, the ORU VMR is assumed to be 1 and the model uses the Poisson distribution. If the ORU VMR is less than 1, the model uses the binomial distribution method to approximate the demand pattern. This method is usually used for wear-related demands that are more predictable than the typical demand pattern for random failures. In those cases, the simulation automatically calculates the VMR. If the ORU VMR is greater than 1, the model uses the negative binomial distribution method to approximate the demand pattern. That is usually the case for ORUs with suspect data quality, drifting demand levels, or greater demand uncertainty than the typical ORU.

When the VMR is less than or greater than 1, the model replaces the Poisson distribution assumed in Equations 4-1, 4-2, and 4-3 with the appropriate distribution. However, the basic methodology remains the same.

Table 4-5 is an example of different distributions with a mean demand of 0.4 but a VMR of 0.6, 1, and 3. The number of spares required to obtain a cumulative probability of 0.999 (an indicator of ORU spares protection) equals 1, 3, and 9, respectively. In other words, when all else is equal, the model shifts more spares to the ORUs with greater demand uncertainty (larger VMRs). [*Note:* Since the binomial distribution method requires certain parameters to be integer values, the input VMR is automatically adjusted to meet that requirement.]

Preventive Maintenance

The model also uses the VMR to estimate spares requirements for another ORU extension, preventive maintenance (PM) or scheduled maintenance ORUs. M-SPARE calculates spares requirements for preventive maintenance actions using the wear preprocessor. The user must enter the annual scheduled replacement ("change-out") frequency into the MSPAREIN.RPT file in the wear "Life" field and

TABLE 4-5

COMPARISON OF DEMAND DISTRIBUTIONS

Spares	Binomial VMR = 0.6 Mean = 0.4		Poisson VMR = 1 Mean = 0.4		Negative binomial VMR = 3 Mean = 0.4	
	Probability	Cumulative	Probability	Cumulative	Probability	Cumulative
0	0.60	0.60	0.670	0.670	0.803	0.803
1	0.40	1.00	0.268	0.938	0.107	0.910
2			0.054	0.992	0.043	0.953
3			0.007	0.999	0.021	0.974
4					0.011	0.985
5					0.006	0.991
6					0.004	0.995
7					0.002	0.997
8					0.001	0.998
9					0.001	0.999

then run the wear preprocessor. The preprocessor calculates the combined failure rate from wear-related failures (PM) and random failures as described in Chapter 10. In the default mode, the wear preprocessor determines the uncertainty on the basis of the replacement frequency. For instance, a monthly, quarterly, semiannual, or annual replacement frequency generates VMRs of 0.1, 0.7, 0.9, and 1.0, respectively. Greater VMRs translate into greater M-SPARE spares requirements above the mean number required for the replacements. Since most scheduled replacements occur with a high degree of certainty, the user can override the wear preprocessor by inserting a 0.01 in the MSPAREIN.RPT file for the ORU's VMR. As a result, M-SPARE will select only enough spares to cover the mean replacements plus one extra spare for the ground inventory and one extra spare for the orbit (if appropriate) inventory.

ORUs with Ground Spares Only

Next, we discuss those ORUs whose spares are only stored on the ground, such as noncritical ORUs (Criticality Code 2 or 3) or critical ORUs when on-orbit storage is not available. With no on-orbit spares, the ORU PSN is very low. It may cause the

station availability to drop below 1 percent. A more meaningful measure is the probability that the ground inventory fully supplies spares needed to replace the previous cycle's on-orbit failures. We term that *ground availability*. The equation for ground availability (Equation 4-11) is similar to the equation for station availability (Equation 3-1). The difference is that for ground availability, the on orbit component of the PSN (Equation 4-3) drops out leaving only the $p(b)$ distribution for unserviceable (broken) units in maintenance.

$$ground\ availability = \prod_{ORU_i} p\left(b \leq s_{gi} | MB\right). \qquad \text{[Eq. 4-11]}$$

Use of the ground availability measure does not affect the spares selection process. The only difference is that the PSN and availability is strictly a measure of ground performance. In Chapter 7, we discuss an operation mode in which all ORU spares are stored on the ground.

CHAPTER 5

MODEL ORU INPUT DATA

Initially, the most difficult part of the model processing is the creation of the input file (MSPAREIN.RPT). That file defines all the ORUs and their characteristics (unit cost, demand, repair times, weight, etc.). This input drives the M-SPARE model. If you wish the model to produce an optimal spares mix for your particular distributed system or subsystem, your data base should contain the ORUs of only that group.

INPUT FILE DESCRIPTION

The input file is in an ASCII text format to allow browsing or editing with standard PC editors. [*Note:* Always save input files in an ASCII or print format.] Examples of the data file headings and a few ORUs from the sample data base are presented in Exhibit 5-1. The file columns are divided into five sections. In the following subsections, we define the data fields of each section, list the type of field in parentheses, and discuss how the data are used in the model.

Description

The data fields of this section are the following:

- *NAME* – a 32-character ORU name (character field).
- *PART NUMBER* – an 18-character part identification number (character field).
- *CAGE#* – a 6-character number representing Commercial and Government Entity (CAGE) codes or the Federal Supplier Code for Manufacturers (FSCM) (character field).
- *CT* – a 2-character criticality code (e.g., 1R, 1, 1S, and 3) used in M-SPARE to segregate different types of ORUs. The model only optimizes one criticality code at a time and assumes all ORUs with the same criticality have equal importance (character field).
- *DIST SYSTEM* – a 7-character distributed system name. The name allows the model to further break down model outputs to a distributed system level.

If the data base contains ORUs for a specific distributed system only, this field can be used to report results at a subsystem level (character field).

The model uses the name, part number, and CAGE number data fields for reporting purposes only. Thus, the fields can contain whatever you need to uniquely identify the ORU (see Exhibit 5-1).

Unit Resources

The data fields of this section are the following:

- *PRICE ($K)* – the unit price of the ORU in thousands of dollars. The model assumes that all unit prices are adjusted to the same baseline year (real value > 0).
- *WEIGHT (LBS)* – the unit weight of the ORU in pounds (real value > 0).
- *VOLUME (INCH ^3)* – the unit volume of the ORU in cubic inches (real value > 0).

Miscellaneous

The data fields of this section are the following:

- MIN.SPR – a value that allows the user some flexibility in determining how the model selects spares. Values greater than 0 force the model to buy at least the number of spares specified (see Chapter 6 for information on alternative ways of setting starting asset levels). (Integer value ≥ 0.)
- P/U *1/0* – a value of 0, 1, or 2 allows the user to specify whether the ORU requires an unpressurized, pressurized, or either environment, respectively (integer value of 0, 1, or 2).
- *PLT $S* – a value that determines the dollar "spread" vector used in allocating budget dollars over PLT. The vectors associated with the PLT $S value (e.g., 1, 2, 3 . .) are stored in the OPTIONS.RPT file (see Chapter 6). For instance, a PLT $S value of 1 may correspond to a vector in the OPTIONS.RPT file of 0.0, 0.85, 0.10, and 0.05. That vector implies that an ORU with a unit price of $100,000 requires $5,000, $10,000, and $85,000 in the first, second, and third year of PLT respectively, and $0 in the delivery year (integer value > 0).

Maintenance Factors

The data in this section are further subdivided into two types of fields, each type having three choices (i.e., three maintenance levels). Level 1 represents activities at

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M-SPAR E ORU INPUT
NOTE: COSTS ARE M

DESCRIPTION					UNIT RESOURCES			
NAME	PART NUMBER	CAGE#	CT	DIST SYSTEM	PRICE ($K)	WEIGHT (LBS)	VOLUME (INCH ^3)	MIN. SPR
PARABOLIC ANTENNA	12345678901234567	123456	1	1234567	2085	409	8640	1
TRANSMITTER-RECEIVER	XXXXXXXXXXXXXXX	YYYYY	1	6	614	65	1728	1
ANTENNA CONTROLLER	XXXXXXXXXXXXXXX	YYYYY	1	6	375	51	1728	1
SGS IF SWITCH	XXXXXXXXXXXXXXX	YYYYY	1	6	128	25	27	1
HIGH RATE MODEM	XXXXXXXXXXXXXXX	YYYYY	1	6	1125	37	2280	1
HIGH RATE FRAME MUX	XXXXXXXXXXXXXXX	YYYYY	1	6	1875	92	3420	1
BASEBAND SIGNAL PROC	XXXXXXXXXXXXXXX	YYYYY	1	6	1050	77	3420	1
VIDEO BASEBAND PROCE	XXXXXXXXXXXXXXX	YYYYY	1	6	242	59	2280	1
IEA STRUCTURE A	XXXXXXXXXXXXXXX	YYYYY	1	12	1517	25	4385550	1
IEA TRANSITION	XXXXXXXXXXXXXXX	YYYYY	3	12	35	32	864	0
IEA ELEC JUNCTI	XXXXXXXXXXXXXXX	YYYYY	3	12	49	42	1728	0
TCS DEPLOY RADI	XXXXXXXXXXXXXXX	YYYYY	3	12	1046	658	491400	0
TCS UTL PLAT T1	XXXXXXXXXXXXXXX	YYYYY	3	12	180	334	1728	0
TCS UTL PLAT T2	XXXXXXXXXXXXXXX	YYYYY	3	12	180	299	1728	0

EXHIBIT 5-1. EXAMPLE (

PUT DATA
E MODIFIED

(KSC = 1, OEM = 2, CONDEMN = 3)

MISC.			MAINTENANCE FACTORS										DEMAND FACTORS							
IN.	P/U	PLT	DAYS		Mths	FRACTION			Log	DUTY	VMR	LIFE	MTBF (HR)	QPA by FY						
PR	I/O	$S	1	2	3	1	2	3	Cyc	CYCLE		(YR)	PER UNIT	1	2	3	4	5	6	7
1	1	1	0	160	8	0	.9	.1	135	1	1	30	68215	1	2	2	2	2	2	2
1	1	1	0	160	8	0	.9	.1	135	1	1	30	18169	2	4	4	4	4	4	4
1	1	1	0	160	8	0	.9	.1	135	1	1	30	91387	2	4	4	4	4	4	4
1	1	1	0	160	8	0	.9	.1	135	1	1	30	113454	1	2	2	2	2	2	2
1	1	1	0	160	8	0	.9	.1	135	1	1	30	55071	1	2	2	2	2	2	2
1	1	1	0	160	8	0	.9	.1	135	1	1	30	18847	1	2	2	2	2	2	2
1	1	1	0	160	8	0	.9	.1	135	1	1	30	13207	1	2	2	2	2	2	2
1	1	1	0	160	8	0	.9	.1	135	1	1	30	38000	1	2	2	2	2	2	2
1	1	2	0	160	8	0	.9	.1	135	1	1	30	525600	2	4	4	4	4	4	4
0	1	2	0	160	8	0	.9	.1	135	1	1	30	260610	2	4	4	4	4	4	4
0	1	2	0	160	8	0	.9	.1	135	1	1	30	164250	2	4	4	4	4	4	4
0	1	2	0	160	8	0	.9	.1	135	1	1	30	42340	2	4	4	4	4	4	4
0	1	2	0	160	8	0	.9	.1	135	1	1	30	45260	4	8	8	8	8	8	8
0	1	2	0	160	8	0	.9	.1	135	1	1	30	49640	12	24	24	24	24	24	24

LE OF ORU DATA BASE

2

the repair facilities of KSC, Level 2 represents activities at the prime contractor or OEM, and Level 3 represents condemnation of an ORU and its replacement.

For each level, the file contains DAYS or months (Mths) fields that specify the time required to repair or replace an ORU and FRACTION fields that specify the expected fraction of ORUs entering the level. The sum of the fractions for the three levels should equal 1. If an ORU has no repair at a level, enter "0" for its fraction. The specific fields are the following:

- *DAYS 1* – the repair time in days for ORUs being repaired at KSC (real value ≥ 0).
- *DAYS 2* – the repair time in days for ORUs being repaired at the prime contractor or OEM (real value ≥ 0).
- *Mths 3* – the PLT in months to replace a condemned ORU (real value > 0).
- *FRACTION 1* – the fraction of broken ORUs that are repaired at the KSC (real value ≥ 0).
- *FRACTION 2* – the fraction of broken ORUs that are repaired at the prime contractor or OEM (real value ≥ 0).
- *FRACTION 3* – the fraction of broken ORUs that are condemned (real value ≥ 0).

As discussed in Chapter 4, the maintenance times and fractions determine the mean number of unserviceable spares that remain from one or several previous logistics cycles. As KSC facilities repair a larger fraction of the broken ORUs, the shorter repair times will translate into fewer spares requirements.

Demand Factors

The data fields of this section are the following:

- *Log Cyc* – the logistics resupply cycle or time in days between shuttle flights. That value is used to estimate the number of anticipated failures over the next cycle and the number of cycles required to repair or replace an unserviceable item. While the logistics cycle can be assumed as any number of days (e.g., 90, 135, 180, . . .), the value remains constant for each model run. The OPTIONS.RPT file also contains a logistics cycle delta value that you can use to increase or decrease all ORU logistics cycles (real value > 0).

- *DUTY CYCLE* – the fraction of time the ORU will operate over the course of a year. This field might also contain the product of the duty cycle and a demand multiplier (real value > 0).

- *VMR* – the VMR measures demand uncertainty. Larger VMRs represent greater demand uncertainty and translate into higher spares requirements in the model. A VMR of 1.0 reflects the assumption of a Poisson demand process. ORUs that wear out (have an expected lifetime) can have a VMR less than 1.0 (see Chapter 10). Conversely, ORUs whose data quality is suspect can have a VMR greater than 1.0 (real value > 0).

- *LIFE (YR)* – the mean "wear life" or "life limits" of an ORU in years. Besides random failures estimated by the MTBF, the mean life addresses failures caused by wear-related factors or preventive maintenance. M-SPARE estimates those time-related failures with a simulation preprocessor (see Chapter 10) (real value > 0).

- *MTBF (HR) PER UNIT* – the MTBF in hours per unit or application (real value > 0).

- *QPA by FY* – the QPA or the total number of a specific ORU type on the station. The QPA input is actually a number of fields and uses two possible formats: cumulative QPA by fiscal year or QPA by element based upon the element launch schedule (mission build). If you choose QPA by fiscal year, the first QPA column (QPA 1) is the quantity assumed throughout the fiscal year for the first model year run; the next column (QPA 2) is the quantity assumed for the second model year; and so on. Quantities of 0 are acceptable. If you choose to express QPA by element, then the first column is the QPA for one element (e.g., Laboratory A), the second column is the QPA for another element (Node 1), and so on. The model then converts the QPA by element into a cumulative QPA by fiscal year given the element launch schedule defined in the OPTIONS.RPT file (see Chapter 6) (integer value ≥ 0).

The model uses those demand factors to obtain the demands per logistics cycle. Demand value is the driver of the M-SPARE model and is derived with Equation 4-8.

Certain ORUs have more demands than actual failures. Environmental problems, false removals, and scheduled maintenance are examples of additional demands that require spares. Sometimes those demands are defined by a demand multiplier called a *K-factor* (e.g., K = 1.2 denotes that the ORU experiences 20 percent more demands than failures). For such ORUs, the duty cycle field can serve an added purpose and contain the product of the K-factor multiplied by the duty cycle fraction.

INPUT FILE FORMAT

The M-SPARE model directly reads the MSPAREIN.RPT file and, thus, requires the data fields discussed to be in a relatively loose data format. The order of the ORUs is not important. Only the relative positions of the data fields are significant. Adherence to the following format rules is necessary when creating an ORU input file:

- The ORU data starts on the line immediately after the ">" character. The ">" character is in the first column.
- The ">" character also marks the end of the file and is on the line immediately after the data for the last ORU. The ">" character is in the first column of that last line.
- Only the first five character fields are required in particular columns of the file. The model assumes each of those fields meet the exact widths specified in our definitions and have no extra characters between them. Make sure the first five column widths are 32, 18, 6, 2, and 7, and start in Columns 1, 33, 51, 57, and 59, respectively.
- None of the other numeric fields have to be in specific columns, but the fields must be separated by one or more blanks. Real values can have as many decimal places as desired.
- Data for all fields must be included. If you do not have data for any resource – QPA, duty cycle, or VMR – place a "1" in those fields and place a "0" in the MIN. SPR field.

Table 5-1 summarizes each field type and file format. Also, the model closely links many of the data fields to the OPTIONS.RPT file discussed in Chapter 6.

INPUT FILE SUMMARY

In conclusion, you have two options for obtaining an input file. You may use the sample data base file we supplied and use an editor to modify the ORU data to more closely reflect your specific work package information, or you may create your own input file with another software package, following the format rules presented earlier. However, you must make sure the package output file is in an ASCII format, sometimes referred to as a report, text, or print file.

TABLE 5-1

SUMMARY OF MSPAREIN.RPT DATA BASE FIELDS

Header	Field type	Column first	Location last	Comment
NAME	32-char.	1	32	
PART NUMBER	18-char.	33	50	
CAGE #	6-char.	51	56	
CT	2-char.	57	58	Criticality code
DIST SYSTEM	7-char.	59	65	Distributed system
PRICE ($K)	Real > 0	space	delimited	
WEIGHT (LBS)	Real > 0	space	delimited	
VOLUME (INCH ^3)	Real > 0	space	delimited	
MIN. SPR	Integer ≥ 0	space	delimited	Minimum spare
P/U 1/0	0, 1, 2	space	delimited	Pressurized/unpressurized
PLT $S	Integer > 0	space	delimited	Dollar spread vector
DAYS 1	Real ≥ 0	space	delimited	KSC repair time
DAYS 2	Real ≥ 0	space	delimited	OEM/prime repair time
Mths 3	Real > 0	space	delimited	PLT
FRACTION 1	Real ≥ 0	space	delimited	KSC repair fraction
FRACTION 2	Real ≥ 0	space	delimited	OEM repair fraction
FRACTION 3	Real ≥ 0	space	delimited	Condemnation fraction
Log Cyc	Real > 0	space	delimited	Logistics cycle
DUTY CYCLE	Real > 0	space	delimited	
VMR	Real > 0	space	delimited	VMR
LIFE (YR)	Real > 0	space	delimited	Mean time before ORU wear-out
MTBF (HR) PER UNIT	Real > 0	space	delimited	MTBF
QPA 1	Integer ≥ 0	space	delimited	
QPA 2	Integer ≥ 0	space	delimited	
QPA 3	Integer ≥ 0	space	delimited	
QPA 4	Integer ≥ 0	space	delimited	
QPA 5	Integer ≥ 0	space	delimited	
QPA 6	Integer ≥ 0	space	delimited	
QPA 7	Integer ≥ 0	space	delimited	

CHAPTER 6

MODEL OPTIONS

The model has several options that are triggered from the OPTIONS.RPT file (see Exhibit 6-1). This file is accessible through the "Options" choice on the interface menu. The OPTIONS.RPT file is provided to set key parameters that usually do not vary from one model run to the next. That simplifies the user-query inputs required for model operation (see Chapter 7). In most cases, the user uses the default values specified below for each option. However, the OPTIONS.RPT file allows you the flexibility to test some special cases by changing the default values.

The user can change any of the option values in the file by selecting the interface menu choice "Options." The interface then invokes the editor and loads the OPTIONS.RPT file. We then suggest you press the "Insert" key to turn off the insert mode and type over any options you want to change. The replaced values do not have to be in exactly the same columns as the originals but merely in the general vicinity. Be careful not to accidentally add any lines because the model will not read the options correctly. When you are done, press "ALT-X" to save the OPTIONS.RPT file and return to the interface menu. The definition and range of global values are discussed for each of the options in the following sections.

LOGISTICS CYCLE DELTA

The M-SPARE model allows the user to change the planned logistics cycle without editing the MSPAREIN.RPT file. The logistics cycle delta allows a positive or negative increment change in the number of days the model applies to each ORU logistics cycle. Thus, to analyze the impact of slipping cycles 45 days, set the delta to "45" and the model automatically adds 45 days to each ORU's cycle. The logistics cycle delta is included in Equations 4-6 through 4-9. The option default value equals "0".

STARTING SPARES

The starting spare option allows the user to set the starting asset position by year. If the value equals "0", the model run year does not consider previous year

```
==========================================================================
                        MODEL OPTIONS FILE
                          (OPTIONS.RPT)
==========================================================================
    GLOBAL
    VALUE                        DESCRIPTION
>-------------------------------------------------------------------------
       0    - LOGISTICS CYCLE DELTA in days: added to all ORU logistics cycles
       1    - STARTING SPARES: run with or without previous year's assets
                0-starting asset levels set to 0 each year
                1-starting level=previous year assets - replaced condemnations.
                2-starting level=MIN SPR for 1st yr demand>0, else previous yr.
      10    - NUMBER OF PASSES: the number of resource tradeoffs performed.
    99.0    - MAXIMUM AVAILABILITY (%) for the resource-vs-availability curve
       1    - PLOT:
                0 - produce no plots
                1 - plot the resource-vs-availability curve and the
                    multiple-pass curve
      11    - TRACE INFO:11-all, 10-Big Budget.RPT, 1-Big OUT.RPT, 0-small both
       8    - NUMBER OF MODEL YEARS in SSF life.
    1998    - FIRST MODEL FY spares required for building SSF.
    1994    - FIRST BUDGET FY that funding dollars are possible
       0    - FUNDING SPLIT:0-single funding profile
                            1-split out development and operational funds
    1991    - BASELINE FISCAL YEAR (fiscal year of ORU price)
       0    - PRICE INFLATOR PERCENTAGE: if 0%, POP constant $, else current $
       0    - LOTUS: 1-output tables formatted for import to LOTUS, 0-do not
       0    - QPA INPUT FORMAT
                0 - QPA is cumulative by FY with First Fiscal year
                corresponding to the QPA(1) column in MSPAREIN.RPT)
                1 - QPA columns represent elements(see Launch Schedule below)
      -1    - DECREMENT DAYS: Moves end FY requirements impact earlier.
               If -1 then decrement = ORU logistics cycle
       5    - WEAR WAKE: Wake+Model Year>life limit for wear item,default=5
       C    - DRIVE LOCATION for temporary files.  Use RAM drive if possible
                and if have 450 bytes of memory per ORU available.
       1    - NUMBER OF CRITICALITY CODES (e.g.,if C1,C2,C3 enter 3)
      28    - REPAIR PERCENTAGE: the ratio of repair to procurement cost
      90    - LABOR PERCENTAGE: the percentage of labor to the total repair cost

CUMULATIVE POP MARKS by crit code: constant $K if inflator=0% else current $K
CRIT  FY90   FY91   FY92   FY93   FY94   FY95   FY96   FY97    FY98    FY99
1st      0      0      0      0      0      0   5000  32000   88000  156000
2nd      0      0      0      0      0      0      0  22222   44444  666666

      SPREAD VECTORS: The Fraction of unit cost spread over the PLT
     Vector¦- Years from Requirement (i.e., Delivery)--¦
       #    ¦-delivery-¦----- Procurement Leadtime -----¦
                0      -1     -2     -3     -4     -5
>start  ----------------------------------------------
        1       0       1      0      0      0      0
        2       0       0.4    0.6    0      0      0
        3       0       0.2    0.5    0.3    0      0
>end of spread vectors

     LAUNCH SCHEDULE TABLE        (Row 1 corresponds to QPA col 1 in the
     Flight # ¦ Calendar¦ Launch   MSPAREIN.RPT, etc.  With this format
ROW  /Element ¦   Month ¦  Year    M-SPARE produces cumulative QPA by
>---start of schedule----------    fiscal year.
 1   LabA          12       1996
 2   LabB          3        2000
>---end of launch schedule----------
```

EXHIBIT 6-1. MODEL OPTIONS.RPT FILE

solutions and assumes that no spares assets exist. If the value equals "1", then each successive year of the model run uses the previous year's assets (minus replaced condemnations) as a starting position and then decides what spare to select next. If the option value equals "2," the model sets all ORU starting spares levels at the specific ORU MIN. SPR value (from the input file MSPAREIN.RPT) for the first model year where ORU demand is greater than 0. All years after that use the previous year's assets. For budget estimates, the model builds on the previous year's solution (option equals 1 or 2). However, users might want to determine the spares requirements based upon 0 starting assets each year (option equals "0"). The default option value equals "1".

NUMBER OF PASSES

The M-SPARE model is capable of running a number of passes for a particular year to help automate the resource tradeoff capability. Exhibit 3-1 displays the iterative price-versus-weight solutions produced by the model. In that example, the maximum number of passes is set to "10". As that value increases, the model increases its range and refines the resource tradeoffs. In the Multiple-Pass Mode section of Chapter 7, we further describe how that value is used. The default option value equals "10".

MAXIMUM AVAILABILITY

This option allows the user to set the maximum availability of the resource-versus-availability curve (expressed in percentages). Depending on the desired range of solutions, you can set the maximum to "99" percent or "99.99" percent. The default option value equals "99".

PLOT

The plot value allows the user to switch the model's plotting function off (value equals "0") or on (value equals "1"). If the plot value is on, the model plots the resource-versus-availability curve and if applicable, the multiple-pass curve. The default option value equals "1".

Hard copies of any plot can only be made when the plot is on your monitor screen. If you have an Hewlett-Packard (HP) laser printer, press the "Space" bar or type a label and then press "Enter" to make a hard copy. If you have an Epson printer, press the "Print Screen" key to make a hard copy. [*Note*: If nothing prints on

your Epson, type the command "GRAPHICS" before you start the model or add the graphics command to your AUTOEXEC.BAT file.] You can type a label, such as the date or number, on the hard copy to distinguish it from other similar plots. To do that, simply type the label before printing. If you only press "Enter", you can continue without printing the plot.

TRACE INFORMATION

The M-SPARE trace option gives the user control of the tables the model generates in the OUT.RPT and BUDGET.RPT files. When first learning about the model, the user can generate all M-SPARE table outputs for an abbreviated model run (enter "11"). For production runs, the user can reduce the size of the model output by some 50 pages but still produce the key solution tables (enter "0"). The specific option values that follow specify the tables the model generates between those two extremes:

- 11 – The model produces all the OUT.RPT and BUDGET.RPT tables as described in Chapter 8 of the M-SPARE documentation.
- 10 – The model does not produce the tables that display QPA, the resource-versus-availability curve, and the ORU input data in the OUT.RPT file. The model produces all other reports from Option 11.
- 1 – The model does not produce the tables that display the gross spares requirements by ORU, the spares budget estimates by ORU, and the next-guess calculation in the BUDGET.RPT file. The model produces all other reports from Option 11.
- 0 – The model does not produce the tables in the BUDGET.RPT and OUT.RPT as described in Options 10 and 1. The model produces all other reports from Option 11.

NUMBER OF MODEL YEARS

The number of model years option determines the number of years to be run on the model (i.e., the number of annual spares requirements forecasts). That time period begins when the station starts the assembly stage and ends near the end of the budget forecast (see Figure 6-1). The station starts assembly at the first element launch, which is based upon your ORU data base (you may specify that value in the next option). The end of the period is the last year that spares requirements impact the budget. The last year of the model equals your last budget year plus the number of years in your maximum spread vector (as described in Chapter 5). Thus, the

number of model years in Figure 6-1 equals "9" (FY96 through FY04). The model includes FY04 because spares requirements still increase budget outlays in your last budget year, FY02 (assuming a maximum spread vector of 2 years).

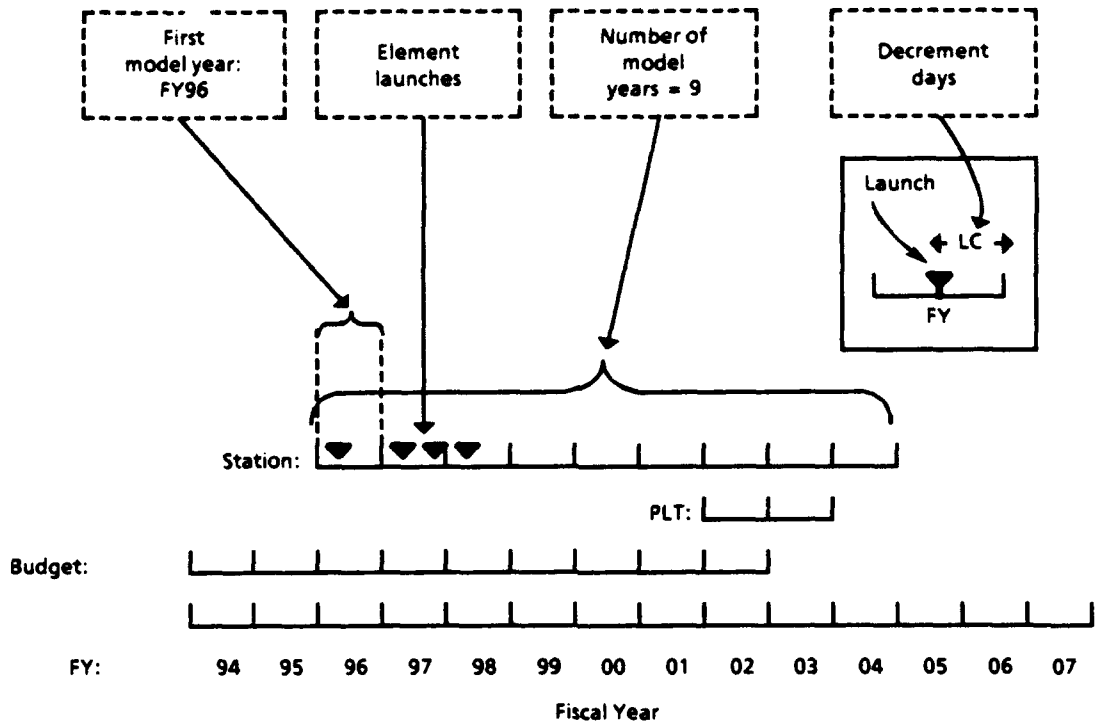

FIG. 6-1. KEY INPUT VARIABLES IN OPTIONS.RPT FILE

FIRST MODEL FY

The first model fiscal year determines what year the model run starts. You must enter the fiscal year that your first system is launched. Specifically, that date represents the first fiscal year that any ORU in your data base (MSPAREIN.RPT) may experience a failure. In Figure 6-1, it corresponds to "1996". The QPA option that follows contains additional information. The default value is dependent upon your MSPAREIN.RPT file format.

FIRST BUDGET FY

The first budget fiscal year specifies the earliest year that outlays can start for any spares procurement. For instance, in Figure 6-1, we assume "1994" is the first budget year. You may want to increase or decrease that year. The main impact of this option is that the model will not allow funding requirements to precede that first

year. For instance, if the model estimates an ORU spare requirement in FY96 and the ORU spread vector is over 3 years, any funds the model would have spread to FY93 are instead added to FY94 (the first budget year). To determine what funds need to be allocated before FY94, set the first year to an earlier year. [*Note*: You cannot set the first fiscal year earlier than "1990."] Our current default value is "1994".

FUNDING SPLIT

The M-SPARE model estimates spares and funding requirements by fiscal year. Certain users may require those estimates to be broken down further into two different budget category estimates: development and operational funding (see Chapter 9 for more discussion). If the user needs that breakdown, enter "1". In general, enter "0" for the default option.

BASELINE FISCAL YEAR

The user enters the dollar year of the ORU's unit prices as the baseline fiscal year value. M-SPARE assumes all ORU prices are for the same year and makes all calculations for future years in constant dollars for that baseline year. The model uses the baseline fiscal year to convert back and forth between constant-year dollars and current-year dollars as described in the next option.

PRICE INFLATOR PERCENTAGE

The price inflator percentage in the OPTIONS.RPT file is the inflation rate the user assumes over the model time frame. The model uses it to convert the cumulative POP marks inputs (a later option) from current-year dollars to constant-baseline-year dollars. Then, M-SPARE uses constant dollars for all its calculations and model output. The one exception is that the BUDGET.RPT displays the last table (a budget summary table) in both constant-year dollars and current-year dollars. If a constant inflator is inappropriate for you, just enter "0" for the inflator and the model assumes that the POP marks are in constant dollars and produces no summary table in current-year dollars.

LOTUS

This option modifies the output tables so that the user can move them for further manipulation to spreadsheet software (e.g., LOTUS 1-2-3, QUATTRO PRO,

or Excel). If you enter a "1", the model places quotes around character fields in the tables of the BUDGET.RPT file and some of the tables of the OUT.RPT file. The quotes allow certain spreadsheet software to retrieve tables and automatically translate them into spreadsheet format. For LOTUS 1-2-3, you "import" the file as "numbers". For QUATTRO PRO, you "import" the file using the 'Comma & "" Delimited' option on the menu bar. For Excel, you open the file as a text file, set the text options delimiter as "Custom" with double quotes, set the text origin to DOS, and then parse the number fields. If you enter a "0" for the M-SPARE LOTUS option, the model does not print the quotes so the table looks like a standard document table. The default value for this option equals "0."

QPA INPUT FORMAT

Station growth, and the corresponding increase in item failure rate, is reflected in M-SPARE by the ORU QPA (quantity per application for each ORU) profile over time (see top of Exhibit 4-1). We currently have two formats for that profile. If the user specifies a "0", the model assumes the QPA is cumulative by fiscal year with the first fiscal year corresponding to the QPA(1) column in MSPAREIN.RPT. If the user specifies a "1", the model assumes QPA columns represent elements and the model calculates cumulative QPA by fiscal year based upon the launch schedule (mission builds) at the bottom of the OPTIONS.RPT file. Figure 6-2 displays the two options. If the QPA is specified by fiscal year, it is only adjusted at the beginning of each fiscal year. If QPA is specified by launch, it is adjusted the month of each launch. The latter is more accurate but requires the data base to contain more detail (see the Demand Factors section in Chapter 5 for more information). The default value is dependent upon your MSPAREIN.RPT file format.

DECREMENT DAYS

Decrement days determines when in the fiscal year the last launch occurs, i.e., the logistics cycle that determines your spares requirements (see Chapter 1). The model usually assumes the last launch is a logistics cycle from the end of the year (see Figure 6-1). The default value of "−1" allows the model to automatically change the decrement to equal the ORU's logistics cycle. If you want to experiment and change the last launch to the middle or end of the year enter a "180" or "0", respectively.

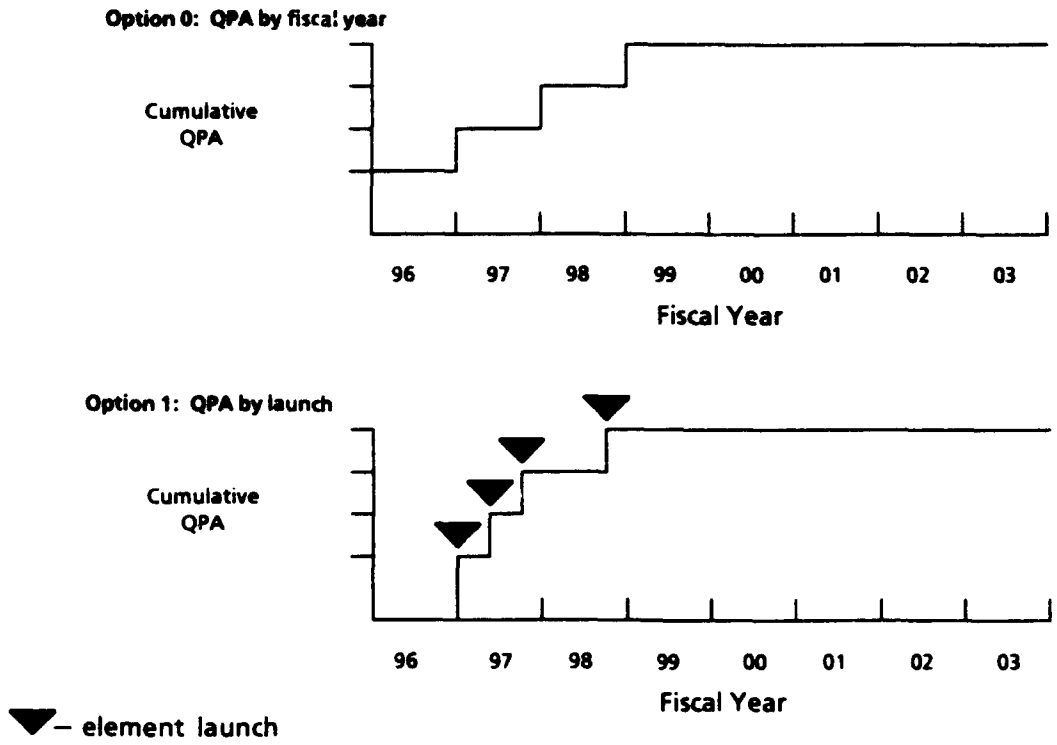

FIG. 6-2 QPA FORMAT OPTIONS

WEAR WAKE

The wear wake helps determine which ORUs require the simulation preprocessor (see Chapter 10). For instance, if the ORU mean wear life is 19 years, a wear failure may occur as early as 14 years. The wear wake for this case equals "5" (19 – 14). Since the maximum number of model years is 15, wear-related failures may occur within the model's timeframe and M-SPARE automatically uses the simulation preprocessor. The user can change the wear wake setting based upon the results of a more detail simulation analysis or to force M-SPARE to use the simulation for additional ORUs. The default value is "5" for this option.

DRIVE LOCATION

The drive location determines where M-SPARE stores its temporary files. If possible, you should create a random access memory (RAM) drive in your PC's memory. This is a simulated disk drive that actually exists in the PCs RAM area. If you have the room (in expanded or standard memory), a RAM drive will improve the speed of the model run. If you use a RAM drive, you enter the letter of the RAM drive

for this option. If you do not have a RAM drive, you enter a letter of the hard disk drive (make sure the drive has at least a few megabytes of free storage). The temporary files require about 1 kilobyte of memory per ORU. The default value is "C" for this option.

NUMBER OF CRITICALITY CODES

The M-SPARE model performs specific passes for each criticality code. If MSPAREIN.RPT file contains Criticality Codes 1, 2, and 3, enter "3" for this value and the model estimates requirements for all codes. If you want to run the model for only one type of criticality code, enter "1". You can use up to 25 different criticality codes but you must specify a POP mark for each (see the next option). The default is dependent on your MSPAREIN.RPT file.

REPAIR PERCENTAGE

The repair percentage is the ratio of repair cost to procurement cost. The model estimates the ORU's repair cost by multiplying the repair percentage times the ORU's procurement cost. The model then multiplies the ORU's repair cost times the annual number of repairs and sums the product across all ORUs to generate the annual repair budget. The default value for this option equals "28" (see Appendix B).

LABOR PERCENTAGE

The labor percentage splits the annual repair budget (discussed in the previous option) into repair cost estimates for labor and material. The model multiplies the labor percentage times the total repair cost to estimate the labor component and one minus the labor percentage to estimate the material component. The default value for this option equals "90" (see Appendix B).

CUMULATIVE POP MARKS TABLE

The cumulative budget marks are fiscal year budgets that constrain the model's spares estimates. The marks are by criticality code, in constant dollars, and in the same dollar year as the unit prices (unless the price inflator is greater than zero than the marks are in current year dollars). The marks help estimate the "price guess" so that M-SPARE produces budget estimates comparable to the POP marks (see Chapter 9). If you decide to run the model for fewer than three criticality codes (i.e., number of criticality codes option is less than 3) then put the budget marks in the

order of your next M-SPARE run. For instance, to run the model for Criticality Code 2 and Criticality Code 3 only, enter "2" for number of codes in the option above and put budget marks for Criticality Code 2 in the first row and Criticality Code 3 in the second row of the marks matrix. You must make sure all columns (from FY90 to FY10) contain a value even if the earlier years equal "0" and the later years are all the same. You can add up to 25 POP mark rows. When adding rows, just increase the row number (first column) by "1" and the number of criticality codes in the previous option.

SPREAD VECTORS

The spread vector table determines the fraction of unit cost that accrues from the start of the PLT until the delivery year. Each ORU in the input data bases has a spread vector number. In Exhibit 6-1, Vector 2 corresponds to a spread of 0.0, 0.4, and 0.6. Those vector numbers specify that no costs accrue in the year of delivery, 40 percent of the ORU's unit price accrues in the year right before the ORU is delivered, and 60 percent 1 year earlier. (This is the vector we used in the Chapter 1 example.) For an ORU with a 3-year PLT, the user may enter a vector similar to Vector 3. Notice that the vectors are reversed: you start by specifying the fraction for the delivery year (e.g., FY99) and then move back over the PLT 1 year at a time (e.g., FY98, then FY97 . . .). So far we assumed that dollar outlays for particular spares requirements occur in the previous fiscal years during the PLT (e.g., a spare in FY99 requires dollar outlays in FY98 and FY97, assuming a 2-year PLT). If you want the funds to accrue in the same year as the requirement (e.g., a spare in FY99 requires dollar outlays in FY99 and FY98), you place a value in the first spread vector column (labeled delivery) and the next column (labeled "−1" year from delivery). Furthermore, if the full price of the spare is paid on delivery, then set the spread vectors to "1" in the delivery year and "0" thereafter. You can add vectors by adding similarly formatted lines between the data marker (">"). When adding vectors, you must increase the spread vector number (first column) by 1.

LAUNCH SCHEDULE TABLE

If the QPA format option equals "1", then M-SPARE requires a launch schedule (see bottom of Exhibit 6-1). The schedule defines the calendar month and year of each SSF element launch (mission builds). M-SPARE automatically converts launch year into fiscal year, since fiscal years are the model's time units. When an entered year

falls after the last model year (e.g., "3000"), the element is not used in the model run. The first row in the table (LabA) corresponds to the first QPA column in MSPAREIN.RPT. The model calculates cumulative QPAs by month by summing QPA quantities for all elements previously launched. In the Exhibit 6-1 schedule, QPAs overtime is based upon launch times for the Lab A, Node 1, Cupola 1, and Airlock launches. The cumulative QPA profile appears at the bottom of Figure 6-2. You can add or delete element launches by adding or deleting lines of the file between the data markers (">"). Just make sure the added launch dates have the same format as what exists in your original OPTIONS.RPT file and that the element name does not extend past Column 15.

CHAPTER 7

MODEL OPERATION AND ANALYSIS

This chapter discusses how to run M-SPARE and the various types of analyses it can perform. By this point, we assume you opened the M-SPARE interface (see Chapter 2) and developed the three inputs required to run the model. Those inputs are the MSPAREIN.RPT file that contains the ORU data base, the OPTIONS.RPT file that contains M-SPARE parameters, and the wear preprocessor that develops aggregate demand parameters. Those inputs change relatively infrequently. Most of the parameters can be adjusted via the M-SPARE query selection we will now discuss.

The basic steps to execute M-SPARE on your PC are the following:

- Enter "CD\SPARE" to move to the SPARE directory if not already there.
- Enter "START" to enter the M-SPARE interface.
- Enter "R" to run M-SPARE.

The basic model operation is to run one criticality code at a time. Once a criticality code is selected by the user, the model then steps through each year of the station's life (see Figure 1-1). For each year, it asks you to enter some basic parameters and then it determines what spares this criticality requires. With each new year, the number and quantity of ORUs in the station change as the station configuration changes. Annual spares requirements reflect these changes. The number of yearly iterations depend upon the number of years in the budget projection and is set by the number of model years you specified in the OPTIONS.RPT file (see Chapter 6). When the model finishes calculating the yearly iterations, it repeats the process for the next criticality code. When it finishes with all the criticality codes, it then computes the budget for all ORUs from all criticality codes.

Exhibit 7-1 is the first query that appears on your monitor when you run M-SPARE. It asks you to select a criticality code. M-SPARE develops spares requirements one criticality code at a time. You now enter a criticality code of one or two characters. If you enter a single character such as a "1", the model selects all

ORUs with a 1, as the first character in its criticality code. That means ORUs with 1 and 1R become the selected ORUs for the spares optimization. If you wish to run a subset of Criticality Code 1 separately, you enter two characters such as "1 " or "1R" for nonredundant and redundant ORUs. The model is sensitive to upper and lower case letters so that a 1R and a 1r are not the same.

```
Enter Criticality Code (1,2,3,1R,2R...)
  To combine Crit 1 & 1R enter "1"
  To separate Crit 1 & 1R enter "1R" & "1_" (add space)
  Careful, the model is sensitive to super & lower case
  so a 1r and a 1R are different codes
  1
```

EXHIBIT 7-1. CRITICALITY CODE QUERY

The screen shown in Exhibit 7-2 appears next. This is the monitor screen you will return to with each new model year or if you want to start over. For now, simply press "Enter" for run. A dialog box similar to Exhibit 7-3 will appear.

Exhibit 7-3 displays the five menu choices (top of box). The text in the bottom part of the box presents the status information on the model year, fiscal year, and criticality code for the current model iteration. The menu choices succinctly summarize the capabilities or modes of M-SPARE. Each mode has a specific purpose and each is described in a separate section in this chapter. The modes are as follows:

- *Multiple-pass mode* performs tradeoffs between ground and on-orbit storage and between two resources. The model performs multiple passes and

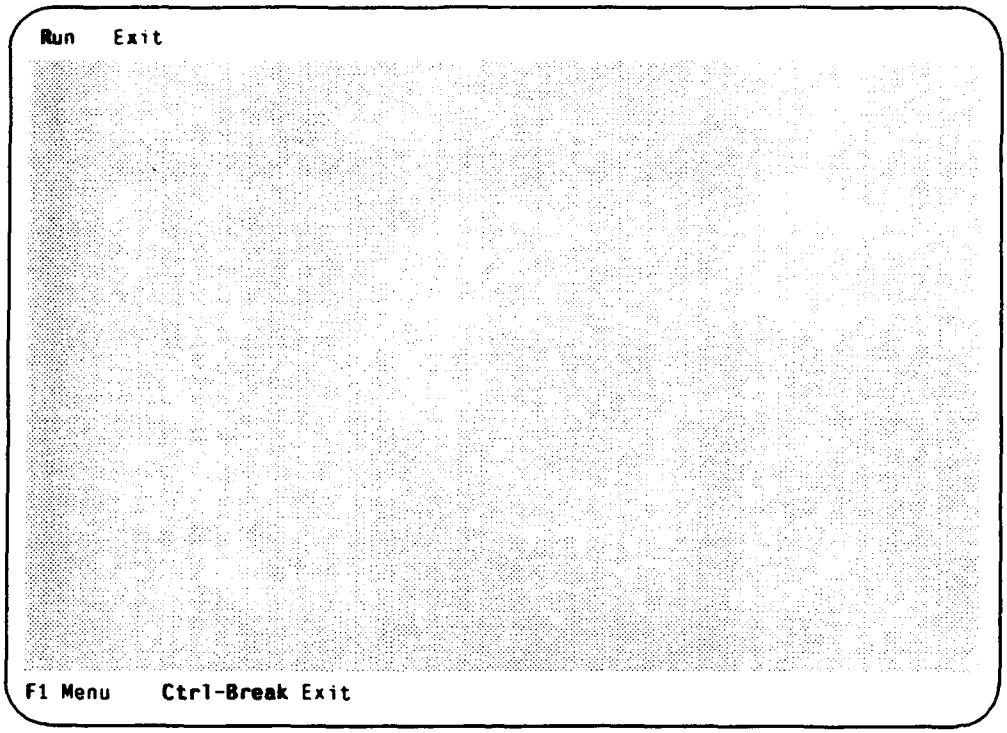

EXHIBIT 7-2. INITIAL YEAR MENU

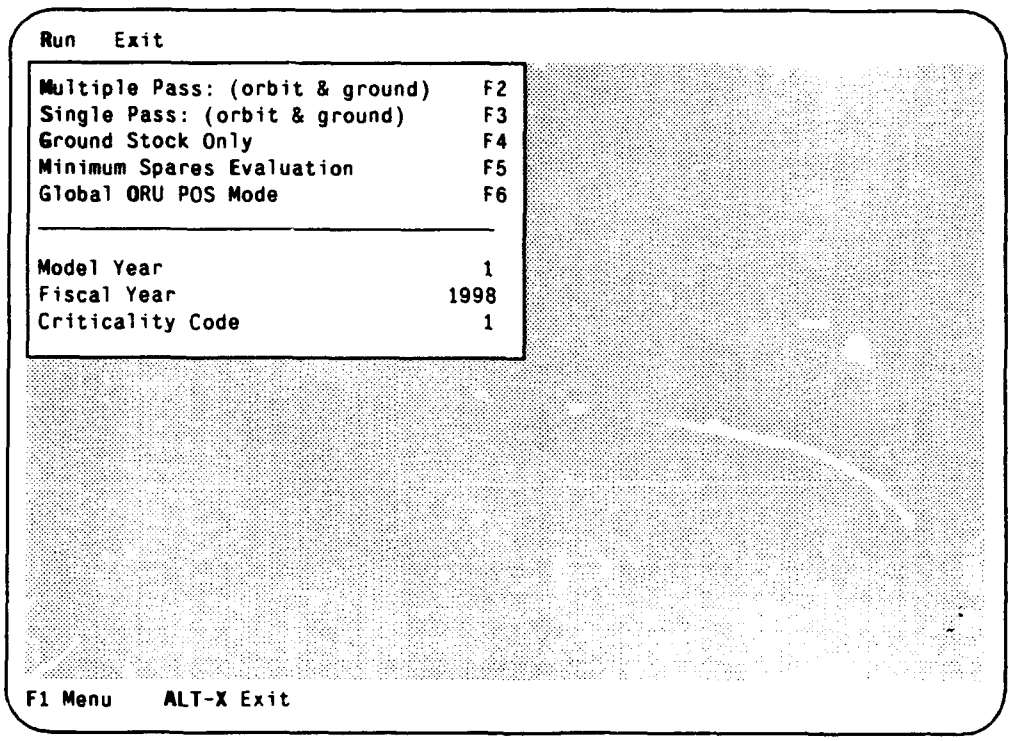

EXHIBIT 7-3. MODEL RUN OPTIONS MENU

automatically varies the relative importance (the coefficients) between resources for each pass.

- *Single-pass mode* allows you to specify the resource coefficients in order to examine a specific pass solution. You may also specify your own coefficients and calculate tradeoffs between ground and on-orbit storage.
- *Ground-stock-only mode* changes the model orientation to handle those ORUs that can only be stored on the ground such as noncritical ORUs.
- *Minimum spares evaluation mode* (not operational).
- *Global ORU POS mode* estimates the ground availability of setting each ORU to a user-specified POS target.

In our discussion of each of those modes and their respective inputs, we start with the single-pass mode and then describe the other modes in the order listed above. We deal with the single-pass mode of operation first because that is the building block for generating more complex analyses such as the multiple-pass mode.

To select the single-pass mode, you press the "↓" key until the mode is highlighted and then press "Enter" (you can also press the bold or red letter of the mode "S" or select the mode with your mouse). Your monitor displays a screen similar to Exhibit 7-4. Once you enter a mode dialog, pressing the "Tab" key will allow you to step through the queries. Press "Enter" (or the "OK" button) when you have answered all queries. If you wish to go back to a query, keep pressing the "Tab" key to cycle through the list again or use a mouse to make a selection. In addition, the model remembers your previous year's dialog selection and keeps them as the starting conditions for the current year. *An important point is that even if the dialogue is properly set from the previous year, you must press the "Tab" key before you press "Enter" to begin execution.* If you select the wrong mode, press the "Escape" key or the cancel button to start over again and the Exhibit 7-2 screen will appear on your monitor. To exit or abort an M-SPARE run entirely, select "Exit" from the menu in Exhibit 7-1. Once the model starts calculating, you can exit by pressing "Ctrl-Break".

SINGLE-PASS MODE

The M-SPARE model requires three types of station (system) inputs: targets, resource coefficients, and PLT months. Targets are station goals (e.g., availability) that determine the spares solution point on the resource-versus-availability curve.

Resource coefficients are factors we have developed to effect the model optimization process. Coefficients determine the relative importance of each of the resources. The more important a resource, the more the model conserves that resource expenditure. The user can further modify the spares selection process by choosing ORUs with PLTs (MSPARIN.RPT field labeled "mths 3") less than some maximum value. Since that input helps the user match a particular budget (POP marks), we describe that last query in the Constrained Budget Product section of Chapter 9. For now, you can ignore this query merely by keeping the default value of "0".

M-SPARE handles four categories of targets, including (1) *availability* – the minimum acceptable station performance the user wants, (2) *cumulative weight* (past and present model years) – the maximum number of pounds allotted for spares on shuttle flights, (3) *cumulative price* – the total investment in spares, and (4) *cumulative volume* – the maximum on-orbit storage volume in cubic inches. You must enter one to four of the targets. If you enter more than one target, the model stops when the first value of any of the targets is met. That determines the spares mix solution. If you do not have to or do not want to consider a target, enter "0". *A "0" automatically sets the target to a maximum value for you.*

The model also handles three resource coefficients: price, weight, and volume. Equation 7-1 presents the linear combination of coefficients and resources used to estimate the on-orbit unit resource for the model (a slight modification to Equation 4-4).

$$unit\ resource_i = (cp)\$K_i + (cw)LBS_i + (cv)IN\hat{}3_i\,, \qquad \text{[Eq. 7-1]}$$

where

i	=	ORU index
cp	=	price coefficient
cw	=	weight coefficient
cv	=	volume coefficient
$\$K$	=	ORU unit price in $1,000s
LBS	=	ORU unit weight in pounds
$IN\hat{}3$	=	ORU unit volume in cubic inches.

Exhibit 7-4 displays the coefficient and target queries you specify for this operation mode. As you increase the relative size of one coefficient to another, the model will tend to "conserve" that total resource expenditure. For instance, you first might wish to treat all resources equally, then enter a "1" for each coefficient and specify your targets. After the model runs, you notice that weight is the only resource at (just below) its target. Run the model again with all the same input, but this time enter an "8" for the weight coefficient. Now weight has relatively greater importance than the other two coefficients. The model will try to conserve weight, sacrificing cost and volume. The result is the station availability increases under the same resource constraints.

```
Run   Exit

[ ═══════════ Single-Pass Mode Dialog ═══════════
                                        Model Year:     1
                                        Fiscal Year:  1998
                                        Crit Code:      1

Enter Volume Coefficient                                0
Enter Price Coefficient                                 1
Enter Weight Coefficient                                0

Enter Cumulative Volume Target in cubic inches:         0
Enter Cumulative Price Target in $1000s:                0
Enter Cumulative Weight Target in pounds:               0
Enter Availability Target from 0 to 100 percent:        0
Enter maximum PLT (months) for spare ORUs:              0
[Note:  A "0" above means ignore (set to Max).]

          OK          Cancel

     Tab Next Query  Return OK-Done
 Tab-Return  OK-Done  Esc  Cancel  Tab  Next  Query

F1 Menu    Ctrl-Break Exit
```

EXHIBIT 7-4. SINGLE-PASS MODE

You might wonder why we suggested an 8 as the weight coefficient. Why not a 5? Is it necessary to try every possible combination? The answer to the last question is yes, to some degree. That is why we have developed a multiple-pass version of the model that will automatically vary the coefficients for you. That is the topic of our next section.

MULTIPLE-PASS MODE

The purpose of the multiple-pass mode is to perform incremental tradeoffs between two resources and to present the possible solutions. In Chapter 3, we discussed how the model varies the relative importance (the coefficient) of two resources and generates the cost-versus-weight solutions of Exhibit 3-1. In this section, we discuss the user inputs that were used to generate that exhibit and the types of analyses the model can perform.

Once you select the multiple-pass mode of operation, a screen similar to Exhibit 7-5 displays model queries. For this mode, the model varies the relative importance of two resource types at a time, though all three resources are included in the unit resource Equation 7-2. Select a resource tradeoff by pressing "Tab" and then the " ↓ " key to highlight the desired tradeoff (a dot appears in front of the selection). For example, select a price-versus-weight tradeoff, then select the next query, "enter a coefficient not in the chosen tradeoff," or the volume coefficient. Pressing the "Tab" key also lets you move to enter target values. When you are finished, press the "Enter" key to start the current model year run.

```
Run   Exit

[                    Multiple-Pass Mode Dialog

            Select desired Trade Off        Model Year:     1
            (·) Price-vs-Weight             Fiscal Year:  1998
            ( ) Price-vs-Volume             Crit Code:      1
            ( ) Weight-vs-Volume
Enter Coefficient not in chosen Tradeoff:                 0
Enter Cumulative Volume Target in cubic inches:           0
Enter Cumulative Price Target in $1000s:                  0
Enter Cumulative Weight Target in pounds:                 0
Enter Availability Target from 0 to 100 percent:          0
Enter maximum PLT (months) for spare ORUs:                0
[Note:  A ")" above means ignore (set to Max).]

          OK                Cancel

  Tab-Return  OK-Done      Esc  Cancel  Tab Next Query

F1 Menu     Ctrl-Break Exit
```

EXHIBIT 7-5. MULTIPLE-PASS MODE

Notice that in Equation 7-2 the three resource coefficients used in Equation 7-1 *cp*, *cw*, and *cv* are now modified to *c*, $(1-c)$, and a *constant*, respectively. If you selected a different resource tradeoff in the first query, then *c* is the coefficient for the first resource, $(1-c)$ is the coefficient for the other tradeoff resource, and you enter the constant for the third resource coefficient.

$$unit\ resource_i = (c)\$K_i + (1-c)LBS_i + (constant)\,IN\hat{}3_i\,, \qquad \text{[Eq. 7-2]}$$

where

i	=	ORU index
$\$K$	=	ORU unit price in $1,000s
LBS	=	ORU unit weight in pounds
$IN\hat{}3$	=	ORU unit volume in cubic inches
constant	=	coefficient that is held constant over all the passes
c	=	$1-$(Pass/MaxPass)
Pass	=	pass number
MaxPass	=	maximum number of passes, set in the OPTIONS.RPT file.

For the example in Chapter 3, Exhibit 3-1, the model pass number ranged from 0, 1, 2, etc., up to 10; the price coefficient, *c*, ranged from 1, 0.9, 0.8, etc., down to 0.0; and the weight coefficient, $(1-c)$, ranged from 0, 0.1, 0.2, etc., up to 1, respectively. (For our example, since we entered a "0" for the volume coefficient constant, volume is basically not considered in the unit resource equation.) For each pass, the relative importance between price and weight is adjusted. That relative importance is the ratio of the coefficients $[(1-c)/c]$. At Pass 1, weight is about one-tenth $(0.1/0.9=0.11)$ as important as price. At Pass 9, weight is 9 times $(0.9/0.1=9)$ more important than price. (That ratio also can be thought of as a factor that converts pounds into dollars.)

If you increase the maximum pass number from "10" to "100", Pass 1 now makes weight one-hundredth as important as price, and Pass 99 makes weight 99 times more important than price. Thus, the maximum pass number is a way to increase the range and refine resource tradeoffs. A large maximum pass number is useful to ensure the model has tested every possible combination, especially if the total resource magnitudes are significantly different (e.g., unit volume is 100 times

larger than unit weight on the average). The key point is that as the resource's relative importance increases, the model "conserves" or reduces its total resource expenditure.

Once the model has run all the passes, it chooses one as a solution. It then reruns that pass to generate the spares mix and resource-versus-availability curve. In general, the solution is the pass with the greatest station availability given the same resource constraints.

If you enter only an availability target or only a price target, the model solution is then the pass that is less than 1 percent over the minimum price and has the least weight. Exhibit 7-6 presents the pass solutions table from the test drive discussed earlier. In that case, the pass with the minimum price is the first pass because it does not consider weight and stores all spares on orbit. Even though there is no weight target, storing all spares on orbit is not a practical solution. As discussed in Chapter 3 (see Exhibit 3-1), a solution that considers weight and price near the elbow of the curve is preferable. Other choices are "penny wise and pound foolish." Thus, the model solution is the pass with the least weight that is within 1 percent of the minimum price. In Exhibit 7-6, that pass is Pass 5. Pass 5 now becomes the model solution. (It is repeated as the last pass in the exhibit.)

PASS SOLUTIONS:	========== RESOURCES ==========			======COEFFICIENTS ========		
PASS	AVAIL	PRICE:$K	WEIGHT:lbs	VOLUME:in^3	PRICE	WEIGHT	VOLUME
0	95.0443	193306	26545	2964042	1.0000	0.0000	0.0000
1	95.5527	196225	16164	2179708	0.9000	0.1000	0.0000
2	95.5168	196225	15717	2165476	0.8000	0.2000	0.0000
3	95.1487	195285	14069	1650340	0.7000	0.3000	0.0000
4	95.1044	195285	13824	1637332	0.6000	0.4000	0.0000
5	95.0214	195230	13556	1613500	0.5000	0.5000	0.0000
6	95.0258	200420	11004	1243078	0.4000	0.6000	0.0000
7	95.0070	200815	10847	1233238	0.3000	0.7000	0.0000
8	95.0158	202708	10514	1219270	0.2000	0.8000	0.0000
9	95.2954	207611	10260	1217178	0.1000	0.9000	0.0000
10	95.6330	403515	9061	1143198	0.0000	1.0000	0.0000
11	95.0214	195230	13556	1613500	0.5000	0.5000	0.0000

EXHIBIT 7-6. PASS SOLUTIONS TABLE

A point about doing analyses with the model in this mode: if you want a complete range of tradeoffs between two resources, only set an availability target; if you want the best solution for a number of targets, enter the targets. However, if you enter the targets, the resource tradeoff curve then becomes less informative.

GROUND-STOCK-ONLY MODE

The ground-stock-only mode is selected when the ORU data base contains ORUs whose spares are only stored on the ground. Those units are usually the noncritical ORUs (Criticality Code 3) for which station availability is less meaningful. With no on-orbit spares, the station availability is determined largely by the probability of no failures over the cycle. (Calculated availability is typically low, reflecting the decision that some shortages of spares of these items can be tolerated.) Because of that, we have modified the model to use a more meaningful availability measure, ground availability. This is a measure of probability that all ORUs have sufficient ground spares to replace all failures from the previous logistics cycle. Using the ground availability measure does not affect the spares selection process we discussed.

Since no spares are stored on orbit, this operational mode is only concerned with one resource, price. Therefore, the price coefficient is automatically set to 1 (the rest are set to 0). You must select between a ground availability or a price target. Exhibit 7-7 shows the queries available when you choose this option. First press the "Tab" key and select the target type with the " ↓ " key. Once you selected a target, press "Tab" again and enter the target in the box (a value between 0 to 100 if you previously selected an availability target or a value in thousands of dollars if you previously selected a price target). Finally, you press return to start the current model year run.

MINIMUM SPARES EVALUATION MODE

(This option is currently not available.)

GLOBAL ORU POS MODE

The global ORU probability-of-sufficiency (POS) mode is available because it provides a common starting point since many NASA work packages are familiar with the POS measure. For the POS mode of operation, the model selects enough spares so that each ORU POS is greater than or equal to a user-specified POS goal.

```
Run   Exit

[ ═══════ Ground-Stock-Only Mode Dialog ═══════

Select Target Type                          Model Year:     1
 (·) Cumulative Price in 1000s of dollars   Fiscal Year:  1998
 ( ) Ground Availability from 0 to 100%     Crit Code:      1

Enter selected Target in appropriate units:          0
Enter maximum PLT (months) for spare ORUs:           0
[Note:  A "0" above means ignore (set to Max).]

          OK                Cancel

 Tab-Return  OK-Done      Esc  Cancel  Tab Next Query

F1 Menu    ALT-X Exit
```

EXHIBIT 7-7. GROUND-STOCK-ONLY MODE

Exhibit 7-8 shows the queries available when you choose this option. Similar to the optimal approach, the POS measure considers two spares locations: ground and on-orbit. The "Ground POS" estimates spares requirements assuming ground stock only; the "Orbit POS" estimates spares requirements under the limiting assumption that all spares are stored on orbit. The POS methodology does not optimize spares locations, nor does it consider resources other than dollars. Thus, it cannot produce an optimal mix of ground and orbit spares. The POS is estimated by a Poisson distribution (see Equation 4-1) with a mean equal to the mean number of unserviceable units at shuttle launch (MB) for the ground POS option or a mean equal to the mean number of orbit failures for the next logistics cycle (MO) plus MB for the orbit POS option.

Once you select this POS mode, you must select either the orbit or ground POS type. First, press the "Tab" key and then select POS type with the " ↓ " key. Then, press the "Tab" key again and enter the POS target from "0" to "100" (percent). This alternative is not used to generate a spares list but rather to give users a familiar value to compare with those of the optimization model runs.

```
Run   Exit

[ ═══════════ Global ORU POS Mode Dialog ═══════════

Select Target Type                          Model Year:     1
 ( ) Orbit POS:  All stock on-orbit         Fiscal Year:  1998
 ()  Ground POS: Ground Stock Only          Crit Code:      1

Enter that POS Target:  0 to 100%      0

            OK                  Cancel

     Tab-Return  OK-Done        Esc  Cancel

F1 Menu    ALT-X Exit
```

EXHIBIT 7-8. GLOBAL ORU POS MODE

CHAPTER 8

MODEL OUTPUTS

Running the model produces two files. One model output file (BUDGET.RPT) summarizes the budget results and targets across all criticalities and fiscal years. The other output file (OUT.RPT) presents the basic inputs and detail spares requirements by criticality and model year. To better understand this chapter's discussion, you may want to follow along by browsing the files using the supplied editor (select the "View" menu option and then select the appropriate file). We will first discuss BUDGET.RPT and then OUT.RPT.

THE BUDGET OUTPUT FILES (BUDGET.RPT)

The model produces six types of budget output tables. The first table is the annual budget by model year and criticality. That table gives summary results so that the user can target the model to select spares based upon the POP marks (as described in Chapter 9). The next three tables produce gross spares requirements, net spares requirements, and spares budget estimates by ORU and fiscal year. Those tables reflect the methodology described in Table 1-2. The next table type displays budget summary information (i.e., dollars summed across all ORUs) for spares budgets, wear ORU budgets (a subset of the spares budgets), and repair budgets (a supplementary model estimate that we discuss shortly). All tables are formatted so that they can be imported to spreadsheet software for further manipulation (as discussed in Chapter 6).

Annual Budgets by Model Year and Criticality

An important function of M-SPARE is to determine what spares are required given the POP marks. Although both M-SPARE inputs and POP marks are presented in constant dollars and closely linked, the two differ significantly. The total annual budgets by model run year table (see Exhibit 9-1) helps the user determine which M-SPARE targets to input so that the resulting budget equals the POP marks. We discuss this process in Chapter 9.

Gross Spares Requirements by Fiscal Year Table

The table in Exhibit 8-1 displays the gross spares requirements by ORU and by fiscal year. (The requirements do not include replaced condemnations.) The table also presents information on each ORU unit price, part number, CAGE numbers, and PLT spread vector (to the right of the fiscal year).

GROSS SPARES REQUIREMENTS BY FISCAL YEAR

> ID	NAME(18)	1994	1995	1996	1997	1998	1999	2000
1	"RADIATOR "	0.0	0.0	0.0	0.0	2.0	2.0	2.0
2	"PFCS "	0.0	0.0	0.0	0.0	3.0	3.0	4.0
3	"BATTERY ORU "	0.0	0.0	0.0	0.0	3.0	5.0	8.0
4	"BCDU "	0.0	0.0	0.0	0.0	6.0	8.0	13.0
5	"DC SWITCH UNIT "	0.0	0.0	0.0	0.0	5.0	7.0	10.0

EXHIBIT 8-1. GROSS SPARES REQUIREMENTS BY FISCAL YEAR

Net Spares Requirements with Replaced Condemnations by Fiscal Year Table

The table in Exhibit 8-2 presents the net spares by ORU and fiscal year and includes replaced condemnations. The model calculates the net spares for a fiscal year by finding the gross spares requirements of the fiscal year minus the gross spares requirements of the previous fiscal year plus replaced condemnations (see Chapter 4 for more discussion). The table also presents (not displayed) total net spares summed across all fiscal years ("Sum FYs"), and whether or not the ORU used the preprocessor (a "1" or a "0" in the "wear" column, respectively).

Spares Budget Estimates by Fiscal Year Table

The table in Exhibit 8-3 presents the spares budgets by ORU and fiscal year. It is similar to the bottom half of Table 1-2c where spares buys are multiplied by unit costs and then spread across the PLT.

Summary Budget Estimates: Total Table

The table shown as Exhibit 8-4 displays budget summaries in thousands of constant dollars. The first budget row is the budget for wear or preventive maintenance (also termed scheduled maintenance) ORUs (i.e., those ORUs that

```
*****************************************************************************
   NET SPARES REQUIREMENTS INCLUDING REPLACED CONDEMNATIONS BY FISCAL YEAR
*****************************************************************************
> ID        NAME(18)        1994     1995     1996     1997     1998     1999     2000
1  "RADIATOR            "    0.0      0.0      0.0      0.0      2.0      0.0      0.0
2  "PFCS                "    0.0      0.0      0.0      0.0      3.0      0.0      1.0
3  "BATTERY ORU         "    0.0      0.0      0.0      0.0      3.0      2.0      3.0
4  "BCDU                "    0.0      0.0      0.0      0.0      6.0      2.0      5.0
5  "DC SWITCH UNIT      "    0.0      0.0      0.0      0.0      5.0      2.0      3.0
```

EXHIBIT 8-2. NET SPARES REQUIREMENTS

```
*****************************************************************************
        SPARES BUDGET ESTIMATES BY FISCAL YEAR IN 1000'S OF CONSTANT DOLLARS
*****************************************************************************
> ID        NAME(18)        1994     1995     1996     1997     1998     1999
1  "RADIATOR            "    0.0      0.0   3502.8   2335.2      0.0   1751.4
2  "PFCS                "    0.0   3205.8   5343.0   3205.8   1781.0    712.4
3  "BATTERY ORU         "    0.0   1075.5   2509.5   2987.5   4063.0  10157.5
4  "BCDU                "    0.0   2678.4   5356.8   5505.6   5208.0   3422.4
5  "DC SWITCH UNIT      "    0.0    793.5   1639.9   1534.1   1005.1    476.1
          .
          .
          .
```

EXHIBIT 8-3. SPARES BUDGET ESTIMATES BY FISCAL YEAR

require the wear preprocessor because their failure rates are time dependent – see Chapter 10). The model displays that subset because some users require a separate budget category for those types of ORUs. The model also produces an aggregate budget (both wear and random ORUs) titled the annual model budget (the next row). Next, the table displays the annual and cumulative POP marks so that you can compare the model's estimates with a potential spending cap.

Summary Budget Estimates: Repairs Plus Spares Table

The M-SPARE model also produces annual repair budgets that are consistent with its spares calculation. The repair budget starts where the spares budget leaves off. That is, once you procure the spare, you then incur repair cost for keeping the spare operational. M-SPARE begins the repair budget calculation at the ORU level

SUMMARY BUDGET ESTIMATES (THOUSANDS OF CONSTANT 1991 DOLLARS)

Total ($K)/FISCAL YEAR:	1994	1995	1996	1997	1998	1999	2000
Annual Wear & PM Subset	0	1076	2510	2988	3346	7529	16252
Annual Model Budget	0	20505	60536	61136	49277	39931	29002
Annual POP Marks	0	0	5000	27000	56000	68000	70000
Cumulative Model Budget	0	20505	81041	142177	191454	231386	260387
Cumulative POP Marks	0	0	5000	32000	88000	156000	226000

EXHIBIT 8-4. SPARES SUMMARY BUDGETS TABLE

by multiplying the annual number of repairs times the ORU's unit repair cost. It then sums that product for all ORUs by year and across all criticalities. Unlike spares budgets that spread the procurement over several years, the repair budgets assume all expenditures affect the fiscal year during which the broken ORU enters the repair process. As we subsequently discuss, the number of repairs is based upon the spares calculation while a component of the repair costs is an exogenous assumption entered by the user.

The M-SPARE model estimates annual repairs by summing all repair actions initiated in the previous 12 months, starting at the most recent launch month and moving backward. [The launch month is the month that is one logistic cycle from the end of the year and is the point at which the model estimates annual spares requirements (see Chapter 4).] M-SPARE estimates repair actions by first estimating total failures (random and wear related) and then subtracting estimated condemnations (random and wear related).

The M-SPARE model estimates repair cost by multiplying the ratio of the repair cost to the procurement cost times the ORU's procurement price. Through analysis of Spacelab historical repair data, we estimate that repair ratio to be 28 percent (see Appendix B). The user can modify the repair ratio as well as the ratio that splits total repair costs into labor costs and material costs in the OPTIONS.RPT file (see Chapter 6).

Exhibit 8-5 displays the repair estimates. The annual repair budget is the result of the methodology just discussed. The table also displays that budget split into labor and material components. Next, the table displays total number of repairs and then the average repair cost (the repair budget divided by the number of repairs). The last rows in Exhibit 8-5 present the sum of the repair budget and the spares budget (Exhibit 8-4). If you enter a price inflator in the options file, the model will produce a table similar to Exhibit 8-5 but in current-year dollars.

SUMMARY BUDGET ESTIMATES (THOUSANDS OF CONSTANT 1991 DOLLARS)

Repair + Spares ($K) /FY:	1994	1995	1996	1997	1998	1999	2000
Annual Repair Budget	0	0	0	0	2181	3528	4098
Labor Repair Costs	0	0	0	0	1963	3175	3688
Material Repair Costs	0	0	0	0	218	353	410
Average Repair Costs	0	0	0	0	152	157	159
Annual Number of Repairs	0	0	0	0	14	22	26
Cumulative Repair Budget	0	0	0	0	2181	5710	9807
Annual Repair+Spares	0	20505	60536	61136	51458	43460	33100
Cumulative Repair+Spares	0	20505	81041	142177	193636	237095	270195

* Repair budget = ORU repairs/yr * Price * 0.280

EXHIBIT 8-5. REPAIR AND SPARES SUMMARY BUDGET TABLE

DETAILED SPARES REQUIREMENT FILES (OUT.RPT)

The other output file (OUT.RPT) that M-SPARE produces presents more detailed model inputs and spares requirements outputs. The data are first separated into different criticality codes, then into model year runs. For each criticality code, the file contains a launch schedule, demand summary, QPA profile, and user input table for all model years. It presents six other tables that are repeated by model year. At the end of the file is the resource and ground packing summary table. The different table locations are mapped out in Table 8-1. Descriptions of the various tables in the file are as follows:

- *Element Launch Schedule Table.* Displays the name, month, and year of each element launch.
- *QPA Profile Table.* Displays the total QPA by month and model fiscal year. Each ORU is in a separate subtable.

- *Demand Summary Table.* Displays mean orbit failures, mean broken spares, replaced condemnations, and VMR by model fiscal year. Each ORU is in a separate subtable.
- *User Inputs and Options Table.* Shows the user inputs entered and the model options selected from the OPTIONS.RPT file.
- *ORU Input Data Table.* Shows the ORU input information from the MSPAREIN.RPT file for each model year.
- *Pass Solutions Table.* Shows the station availability and resource information at the solution point for each pass of the model.
- *Spares Mix for Solution Point Table.* Shows the spares requirements (on orbit and ground) for the best pass solution.
- *Distributed Systems Results Table.* Shows the availability and station resource expenditures disaggregated to a distributed system level.
- *Resource-Versus-Availability Curve Table.* Presents the data used for the curve in tabular form.
- *Resource Summary Table.* Shows the weight and volume of Criticality Code 1 ORUs stored on orbit and all ORU codes resupplied each year.
- *Annual Ground Packing Volume.* Displays the ground inventory volume of serviceable spares, i.e., the working spares volume on inventory shelves.

Each output table is discussed in a separate subsection of our guide and is identified by the table title.

Element Launch Schedule Table

If your ORU input data is by element launch, the model produces the launch schedule (see Exhibit 8-6). The first two columns in this table displays the M-SPARE element number and name, which corresponds to the order and name of the elements in the OPTIONS.RPT file and the ORU input file. The next two columns present the element launch dates in calendar month and year (the information you entered in the OPTIONS.RPT file). The final two columns present the launch by fiscal month and year. Since most people use calendar timeframes while M-SPARE uses fiscal timeframes, we present the translation for you. A fiscal timeframe places the launch 3 months later than calender information.

TABLE 8-1

TABLE LAYOUT OF OUT.RPT FILE

- Criticality Code 1
  - Element Launch Schedule Table
  - QPA Profile Table
  - Demand Summary Table
  - User Inputs and Options Table
  - First Model Year
    - ORU Input Data Table
    - Pass Solutions Table
    - Spares Mix for Solution Point Table
    - Distributed Systems Results Table
    - Resource-Versus-Availability Curve Table
  - Second Model Year (same type of tables as first year)
  - •
  - •
  - •
- Criticality Code 2 (same type of tables as Code 1)
  - •
  - •
  - •
- Criticality Code 3 (same type of tables as Code 1)
  - •
  - •
  - •
- Resource Summary Table
- Annual Ground Packing Volume Table

QPA Profile Table

The QPA profile presents the total QPA (summed across all elements) by month and model fiscal year for each ORU (see Exhibit 8-7). QPA is the only demand variable that changes from one model year to the next. Depending on the format of your ORU input data, the QPA could change each fiscal year (i.e., each row) or on a specific month of the element launch. If the input data is by element launch, the QPA profile is followed by a list of QPA quantities by element. If the ORU is a wear item, the simulation input file (PREPIN.DAT) contains the QPA profiles.

```
**************** Element Launch Schedule **************
 Element #/Name   Calendar:Mth  Year ¦ Fiscal:Mth   FY
 1   LabA                 10   1995          1   1996
 2   HabA                 10   1999          1   2000
 3   PLM3                  4   2001          7   2001
```

EXHIBIT 8-6. ELEMENT LAUNCH SCHEDULE TABLE

```
ORU#    1 EXAMPLE STATION ORU            LogCycle= 180 NOT  a wear item
QPA BY MONTH (COL), YEARS (ROW)
        1   2   3   4   5   6   7   8   9  10  11  12
 ---------------------------------------------------
 1996   2   2   2   2   2   2   2   2   2   2   2   2
 1997   2   2   2   2   2   2   2   2   2   2   2   2
 1998   2   2   2   2   2   2   2   2   2   2   2   2
 1999   2   2   2   2   2   2   2   2   2   2   2   2
 2000   4   4   4   4   4   4   4   4   4   4   4   4
 2001   4   4   4   4   4   4   6   6   6   6   6   6
 2002   6   6   6   6   6   6   6   6   6   6   6   6
 2003   6   6   6   6   6   6   6   6   6   6   6   6
 2004   6   6   6   6   6   6   6   6   6   6   6   6
 2005   6   6   6   6   6   6   6   6   6   6   6   6

 Element #      1   2   3
 Element QPA    2   2   2
```

EXHIBIT 8-7. QPA PROFILE TABLE

Demand Summary Table

The table in Exhibit 8-8 contains detailed demand information by ORU and by model year. The purpose of the table is to display the most detailed calculations of the model. (You might want to skip this information initially.) Each column of the ORU matrix corresponds to different factors such as the mean orbit failures, the mean broken spares (number of unserviceable ORUs), the replaced condemnations, and the VMR. We discuss each variable in Chapter 4. However, if the ORU uses the wear simulation, we discuss those factors in Chapter 10.

AT ORU 1 EXAMPLE STATION ORU

Model YR	Mean Orbit	Mean Broken	Replace Condemn.	VMR
1996	4.00	4.00	0.00	1.00
1997	4.00	6.00	0.00	1.00
1998	4.00	8.00	0.00	1.00
1999	4.00	8.00	2.00	1.00
2000	8.00	12.00	2.00	1.00
2001	12.00	14.00	2.00	1.00
2002	12.00	21.00	2.00	1.00
2003	12.00	23.00	4.00	1.00
2004	12.00	24.00	5.00	1.00
2005	12.00	24.00	6.00	1.00

EXHIBIT 8-8. DEMAND SUMMARY TABLE

User Inputs and Options Table

The next table in the OUT.RPT file displays user inputs from the query session and model options from the OPTIONS.RPT file. The table first displays the availability and resource (price, weight, and volume) targets. Remember, a target number that shows a string of 9s, indicates you entered a "0" (do not consider) for the target value and the model reset it to a maximum value to implement your direction. The last lines in the table show the global values for all the model options.

ORU Input Data Table

The next table is the ORU input data read from the MSPAREIN.RPT file. The column headings of the table are similar to the input file headings defined in Chapter 5, but with four modifications. The file contains only the first 20 characters of the name field. Mean orbit demand is the mean demand in a logistics cycle for all ORU applications for a specific model year and is the product of several input fields (see Equation 4-8). The VMRs from the ORU input that are less than 1 are slightly modified so that the binomial distribution produces valid results. Mean broken indicates the mean number of unserviceable (broken) units in the maintenance process (see Equation 4-6).

Pass Solutions Table

A pass solution is the point on the resource-versus-availability curve at which one of the station targets is exceeded. The pass solutions table displays the availability, resources, and coefficients for each pass solution. The model selects those solutions as the best pass (see Exhibit 7-6 and discussion). The best pass data are repeated at the bottom of the pass solutions table and also used to help generate the initial spares list that follows. All resources are cumulative (for past and present years).

Spares Mix for Solution Point Table

The key model output is the mix of spares that maximizes availability given a set of targets and resource coefficients. In the spares mix table (see Exhibit 8-9), the spares solution point on the resource-versus-availability curve is given first. (With multiple passes, the selected solution point is the best pass.) Next, the table lists each ORU's name and respective gross spares requirements (both on orbit and on the ground), the assets, and the net spares requirements (requirements minus assets). The on-orbit and ground spares are the results of the optimal solution. The next column is the ORU PSN (see Chapter 4). If you multiply the individual PSNs together, you will quantify the predicted station availability. The next column in the spares mix table is the annual investment price (the net spares times the unit price) for each ORU. The next columns give the breakdown of the asset value. "Assets" equal previous years' gross spares minus replaced condemnations. If the starting spares option (see Chapter 6) is set to "0", the model ignores previous assets (i.e., asset position is set to 0), and the entire spares mixes are selected in that year. The last columns (not displayed) present the serviceable ground spares that we will discuss in the last chapter section.

Distributed Systems Results Table

The distributed systems results table is a more detailed breakdown of the station solution point discussed above and is derived in a similar manner. The table in Exhibit 8-10 shows those results from our test drive. The bottom line of that table gives the station spares solution point on the curve (95.0) as well as the cumulative prices, weight, and volume of the gross spares requirements [Note: The price value does not include replaced condemnations, so it differs from other price values]. The table displays the on-orbit volume and weight for all ORU spares (total) and for

```
====================SPARES MIX FOR SOLUTION POINT ==========================
        CRITICALITY CODE 1     YEAR   2000
"       AVAILABILITY     95.03       RESOURCE  140579.80          |--Asset Breakdown-| "
"                   |---- INITIAL SPARES ---|                      Last Yrs _ Condemns
" ORU          NAME Orbit+Ground-Assets = Net    PSN     $K       SpareSoln    ThisYr
  1 "RADIATOR      "   1      1       2     0   99.13      0.0       2          0
  2 "PFCS          "   3      1       3     1   99.52   3562.0       3          0
  3 "BATTERY ORU   "   4      4       5     3   99.84   3585.0       5          0
  4 "BCDU          "   6      7       8     5   99.68   7440.0       8          0
```

EXHIBIT 8-9. SPARES MIX FOR SOLUTION

pressurized spares (an ORU with a 1 for the "P/U" field in the ORU input data). The weight and volume units are in pounds and cubic inches and in racks (1 rack equals 1,000 pounds or 77,760 cubic inches). The table also lists the number of distinct ORUs ("# ORUs"), and the cumulative number of spares selected ("Spares"). In the final column, M-SPARE presents a rough approximation of the improvement in availability if the model considers ORU redundancy. For that, the model adds an extra on-orbit spare to every redundant ORU (an "R" in the ORU criticality code field in the ORU input data) and recalculates its PSN and the availability.

The table disaggregates the total space station system results to distributed systems. The distributed systems are ORU subsets of the total space station and are defined by the DIST SYSTEM field of the ORU input data. The model calculates the system results for each ORU subset in a similar manner as the station results. For instance, a distributed system availability is the product of its ORU's PSN. Each ORU must be associated with a single distributed system.

Resource-Versus-Availability Curve Table

The resource-versus-availability curve table shows all the points that make up the curve. Point by point (spare by spare), the table lists the station availability, accumulated resources, and the ORUs selected. The table starts with the current asset position or all spare levels at 0 (no resources expended for the first fiscal year)

```
==========================DISTRIBUTED SYSTEMS RESULTS ====================
        CRITICALITY CODE 1   FY   2000
                        ¦--Weight-lbs--¦¦-Volume-inch^3-¦              R=Extra
 SYSTEM  AVAIL  *PRICE   Total Pressure  Total  Pressure #ORUs  SPARES  Spare
      6   97.6   78202    7617       0  926992       0      8     51     97.6
     12   97.3  116262    6680       0  733836       0     18    149     97.3
-----------------------------------------------------------------------------
 SYSTEM   95.0  194464   14297       0 1660828       0     26    200     95.0
 Number of Racks         14.30    0.00   21.36    0.00
 1 RACKS= 1000 lbs or 77760 in^3 (45ft^3)
* price does not include condemnations
  Average System Availability and Extra Spare%    97.48  97.48
```

EXHIBIT 8-10. DISTRIBUTED SYSTEMS RESULTS TABLE

and ends when the station availability reaches 99 percent (the maximum availability set in the OPTIONS.RPT file).

Resource Summary Table

The purpose of this table is to present a complete picture of the spares weight (sometimes referred to as "upmass") and volume launched into space. To do that the model estimates the weight and volume for two resource categories: (1) the spares stored on orbit usually for the Criticality Code 1 ORUs (see top of Exhibit 8-11) and (2) the spares "resupplied" to SSF to replace failures for Criticality Codes 1, 2, and 3 ORUs (see bottom of Exhibit 8-11). We discussed the weight and volume of spares stored on orbit already and displayed the results in the pass solutions table and the resource-versus-availability curve table. We will now discuss the weight and volume of the resupplied spares.

The M-SPARE model assumes that if a failure occurs, the next shuttle will resupply the station with a spare (if available) to replace the failure. That is true except for the ORU spares stored on-orbit. With those spares, astronauts may have already replaced the failure with a spare from the on-orbit inventory. In that case, the resupplied spare replenishes the on-orbit inventory. To estimate the resupply weight and volume, M-SPARE multiples an ORU's average number of failures in a year times its unit resource requirement and then sums across all ORUs for all criticalities. The model calculates annual failures by summing all failures that occur for the previous 12 months, starting at the most recent launch month and moving backwards.

RESOURCE SUMMARY (VOLUME & WEIGHT/UPMASS)

Station Configuration Fiscal Year	1998	1999	2000	2001
On-orbit Spares Resources				
Cumulative Orbit Spares Volume:In^3	0	0	1613500	1264998
Cumulative Orbit Spares Weight:lbs	0	0	13556	11107
Annual Orbit Spares Weight:lbs	0	0	13556	0
Resupply Resources (Unit Resource * Demands/Yr) for all crit codes				
Annual Resupply Weight,all ORUs:lbs	2329	3726	4308	4832
Annual Resupply Volume,all ORUs:In^3	254060	411017	457334	490869

EXHIBIT 8-11. RESOURCE SUMMARY TABLE

For consistency, M-SPARE presents the on-orbit weight and volume estimates (as well as price estimates) as cumulative values for past and present years. However, weight estimates really are somewhat different since unused launch capacity in 1 year cannot be applied in following years. (That is not the case for volume capacity.) Thus, for some applications, it is appropriate to consider annual values (the difference between successive cumulative values) on-orbit spares weight. Thus, Exhibit 8-11 also presented annual values. For similar reasons, Exhibit 8-11 presented resupply weight and volume as annual estimates rather than as cumulative estimates.

Annual Ground Storage Packing Volume Table

Ground-storage packing requirements equal the volume of the inventory of serviceable spares on the ground, i.e., working spares on inventory shelves. The M-SPARE model estimates that value by multiplying the number of average annual serviceable units on the ground by the unit volume of each ORU. It then sums that product for all ORUs and across all criticalities (see Exhibit 8-12). The average serviceable units on the ground equal the ground spares minus the mean number of unserviceable units (s_g minus MB).

The model also estimates a possible maximum ground packing volume so that the user can identify likely peaks in packing requirements. For that, the model assumes the peak requirements occur when newly procured spares arrive at KSC and require additional storage. Although the new spares (M-SPARE's net spares) may

eventually move elsewhere, this estimate assumes the worst case – all new spares require ground storage in the first year. For that estimate, the model adds net spares to the existing serviceable units on the ground. To approximate existing serviceable units on the ground, the model scales down the average serviceable spares by the ratio of last year's requirements to this year's requirements.

ANNUAL GROUND PACKING VOLUME AND GROUND SERVICEABLE SPARES

Station Configuration Fiscal Year	1998	1999	2000	2001	2002
Average Ground Serviceable Spares	86	110	48	81	63
Avg. Ground Serviceable+ Net Spares	110	121	86	102	83
Avg. Pack Volume:[#Serv*Vol] (In^3)	1675904	1917902	672775	1838385	956007
Avg Pack+Net Spare Volume: (In^3)	1930150	2022547	1176637	2284638	1280291

EXHIBIT 8-12. GROUND PACKING VOLUME TABLE

CHAPTER 9

M-SPARE USE FOR THE PROGRAM OPERATING PLAN

The SSF project offices primarily uses M-SPARE to produce spares estimates and funding estimates for their annual POP cycle. M-SPARE produces three basic products for the POP cycle. The following products will each be discussed in a separate section:

- *Spares Requirements Product.* For the first POP product, M-SPARE estimates what spares the station requires to reach a specified availability target. As always, the mix is optimal and is the least cost mix to reach the availability target, but no overall funding constraint is applied. To produce that product, the user enters annual availability targets and the model estimates the spares requirements (as we described in Chapter 1 and in the test drive in Chapter 2).

- *Constrained Budget Product.* For the next POP product, the user specifies the expected annual budgets (POP marks), and M-SPARE determines how many spares NASA can acquire for the money. We will discuss this product in detail since it is more complicated to generate than the others.

- *Development and Operational Product.* This product produced a further breakdown of requirements into two subcategories: spares requirement that support the station in the first year of the ORU's life and spares requirements that support the ORU thereafter. For the purpose of this guide, we term those two subcategories as "Development" and "Operational" requirements, respectively.

For all POP products and criticality codes, the user usually runs the model with the ground-stock-only option. The exception usually is for spares designated Criticality Code 1. For Criticality Code 1, the user usually assumes ground-stock-only through FY99 then both on-orbit and ground stock thereafter. That means the user selects the ground option through FY99 and then selects the multiple-pass option for the remaining model years. We will now discuss each of the M-SPARE products in greater detail.

SPARES REQUIREMENTS PRODUCT

For the spares requirements product, the model determines what spares NASA would like to have, given only an availability target (i.e., no funding constraints). The user inputs yearly availability targets and M-SPARE generates spares requirements for the first years of the station's life (e.g., FY96 through FY04). It also estimates the corresponding funding requirements for the next 9 fiscal years (e.g., FY94 through FY02) to meet those specified targets. The availability targets usually vary by criticality code – an availability of 95 percent for Criticality Code 1 and an availability of 85 percent for Criticality Codes 2 and 3. The availability targets can also vary by year although for the last POP cycle, they remained constant. For more information, see the overview discussion in Chapter 1, the detailed operating instructions in Chapter 7, or the model demonstration in Chapter 2.

CONSTRAINED BUDGET PRODUCT

For the constrained budget product, the user specifies annual budgets for the next 9 fiscal years (the POP marks), and M-SPARE determines how many spares NASA can obtain with those funds. The constrained product is more difficult to produce than the requirements product because budget estimates are typically an output, not an input, of M-SPARE. Though M-SPARE can use an input in dollars, those dollars are very different from budget dollars. M-SPARE requires inputs based upon a specific fiscal year in the SSF's life and those inputs are actually the cumulative spares resources (weight, volume, and price). M-SPARE uses cumulative price because station availability is based upon the entire inventory, not just the incremental spares delivered for the year. Budgets are incremental actions over several years that eventually result in spares deliveries. Thus, the budget level determines the incremental dollar "lay-away" plan required for future spares deliveries; on the other hand, M-SPARE price inputs are the cumulative (past and present) investments of the delivered spares.

Table 9-1 illustrates the distinction between the price input and the budget output. That table continues our single ORU example stated earlier in Table 1-2c. M-SPARE requires the cumulative price as input (displayed in the shaded column) to produce that annual budget (displayed second to last row). If the PLT in our example was 1 day (or NASA paid for the spares on the delivery day), then the cumulative budget (shaded row) would equal the input price. If the PLT was 1 year, then the

cumulative budget would lag 1 year behind the input price. But since the PLT is 2 years and the ORU unit cost is spread over both, the cumulative budget is quite different from the cumulative price until the last year. So, the model must convert the POP marks into input price so that M-SPARE output approximates the POP marks. What makes that process complicated is that a POP mark in FY95 can impact two different model years, FY96 and FY97. In addition, each ORU can have a different PLT (1 to 5 years) and can spread the unit cost over that PLT differently (i.e., different spread vectors). We will now discuss how the model performs the conversion.

TABLE 9-1

INVESTMENT INPUT VERSUS BUDGET OUTPUT

Logistics cycle	FY96		FY97		FY98		FY99	
	1	2	3	4	5	6	7	8
Requirements/LogCycle	4	8	9	10	11	12	13	14
Requirements/year		8		10		12		14
Net requirements/year		8		2		2		2

Outlays ($000)	FY94	FY95	FY96	FY97	FY98	Cumulative price input
For SSF FY96	600	400				1,000
For SSF FY97		150	100			1,250
For SSF FY98			150	100		1,500
For SSF FY99				150	100	1,750
Annual budget	600	550	250	250	100	
Cumulative budget	600	1,150	1,400	1,650	1,750	

How to Target M-SPARE to Match POP Marks

Our objective is to produce spares funding estimate by year that are within the budget POP marks. We assume that the user knows the annual POP marks, by year, in current-year dollars for all criticality codes. To convert POP marks to cumulative price inputs the user performs the following steps:

- If you do not use an M-SPARE price inflator (see Chapter 6), deflate the annual POP marks from the current year to constant-baseline-year dollars (the baseline year is the dollar year of the ORU unit prices). If you want to use a constant price inflator for all model years, insert it into the OPTIONS.RPT file and the model deflates the POP marks automatically.

- Disaggregate your POP marks into marks set by criticality codes. You might want to split the budget based upon some fixed ratio (e.g., 50 percent for Criticality Code 1 ORUs, 30 percent for Criticality Code 2 ORUs, and 20 percent for Criticality Code 3 ORUs) or perhaps divide the total POP budget based upon the results of the M-SPARE requirements products discussed earlier.
- Sum the previous year's POP marks to produce cumulative marks by fiscal year.
- Insert the cumulative marks into the OPTIONS.RPT file (see Chapter 6).
- Run the model using availability targets to generate the spares requirements products and allow the model to "get smart enough" to make an initial guess for the input price.
- Rerun the model using the "price guess" targets (shaded area) generated as part of the total annual budgets by model run year table (see Exhibit 9-1). That price guess is the cumulative investment that should reproduce the POP marks.

By rerunning the model a few times using the latest price guess, model results should converge towards the cumulative POP marks.

Targeting Methodology

The table in Exhibit 9-1 displays the methodology the model uses to convert POP marks into input price targets (some of the right-hand columns are not displayed). The top part of the exhibit is the latest M-SPARE output, and the bottom part is what M-SPARE guesses the output needs to be to match the POP marks. The model targets each criticality code separately. We first run the model based upon availability targets to determine how the model spreads net spares requirements dollars over previous fiscal years. In our exhibit, we assume Criticality Code 1 ORUs, so we used a 95 percent ground (Grd) availability in the first 2 years and then a 95 percent station (Orb) availability in the remaining years. The top part of Exhibit 9-1 presents the resulting output. The first columns of Exhibit 9-1 present the output availabilities.

The top part of Exhibit 9-1 also displays the dollar outputs by model year (the rows) and the budget estimates (the columns). All values are in thousands of constant dollars. Notice for model year FY98, the model spreads dollars back to FY95, FY96, and FY97. That spread is generate when M-SPARE takes an ORU's net

Total Annual Budgets by Model Run Year for CRITICALITY CODE 1
All Values in thousands of constant dollars
(Purpose: Helps you get model budgets equal to POP Marks)

BUDGET ESTIMATE FROM *LAST* MODEL RUN

Availability/Fiscal Year	1994	1995	1996	1997	1998	1999	2000
Grd 96.2/Model Year= 1998	0	20505	50526	24570	0	0	0
Grd 95.2/Model Year= 1999	0	0	10010	21874	10133	0	0
Orb 95.1/Model Year= 2000	0	0	0	14493	29411	13166	0
Orb 95.1/Model Year= 2001	0	0	0	0	10708	22406	10178
Orb 95.1/Model Year= 2002	0	0	0	0	0	7146	13489
Orb 95.0/Model Year= 2003	0	0	0	0	0	0	6700
Orb 95.1/Model Year= 2004	0	0	0	0	0	0	0
Orb 95.1/Model Year= 2005	0	0	0	0	0	0	0
Annual Model Budget	0	20505	60536	60936	50252	42718	30367
Annual POP MARKS	0	0	5000	27000	56000	68000	70000
Cumulative Model Budget	0	20505	81041	141977	192229	234947	265314
Cumulative POP MARKS	0	0	5000	32000	88000	156000	226000
Ratio (Cum. POP/Model)	0.0000	0.0000	0.0617	0.2254	0.4578	0.6640	0.8518

BUDGET ESTIMATE FOR *NEXT* MODEL RUN

Model Year	Price Guess	Factor	1994	1995	1996	1997	1998	1999	2000
1998	0.1	0.00	0	0	0	0	0		0
1999	20987	0.50	0	0	5000	10926	5062		0
2000	84284	1.11	0	0	0	16074	32620	14603	0
2001	158343	1.71	0	0	0	0	18318	38329	17411
2002	211288	2.00	0	0	0	0	0	14303	27000
2003	262731	2.00	0	0	0	0	0		13410
2004	305778	2.00	0	0	0	0	0		0
2005	338454	2.00	0	0	0	0	0		0
Next Cumulative Budget			0	0	5000	32000	88000	155235	213056
Cumulative POP Marks			0	0	5000	32000	88000	156000	226000
Ratio (Cum. POP/Model)			999.0000	999.0000	1.0000	1.0000	1.0000	1.0049	1.0608

SUMMARY BY MODEL YEAR	1998	1999	2000	2001	2002	2003	2004
Next Price Guess	0.1	20987.3	84284.2	158343.2	211288.6	262730.9	305778.6
Last Price Guess	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Last Availability Output	96.2	95.2	95.1	95.1	95.1	95.0	95.1
Average Availability	95.24						

EXHIBIT 9-1. TARGETING M-SPARE TO POP MARKS

spares requirements and applies the ORU's spread vector. Exhibit 9-1 is the sum of that spread for all Criticality Code 1 ORUs.

The model next displays the annual model budget (the sum of the columns) and the cumulative model budget outputs (the sum of the previous and current annual values). For comparison, the model also displays the annual and cumulative POP marks you entered in the OPTIONS.RPT file earlier. The model next displays the ratio of the cumulative POP marks to the cumulative model budget. Our objective is to make sure that ratio is greater than or equal to 1 (i.e., the model funding is always within the budget).

To do that for our example, we must reduce certain model year budgets. We assume that the spread of dollars by model year does not significantly change from one run to the next. So to reduce a model year budget, we must reduce all spread values by the same factor. M-SPARE reduces each model year until all ratios are near "1."

The bottom of Exhibit 9-1 displays the result of multiplying the previous spread values (the corresponding top part of the exhibit) by a "factor" (third column) so that the resulting ratios (cumulative POP mark/cumulative model budget – bottom row) for the affected years approximately equals 1. The model starts with the first year (FY98) and adjusts the factor until of the appropriate cumulative ratios (FY95, FY96, and FY97) are greater than or equal to 1. Since the POP mark is 0 in FY95, the factor must equal 0 and all spread values become "0". The model then moves to the next model year, looks at the new ratios, and repeats the process. In some cases, the factor is less than 0 (i.e., the model reduced the funds), and in other cases, it is greater than 0 (i.e., the model increased the funds). The resulting ratios are never less than 1, though sometimes greater than 1. *The latter assumes that NASA can apply POP dollars in later years.*

Once the ratios are approximately equal to 1, the model sums the current and previous spread values to produce the price guess (see the shaded area of Exhibit 9-1). You then rerun the model using that price guess. For our example, enter the price guess values of 0.1, 21009, 83229, etc., as the M-SPARE price targets for model years FY98, FY99, FY00, etc., respectively. (You must enter a target of "0.1" instead of a "0" for FY98 because M-SPARE assumes a 0 means the maximum resource, and you really want a small value to prevent the model from selecting spares.) Repeating that process should produce budgets close to the POP marks within a few iterations. However, as you get close to matching the POP marks, you may need to override the price guess feature and fine tune the estimates if the price guess goes astray. One way to fine tune the price guess is with our next model feature.

Spares Selection Based Upon PLT

The M-SPARE model has a feature (accessed through the user queries described in Chapter 7) that lets the user specify what ORUs the model selects on the basis of the ORU's PLT. In that way, M-SPARE selects spares with shorter PLTs as soon as

funds become available. [*Note:* This feature usually generates a nonoptimal spares mix as we will discuss.]

You may note that in the example shown in Exhibit 9-1, M-SPARE does not select spares until 1999 (the first fiscal year when the price guess is greater than zero). That delay is because ORUs with 3-year PLTs require 3 years of available outlays (FY96, FY97, and FY98). However, M-SPARE could select ORUs with shorter PLTs. For that selection, M-SPARE lets the user specify ORU selection based upon PLT. The actual model dialog is, "Enter the maximum PLT (months) for spare ORUs." For instance, if the model year is FY98 and the POP budget only has funds in FY96 and FY97, the user enters a "24" and the model only selects ORUs with a 24-month PLT or less. ORUs with greater PLTs require funds that are not available, i.e., they require FY95 dollars, and thus the M-SPARE model does not select them.

The user must enter a price (dollar) target, not an availability target when using this option since M-SPARE does not select spares for ORUs whose PLTs are too large, the ORU's PSN and resulting system availability are very low. If the user enters an availability target with this option, the model selects too many spares for the ORUs with shorter PLTs and still never reaches the target. A price target forces M-SPARE to stop selecting spares when the dollars run out. A second area of caution is not to use the minimum spares option when using a maximum PLT because M-SPARE selects the minimum spares regardless of the PLT.

A final area of concern about using PLT selection is that you procure ORUs with shorter PLTs sooner and those with longer PLTs later. That condition occurs because the ORUs with shorter PLTs may use up the funds needed to start procuring those with longer PLTs. Thus, you may improve availability slightly in the earlier years but delay reaching your availability targets in the later years.

DEVELOPMENT AND OPERATIONAL PRODUCT

The model user may require further breakdown of spares requirements into what we term development and operational spares. Development spares support the station in the first year of an ORU's life, and operational spares support the ORU thereafter. To estimate the split, the model first calculates spares and budgets requirements as we described in Chapter 8 (for this chapter section, we call them "aggregate" requirements). Then, it determines the percentage of spares and resulting budget requirements associated with development. Finally, the model

subtracts development budgets from aggregate budgets to estimate operational budgets.

To produce that disaggregation, the user sets the funding split option in the OPTIONS.RPT file to "1". The model then produces two additional tables in the BUDGET.RPT file similar to the net spares requirements (but displays only development spares) and the spares summary budget table (see Chapter 8). The following steps are required for the disaggregation.

The M-SPARE model first calculates total spares requirements over time given an availability or price target. That calculation is standard for all options.

Next, M-SPARE determines what portion of the total spares are development spares. Once each year, it takes the ratio of the total QPA of elements launched within that year, to the QPA for elements previously launched (the top right and top left side of Exhibit 9-2, respectively). M-SPARE generates those tables (see QPA profile table in OUT.RPT file) based upon the element launch schedule. We assumed 2 launches for this ORU in Months 3 and 9 for FY97. The element QPA for both launches equaled 2. The shaded column in the exhibit is the QPA ratio for the launch Month 7. M-SPARE uses that month for the QPA ratio because it estimates gross spares requirements at that month.

ORU# 1 DESICCANTSORBENT BED (CRM) LogCycle = 135 NOT a wear item
QPA BY MONTH (COL), YEARS (ROW)

	1	2	3	4	5	6	7	8	9	10	11	12	Develop	1	2	3	4	5	6	7	8	9	10	11	12	Devel. at Yr End-LC = 7
1996	0	0	0	0	0	0	0	0	0	0	0	0	Develop	0	0	0	0	0	0	0	0	0	0	0	0	1.0000
1997	0	0	2	2	2	2	2	2	4	4	4	4	Develop	0	0	2	2	2	2	2	2	4	4	4	4	1.0000
1998	4	4	4	4	4	4	4	4	4	4	4	4	Develop	4	4	2	2	2	2	2	2	0	0	0	0	0.5000
1999	4	4	4	4	4	4	4	4	4	4	4	4	Develop	0	0	0	0	0	0	0	0	0	0	0	0	0.0000
2000	4	4	4	4	4	4	4	4	4	4	4	4	Develop	0	0	0	0	0	0	0	0	0	0	0	0	0.0000
2001	4	4	4	4	4	4	4	4	4	4	4	4	Develop	0	0	0	0	0	0	0	0	0	0	0	0	0.0000

Element #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Element QPA	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0

EXHIBIT 9-2. ESTIMATING THE PROPORTION OF DEVELOPMENT SPARES

The M-SPARE model then multiplies the ORU QPA ratio times the gross spares requirements to estimate the development spares by fiscal year. That result is given in the table that follows the standard budget reports and is labeled development net spares requirements (identical in format as the aggregate net spares including replaced condemnations table discussed in Chapter 8). The model also ensures that the development net spares does not exceed the aggregate net spares requirements.

For example, if an ORU gross and net spares equals 10 and 4, respectively, and the QPA ratio equals 0.5, the model assumes that 50 percent of the gross spares (i.e., 5 spares) is for development. However, since the model net spares equals 4 for the current year, M-SPARE assumes that 4 is the maximum number of development net spares. The model then calculates budgets by multiplying the development net spares by the ORU spread vectors to produce the development spares budgets table.

Finally, the model subtracts the development budget, summed across ORUs, from the aggregate spares budget to produce the operational budget. M-SPARE displays the development, operational, and aggregate totals (annual and cumulative) at the bottom of the BUDGET.RPT file.

Development and Operational Budgets by Element Launch

The model further extends the development and operational budgets by subdividing both into element launch budgets (see Exhibit 9-3). That estimate gives a rough idea of the funds required to support each launch. For those element budgets, the model multiplies an ORU's development or operational budget (just discussed) for a particular year by a QPA ratio. For the development budget, the QPA ratio is the relationship between the element QPA (bottom line of Exhibit 9-2) for elements launched within the year (i.e., between the current and previous launch months) and the total QPA for all element launchings within the year (QPA at the launch month: top right side of Exhibit 9-2). For operational budgets, the QPA ratio is the relationship between the element QPA (bottom line of Exhibit 9-2) for elements launched within or before the year (i.e., before the previous launch month) and the total QPA for all element launchings within or before the year (top left side of Exhibit 9-2).

" Budget Values below in Thousands of Constant 1992 Dollars"

"Summary $K / FISCAL YEAR:"	1995	1996	1997	1998	1999	2000
"Development budgets by Element						
" Element 1 LabA MB6 "	2785	3653	1219	0	0	0
" Element 2 LabB MB20 "	0	0	0	0	0	0
" Element 3 HabA MB16 "	0	0	523	9461	9271	0
" Element 4 HabB MB21 "	0	0	0	0	0	0
"Annual Development "	2785	3653	1742	9461	9271	0
"Operational budgets by Element						
" Element 1 LabAm MB6 "	0	13	524	1924	1921	579
" Element 2 LabB MB20 "	0	0	0	0	0	0
" Element 3 HabA MB16 "	0	0	46	766	8147	11090
" Element 4 HabB MB21 "	0	0	0	0	0	0
"Annual Operational "	0	13	570	2690	10068	11669

EXHIBIT 9-3. ELEMENT LAUNCH BUDGETS

CHAPTER 10

THE WEAR PREPROCESSOR

INTRODUCTION

So far we have assumed the MTBF specifies the likelihood of an ORU random failure. However, an ORU also fails after being in operation for some period of time. It simply wears out. The average period of time it takes to wear-out is the mean "wear" life of an ORU and is specified in the ORU data base (see Chapter 5). For most ORUs, that wear life is 20 to 30 years; thus, they do not wear out within the model time horizon of 15 years (i.e., the maximum number of model years). For some ORUs, however, the wear life is shorter and related failures may occur in the model time horizon. For those ORUs, we use the "wear" preprocessor to simulate both types of failures (those that are random and those in which an ORU wears out) and automatically pass the aggregate information to M-SPARE.

The "wear" preprocessor, from the M-SPARE interface (see Chapter 2), selects and prepares the proper ORU input data for M-SPARE. It selects the ORU if the mean life of an ORU minus the "wear" wake (set in the OPTIONS.RPT file described in Chapter 6) is less than the maximum number of model years. For instance, if the ORU has a mean life of 19 years, failures attributable to wear may occur as early as 14 years into the ORU life (i.e., a "wear" wake of 5 years). Since, the maximum number of model years is 15, failures from wearing out may affect the model calculation, and the preprocessor is automatically used. You run the wear preprocessor initially and again whenever you update the ORU data base or the launch schedule (in the OPTIONS.RPT file).

Exhibit 10-1 displays two preprocessor options once you select the "Wear" option from the M-SPARE interface. If you select "Automatic", the preprocessor selects the proper ORUs, generates the necessary input data, and runs the preprocessor. If you select "Manual", the preprocessor gives you a chance to override simulation input. It will bring you directly to the editor and the preprocessor input file (described later in this chapter), allowing you to change any of the inputs. When finished, press the "ALT-X" key combination to save the file and complete the

execution of the preprocessor. Before running the manual option, you should run the automatic option once so that the input file is generated in the proper format. Then you can run the manual option and make your edits. The purpose of the manual option is to allow you to perform sensitivity analyses (such as changing the condemnation assumptions) with the simulation.

```
View   Options   Wear   Run   Exit
                 Automatic
                 Manual

F1 Menu    Ctrl-Break Exit
```

EXHIBIT 10-1. OPTIONS FOR THE WEAR PREPROCESSOR

The preprocessor calculates, by month, the mean demand (due to random and wear-out failures), the VMR of demand, and the cumulative average condemnations. M-SPARE automatically uses those data in a multi-ORU optimization run to determine the spares mix, location, and budgets. There may be several ORU units and the number may change over time as SSF is built up. We will now discuss the logic, inputs, processing, and outputs of the preprocessor.

PROGRAM LOGIC

The preprocessor is a Monte Carlo simulation. For each installed unit of the ORU, the simulation uses an exponential probability distribution to estimate the time of the next random failure and uses another probability distribution (normal or Weibull) to estimate the time the next unit will wear out. The smaller time is

selected as the time of the next failure. The simulation then determines probabilistically whether the failure can be repaired or whether it must be condemned. It is assumed there is a probability (*cp*) that a random failure results in condemnation. After *N* random failures the unit must be condemned. Of course, *cp* may be 0, *N* may be 0 (meaning no deterministic condemnation mode), or both may be 0 (the ORU is always repaired).

Similarly, there is a probability that a worn out unit will be condemned and after *M* wear-out failures the unit *must* be condemned. Usually the *cp* that a unit will wear out is larger than a random *cp*, and in some cases (batteries, for example) the probability, *cp*, that a unit will wear out is equal to 1.

If the first failure is a random failure that does not result in a condemnation, the simulation then draws the time to the next random failure and keeps track of the fact that there has been one repair of a random failure. The simulation compares the time of the next random failure to the time the unit was expected to wear out, selects the smaller time, and repeats the procedure described above to determine whether there should be a condemnation. An analogous procedure is followed for a failure due to wear that does not result in a condemnation and establishes a new time that it will wear out. When the unit is condemned because of a random failure or because it wore out, a new unit of the ORU is installed and the failure and age counters are reset to 0.

INPUT

The data for the program is kept in an ASCII file called PREPIN.DAT developed from the MSPAREIN.RPT and the OPTIONS.RPT files. The first three lines (not used by the program) contain headings to assist the user in identifying the data elements on the next line. Similarly, the next three lines (also not used by the program) contain headings to assist the user in identifying the data elements on the succeeding rows – one row for each ORU.

A sample input data file is shown in Exhibit 10-2. Note that each ORU name/identification is assumed to be 15 characters in length, but the other fields may be of any length. The program interprets a space as a delimiter between numeric fields. There must be at least one space between fields, and a value of 0 must be entered for a numeric value of 0 (not blank as it would be in fixed format FORTRAN

input). If no decimal point is provided, the decimal point is assumed to be at the right of the field. Entering a decimal point overrides this default.

```
******************* INPUT TO CONDEMNATIONS AND DEMAND PREPROCESSOR ************
¦---------------------------- GLOBAL PARAMETERS -----------------------¦
WEIBULL  W/Con  Years  Delays  Seed  #Reps  Print    Mth/Period #Mth Input
  1        1      15    0.0    31313  1000    0           12        180

                                   ORU DATA
¦-- NAME --¦--MTBF(Years)--¦WEAR¦-RANDOM-¦-WEAR-¦----¦-- Cumulative QPA # by Month --¦
              RANDOM  WEAR  SD   cp  C#  cp  C#  Wgt   1  2  3  4  5  6  7  8  9  10
BATTERY ORU  41.8524  5.00  10  1.00  0   1   1  356  24 24 24 24 24 24 24 24 24  24
SAMPLE ORU     4.000  6.00  10  0.60  4   1   1   50  12 12 12 12 12 12 12 12 12  12
```

EXHIBIT 10-2. SAMPLE INPUT DATA FILE

The first line of numerical data applies to all ORUs with each field defined as follows:

- *WEIBULL.* There are two choices for the distribution of units wearing out: "1" equals Weibull (the M-SPARE default assumption) and "0" equals normal. The same distribution is used for all ORUs, but the parameters may vary by ORU.

- *W/Con.* When a value of "0" is entered, repairable item demand is displayed in the output. This is useful if the user wants to compute spares for condemnations separately. If a "1" is entered (the M-SPARE default assumption), repairable demand is combined with demands that result in condemnations (W/Con). The usage of this input variable is discussed in more detail in the utilization of preprocessor input in the last section.

- *Years.* This is the number of years for which output is desired. It is limited to 30 years or less. If the number of years of output exceeds the #Mth Input (described below), the program assumes that the units of each ORU (QPA) in the last month remain constant until the end of the last year.

- *Delays.* This is the delay between the time a failure occurs and the time when the condemnation determination is made.

- *Seed.* This is a random number seed used to draw failure times and is an odd number less than 32767.

- *#Reps.* This is the number of repetitions desired of the simulation for all units of the item. A repetition is the number of demands from 0 to 15 years

for all units of the item. A value of 1000 is suggested, but larger values should be used if ORUs have large MTBFs.

- *Print.* This is a print control so that the user can check the program logic. Normally the print detail switch is set to "0" (or blank). If print equals "1," the screen shows each demand for each unit of the ORU, whether the demand was the result of a random failure or a worn out unit and whether a condemnation resulted. This is done for the first repetition of the simulation on each item.

- *Mth/Period.* The number of months per period is used to combine monthly input data into output data by period.

- *#Mth Input.* The number of months for which the QPA of each ORU is entered below in the detail data by ORU.

The next inputs are for each ORU. An unlimited number of ORUs may be entered, but graphs are prepared only for the first ORUs. The simulation directly obtains most of the ORU data that follow from the MSPAREIN.RPT data base.

- *NAME.* This is any identification of the ORU in a 15-character field.

- *MTBF (Years) RANDOM.* This is the random failure mean (in years) with an exponential distribution.

- *MTBF (Years) WEAR.* This input provides the MTBF (in years) mean life caused by wear for the Weibull or normal distribution, as specified in the first data element on the top line. (For the Weibull, the simulation develops its parameters based upon the mean.) For preventive maintenance ORUs, this value is the replacement frequency.

- *WEAR SD.* This is a the standard deviation (in years) for the normal or the shape parameter for the Weibull distribution of failures caused by wear. (For the Weibull, smaller values result in larger standard deviations.)

- *RANDOM cp.* This is a random failure condemnation probability (MSPAREIN.RPT fraction 3 field), a number between 0 and 1; otherwise, the ORU is repaired.

- *RANDOM C#.* This is the number of random failures before an ORU is condemned. A value of "4" signifies that on the fourth random failure of a particular unit of the ORU (there have been 3 repairs), it must be condemned regardless of the value of RANDOM *cp* above. A value of "0" (the default) means that this type of deterministic condemnation does not occur.

- *WEAR cp.* This is the probability that an ORU will be condemned because of wearing out, a number between "0" and "1"; otherwise, the ORU is repaired (MSPAREIN.RPT fraction 3 field).

- *WEAR C#.* This is the number of failures attributable to wear before a condemnation, similar to RANDOM C#.

- *Wgt.* The weight of the item used to calculate the total weight per period for all ORUs to replace failures in orbit. This is the resupply weight needed over and above the initial spares requirement.

- *CUMULATIVE QPA # by Month.* This is the quantity of the ORU installed at each month. This should be nondecreasing over the months. (Note the input specifies 180 months in this example, and the model develops these data elements for 180 months, not just the 10 shown for brevity in Exhibit 10-2.) Exhibit 10-2 data is the QPA profile we discussed in Chapter 4. In this example, the QPA increases to 18 in month 13 for ORU 1 and to 36 for ORU 2.

PROCESSING

To run the simulation, the M-SPARE interface executes the preprocessor (PREPSIM.EXE) to prepare PREPIN.DAT data, the simulation (PREP.EXE), and the plot program (PREPPLOT.EXE). To move from one plot to the next, press the "Enter" key. To print any graph on the screen, type anything and press "Enter". This allows you to type labels if desired. The numeric screen output is written to OUT.DAT, and data input for M-SPARE is written to PREPOUT.DAT. Again, a math co-processor for your computer is not required but is highly recommended, as the calculation will be speeded up by a factor of about 10.

OUTPUT

The numerical output for this example is shown in Exhibit 10-3. If the input random mean is much smaller than the wear mean, the output mean would equal the random mean. The VMR would equal 1 because the distribution is Poisson. If the wear mean is much smaller than the random mean, the output mean and variance would mimic the normal or Weibull distribution input values. With the sample ORU, the wear and random means are comparable (e.g., 4 and 6 years), so the output mean is less than both (e.g., 2.8 years) and the VMR is less than 1 (e.g., 0.92).

Number of months/period= 1

BATTERY ORU

Fail Time Mean= 4.4966 Var= 1.0474

MEAN DEMAND PER PERIOD INCLUDING CONDEMNATIONS

	1	2	3	4	5	6	7	8	9	10
0	0.05	0.05	0.04	0.05	0.05	0.06	0.04	0.04	0.05	0.05
1	0.04	0.05	0.07	0.06	0.05	0.06	0.05	0.08	0.06	0.06
2	0.06	0.06	0.07	0.06	0.12	0.07	0.10	0.10	0.09	0.10
3	0.10	0.08	0.12	0.12	0.12	0.12	0.13	0.16	0.17	0.19
4	0.21	0.22	0.24	0.29	0.34	0.38	0.45	0.56	0.61	0.71
5	0.74	0.86	0.95	1.14	1.17	1.36	1.41	1.52	1.52	1.62
6	1.61	1.57	1.47	1.43	1.29	1.22	1.11	1.09	1.04	0.93
7	0.87	0.94	0.90	0.96	0.99	1.00	1.03	0.99	1.02	1.05
8	1.09	1.07	1.03	1.05	1.09	1.04	0.96	0.89	0.77	0.69
9	0.57	0.55	0.41	0.38	0.39	0.38	0.35	0.35	0.41	0.43
10	0.46	0.50	0.56	0.60	0.62	0.69	0.71	0.78	0.88	0.87
11	0.98	1.05	1.04	1.15	1.07	1.23	1.18	1.22	1.21	1.19

VARIANCE/MEAN DEMAND PER PERIOD

	1	2	3	4	5	6	7	8	9	10
0	1.04	0.99	1.06	0.95	1.07	0.97	0.96	0.96	1.00	0.95
1	1.00	1.02	1.02	1.01	1.03	1.00	0.95	0.95	1.06	0.97
2	0.94	0.98	1.03	1.00	1.04	1.04	0.99	0.99	1.01	0.92
3	0.96	0.94	0.97	0.95	1.07	1.09	0.95	1.03	0.99	1.03
4	0.97	0.97	0.97	1.07	0.89	1.03	0.91	1.01	0.95	0.88
5	1.01	0.90	1.00	0.89	0.99	0.93	0.98	0.92	0.97	0.91
6	0.92	1.01	0.96	0.92	1.01	0.87	1.03	0.92	0.94	0.99
7	0.92	0.91	0.96	1.01	0.91	1.02	0.95	0.92	0.92	0.97
8	0.98	0.92	0.91	0.99	0.91	0.95	0.89	0.94	0.94	1.00
9	0.98	0.97	1.00	0.97	0.98	0.97	0.97	0.98	0.99	1.12
10	1.05	0.94	0.96	0.96	1.00	0.98	0.98	0.99	0.92	0.97
11	0.96	1.02	0.96	0.99	1.04	0.97	0.95	1.03	0.89	0.91

Period Mean= 0.6158 V/M= 0.9600

Aver demand/unit= 0.0130 Max demand/unit= 0.0336 Max Period= 60

CUMULATIVE AVERAGE CONDEMNATIONS BY PERIOD

	1	2	3	4	5	6	7	8	9	10
0	0.05	0.09	0.14	0.18	0.23	0.29	0.33	0.37	0.41	0.46
1	0.50	0.56	0.63	0.69	0.74	0.80	0.85	0.92	0.98	1.04
2	1.11	1.16	1.24	1.30	1.42	1.49	1.59	1.69	1.78	1.88
3	1.99	2.07	2.18	2.30	2.42	2.54	2.66	2.82	2.99	3.18
4	3.40	3.62	3.86	4.15	4.49	4.87	5.32	5.88	6.49	7.20
5	7.94	8.80	9.75	10.89	12.07	13.42	14.83	16.35	17.87	19.49
6	21.09	22.66	24.13	25.56	26.85	28.07	29.18	30.27	31.30	32.24
7	33.11	34.04	34.95	35.90	36.89	37.89	38.92	39.91	40.93	41.98
8	43.07	44.14	45.17	46.22	47.32	48.35	49.32	50.21	50.98	51.67
9	52.24	52.79	53.20	53.58	53.97	54.35	54.70	55.06	55.47	55.89
10	56.35	56.85	57.41	58.01	58.63	59.31	60.03	60.81	61.69	62.56
11	63.53	64.58	65.63	66.78	67.85	69.08	70.26	71.49	72.70	73.89

STANDARD DEVIATION OF CUMULATIVE CONDEMNATIONS BY PERIOD

	1	2	3	4	5	6	7	8	9	10
0	0.22	0.31	0.38	0.43	0.49	0.55	0.59	0.62	0.66	0.70
1	0.73	0.77	0.83	0.88	0.91	0.95	0.97	1.01	1.03	1.05
2	1.08	1.11	1.14	1.18	1.23	1.25	1.30	1.34	1.38	1.41
3	1.44	1.46	1.49	1.52	1.55	1.59	1.62	1.61	1.65	1.70
4	1.76	1.79	1.86	1.90	1.94	2.00	2.13	2.24	2.33	2.47
5	2.58	2.65	2.75	2.79	2.85	2.94	2.97	3.00	3.07	3.01
6	2.98	2.90	2.79	2.71	2.66	2.60	2.50	2.49	2.44	2.46
7	2.56	2.57	2.59	2.56	2.57	2.64	2.68	2.74	2.79	2.76
8	2.77	2.86	2.84	2.79	2.73	2.69	2.60	2.54	2.42	2.38
9	2.34	2.30	2.29	2.29	2.35	2.39	2.44	2.53	2.57	2.65
10	2.72	2.76	2.81	2.86	2.93	2.98	3.04	3.14	3.23	3.30
11	3.36	3.42	3.46	3.48	3.49	3.47	3.40	3.41	3.38	3.39

EXHIBIT 10-3. OUTPUT FOR BATTERY ORU

In the example, the battery failures are dominated by wear-out. That is the reason that the mean demand – including condemnation demand – has large peaks and valleys, and why the VMR per period is substantially less than 1. Whenever the battery wears out it must be condemned. This accounts for the large fluctuations in annual condemnations.

Exhibit 10-3 also shows the average demand per unit and the maximum demand per unit. Though not displayed, the simulation also estimates the weight required per period to replace repairable failures and condemnations on orbit for all ORUs that have been processed.

Exhibit 10-4 shows the failure rate plot, $m(t)$, for a Battery ORU unit that is connected to the probability distribution of time to failure, $f(t)$, by the equation:

$$m(t) = \frac{f(t)}{[1 - F(t)]} \qquad \text{[Eq. 10-1]}$$

where $F(t)$ is the cumulative distribution of the probability density, $f(t)$ from 0 to t.

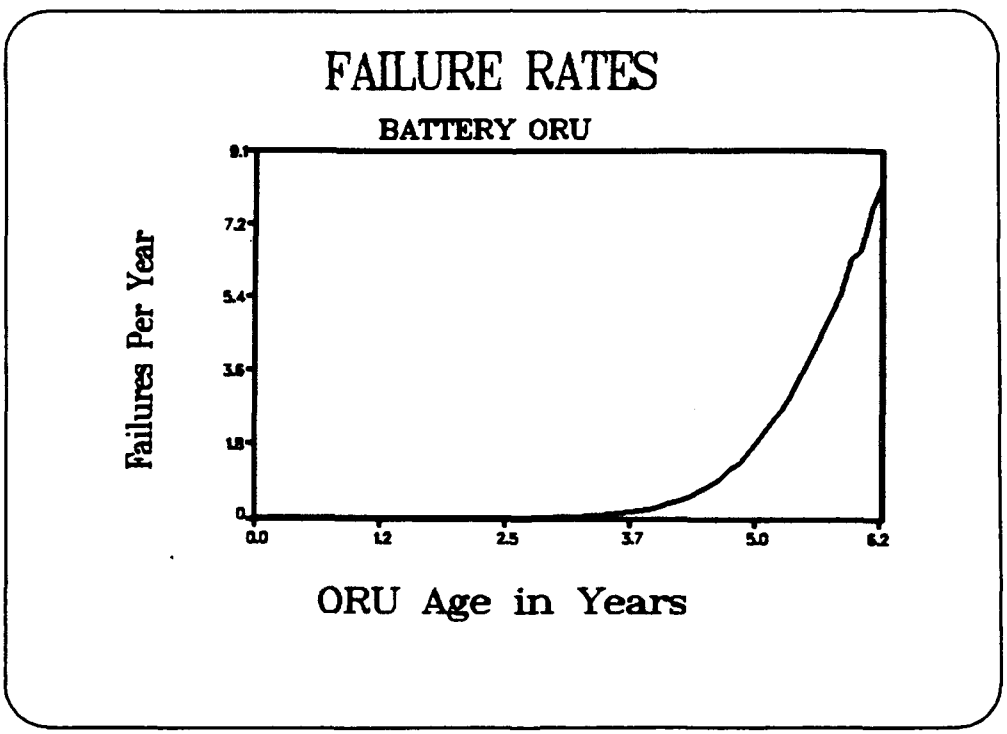

EXHIBIT 10-4. FAILURE RATES

Exhibits 10-5 to 10-7 display battery ORU plots for the following:

- The probability distribution of time to failure for a unit.
- The mean demand per year for all units, including those that result in condemnation.
- The annual condemnations for all units (not the cumulative as in the numeric output above). (The first peak in the condemnation plot is at about 5 years – near the wear-out lifespan of the battery.)

Exhibit 10-8 shows the shuttle weight requirement for resupply per period for all wear-out ORUs to replace all on-orbit failures of any type.

UTILIZATION OF PREPROCESSOR OUTPUT

The output from the preprocessor may be used for three different purposes: budget, procurement, and shuttle manifests. Depending on the purpose, the user may want to separate the condemnation output from the repairable demands (W/Con = 0 in the input), particularly if multiple years of condemnations are bought at one time. On the other hand, if condemnations are replaced by orders placed at the time of failure, it is more appropriate to combine condemnation demand and repairable demands (W/Con = 1). This is the assumption M-SPARE uses. To allow the user maximum flexibility, we have provided the capability to combine the condemnation and repairable demand output or keep them separate.

Integration with M-SPARE

The M-SPARE model uses most of the monthly simulation output presented in Exhibit 10-3 to estimate an ORU's mean on-orbit failures, mean serviceable (broken) spares, replaced condemnations, and the VMR. The VMR value is the monthly value at the launch month. [M-SPARE does not use the simulation VMR if the user specifies an override VMR that is less than one in the MSPAREIN.RPT file (see Preventive Maintenance discussion in Chapter 4).] M-SPARE also calculates other variables at the launch month by looking back to determine the number of unserviceables and replaced condemnations. It also looks forward to determine what fails on the station in the next cycle. The formats of the equations are similar to the formats of Equations 4-6 to 4-10, except instead of summing monthly QPA values the model sums the appropriate demand values from the simulation.

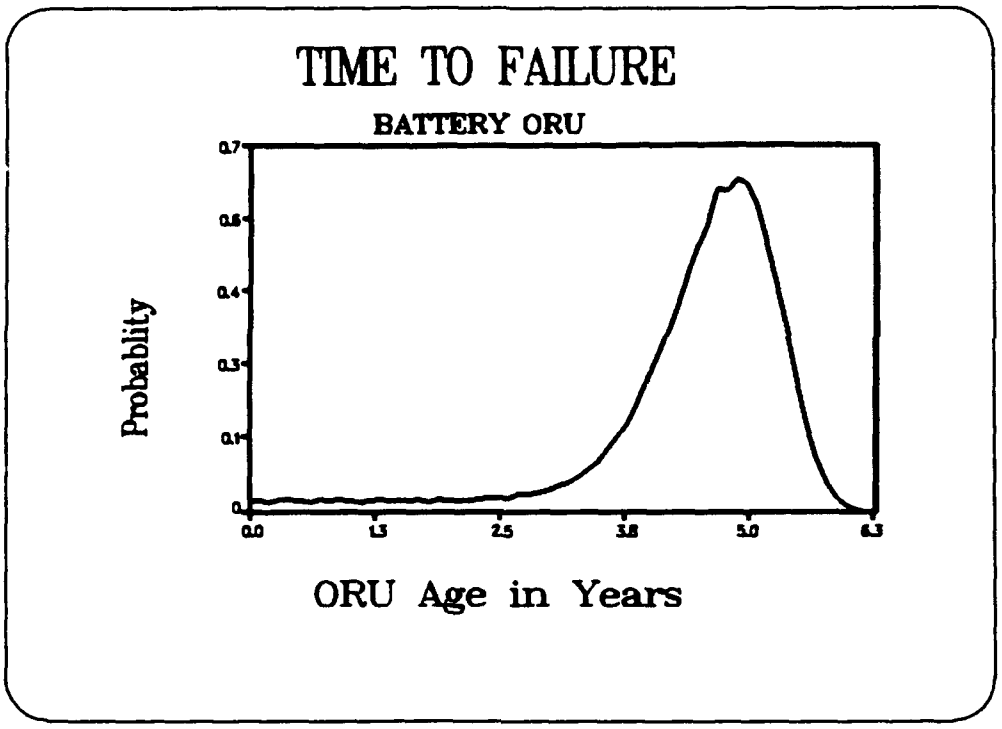

EXHIBIT 10-5. TIME TO FAILURE

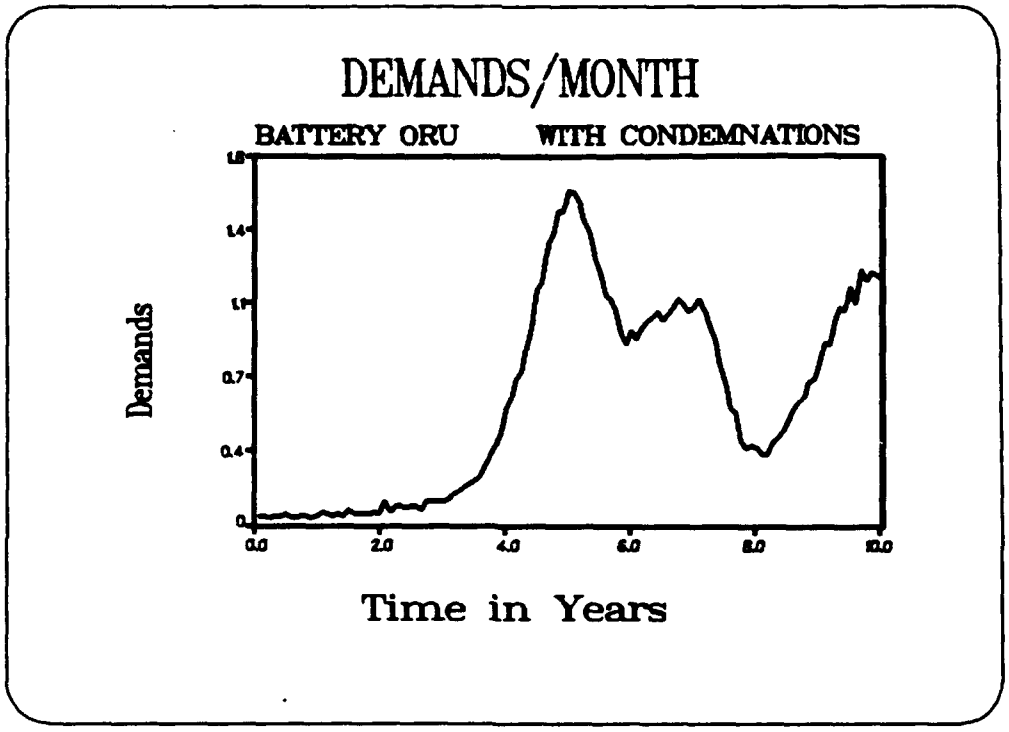

EXHIBIT 10-6. DEMANDS PER MONTH

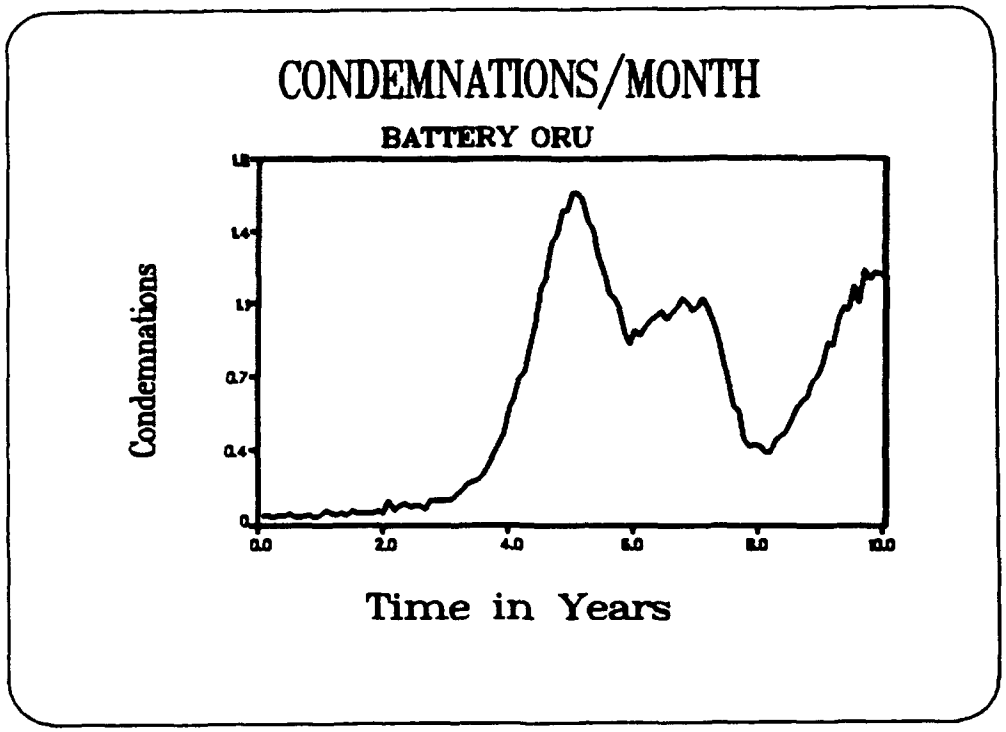

EXHIBIT 10-7. CONDEMNATIONS PER MONTH

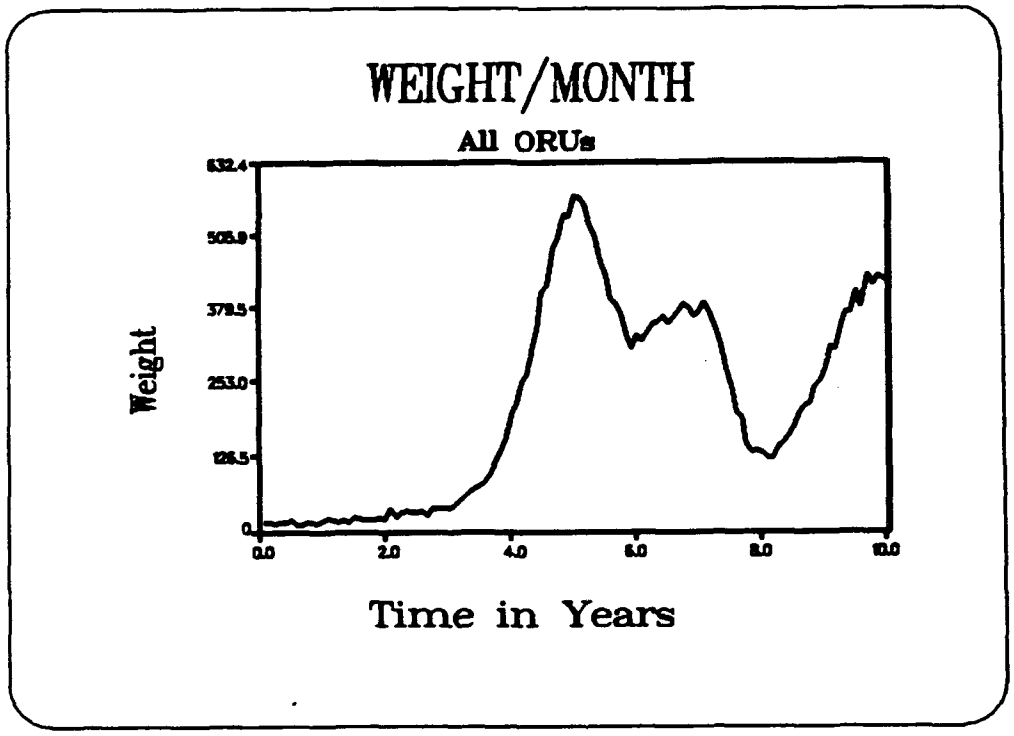

EXHIBIT 10-8. WEIGHT PER MONTH

The four key demand values are total demand (TD) – the mean demand subtable in Exhibit 10-3; cumulative condemnations (CC) – the third subtable in Exhibit 10-3; condemnation demands (CD) – the difference in successive-year values of the cumulative demands; and repair demand (RD) – the difference of total minus condemnation demand. Equations 10-2 to 10-8 estimate mean broken spares, mean orbit failures, and replaced condemnations.

$$MB(yr) = \sum_{l=1}^{3} B_l. \qquad \text{[Eq. 10-2]}$$

$$B_1 = \frac{F_1}{F_1 + F_2} \times \sum_{m=LM(yr)-MM_1}^{LM(yr)-1} RD(m). \qquad \text{[Eq. 10-3]}$$

$$B_2 = \frac{F_2}{F_1 + F_2} \times \sum_{m=LM(yr)-MM_2}^{LM(yr)-1} RD(m). \qquad \text{[Eq. 10-4]}$$

$$B_3 = \sum_{m=LM(yr)-MM_3}^{LM(yr)-1} CD(m). \qquad \text{[Eq. 10-5]}$$

$$MO(yr) = \sum_{m=LM(yr)}^{LM(yr)+MLC-1} TD(m) \qquad \text{[Eq. 10-6]}$$

$$CRC(yr) = \left[CC(yr) - B_3(yr) \right]. \qquad \text{[Eq. 10-7]}$$

$$RC(yr) = CRC(yr) - CRC(yr-1). \qquad \text{[Eq. 10-8]}$$

where

λ	=	mean orbit failures per month
m	=	1, 2, . . . (year × 12), where year is the number of model years the user specifies (see Chapter 6)
l	=	maintenance levels (1 = KSC, 2 = prime/OEM, 3 = condemnations)
F	=	fraction of total failures entering each maintenance level

MM = maintenance months = NLC × MLC

NLC = number of logistics cycles in the entire maintenance time

$$= \left[\frac{LogCycle\ (days) + repair\ or\ replace\ (days)}{LogCycle\ (days)} \right]$$

$[\ ]$ = largest integer value, i.e., truncate real into an integer value

MLC = Months in a LogCycle

$$= \left[\frac{LogCycle\ (days)}{30\ (days/month)} \right]$$

$LM(yr)$ = launch month, calculation point of spares requirements, assumes that it is one LogCycle from end of fiscal year

= (yr × 12) − MLC − 1

yr = model year

RC = replaced condemnations

CRC = cumulative replaced condemnations.

APPENDIX A

SPARES OPTIMIZATION PROOF

APPENDIX A

SPARES OPTIMIZATION PROOF

The Multiple Spares Prioritization and Availability to Resource Evaluation (M-SPARE) model is based upon a marginal-analysis approach. Spares are ranked in order of decreasing benefit per cost and added, in that order, to the inventory until a target resource expenditure or station availability is reached. This appendix proves that the marginal-analysis technique generates the optimal spares solution; that is, no spares solution set produces a greater availability for the same cost or produces equal availability for less cost.[1]

From Equation 3-1 of the main text, station availability is defined as

$$A = \textit{station availability} = \prod_i PSN_i\left(s_i\right), \qquad \text{[Eq. A-1]}$$

where probability of a spare when needed (PSN_i) (s_i) is the probability that a spares level of s_i is sufficient for ORU_i over the station logistics cycle, i.e., that the number of demands over the cycle is less than or equal to s_i.

We want to maximize Equation A-1 subject to a cost constraint. An equivalent problem is to maximize the logarithm of Equation A-1 because a function and its logarithm achieve their maximum at the same point. Since the logarithm of a product is the sum of the logarithms, this converts the objective function into an additive separable function of the orbital replaceable unit (ORU) probabilities:

$$ln(A) = ln(\textit{station availability}) = \sum_i ln\left[PSN_i(s_i)\right], \qquad \text{[Eq. A-2]}$$

[1]Further discussion of these and related issues can be found in LMI Report AF201, *The Aircraft Availability Model: Conceptual Framework and Mathematics*, T. J. O'Malley, June 1983 and Craig C. Sherbrooke, *Optimal Inventory Modeling of Systems: Multi-Echelon Techniques*, New York: Wiley, to be published in September 1992.

Denote the benefit per cost ratio of buying the nth spare of ORU_i by r(i,n). Then,

$$r(i,n) = \frac{\ln PSN_i(n) - \ln PSN_i(n-1)}{c_i}, \qquad \text{[Eq. A-3]}$$

where c_i is the cost of ORU_i. We will sometimes simply refer to r(s) when the exact values of i and n are immaterial. The marginal analysis algorithm in M-SPARE sorts the ORU spares in terms of $r(i,n)$, which we will call the sort value. We wish to show that buying in this order is optimal.

We first note that for this procedure to even make sense, $\ln PSN$ must be convex, i.e., r must be a decreasing function of spares level for each ORU_i; otherwise, one could be led to the meaningless situation of, say, wanting to buy the third spare of an ORU before buying the first spare. This is physically nothing more than the law of diminishing returns for spares – each additional spare is worth less than (or equal to) the one preceding it.

We will show that r is decreasing in the case of a Poisson failure process. The same approach can be used in the case where failures are distributed according to the binomial or negative binomial distribution.

Let

$$p(x) = \frac{\lambda^x}{x!} e^{-\lambda}. \qquad \text{[Eq. A-4]}$$

represent the (Poisson) probability of x unserviceable items in resupply and where λ represents the mean number of unserviceables in resupply. Then

$$PSN(s) = \sum_{x=0}^{s} p(x). \qquad \text{[Eq. A-5]}$$

It is enough to show that, for all s,

$$\ln PSN(s) - \ln PSN(s-1) \geq \ln PSN(s+1) - \ln PSN(s) \qquad \text{[Eq. A-6]}$$

Equation A-6 is equivalent to

$$ln\left(\frac{\sum_{x=0}^{s} p(x)}{\sum_{x=0}^{s-1} p(x)}\right) \geq ln\left(\frac{\sum_{x=0}^{s+1} p(x)}{\sum_{x=0}^{s} p(x)}\right) \qquad \text{[Eq. A-7]}$$

$$\Leftrightarrow$$

$$\frac{\sum_{x=0}^{s} p(x)}{\sum_{x=0}^{s-1} p(x)} \geq \frac{\sum_{x=0}^{s+1} p(x)}{\sum_{x=0}^{s} p(x)} \qquad \text{[Eq. A-8]}$$

$$\Leftrightarrow$$

$$\frac{1+p(s)}{\sum_{x=0}^{s-1} p(x)} \geq \frac{1+p(s+1)}{\sum_{x=0}^{s} p(x)} \qquad \text{[Eq. A-9]}$$

$$\Leftrightarrow$$

$$\frac{p(s)}{\sum_{x=0}^{s-1} p(x)} \geq \frac{p(s+1)}{\sum_{x=0}^{s} p(x)} \qquad \text{[Eq. A-10]}$$

$$\Leftrightarrow$$

$$p(s)\sum_{x=0}^{s} p(x) \geq p(s+1)\sum_{x=0}^{s-1} p(x) \qquad \text{[Eq. A-11]}$$

Substituting $p(x) = \left(\frac{\lambda^x}{x!}\right)e^{-\lambda}$ in the above yields,

$$\frac{\lambda^s}{s!}e^{-\lambda}\sum_{x=0}^{s}\frac{\lambda^x}{x!}e^{-\lambda} \geq \frac{\lambda^{s+1}}{(s+1)!}e^{-\lambda}\sum_{x=0}^{s-1}\frac{\lambda^x}{x!}e^{-\lambda} \qquad \text{[Eq. A-12]}$$

$$\Leftrightarrow$$

$$\sum_{x=0}^{s} \frac{\lambda^{s+x}}{s!\,x!} \geq \sum_{x=0}^{s-1} \frac{\lambda^{s+1+x}}{(s+1)!\,x!} \qquad \text{[Eq. A-13]}$$

$$\Leftrightarrow$$

$$\frac{\lambda^{s}}{s!} + \sum_{x=0}^{s-1} \frac{\lambda^{s+x+1}}{s!\,(x+1)!} \geq \sum_{x=0}^{s-1} \frac{\lambda^{s+x+1}}{(s+1)!\,x!} \qquad \text{[Eq. A-14]}$$

Since $x+1 \leq s+1$, each of the terms in the left-hand summation exceeds the corresponding term in the right-hand summation. Thus, the inequality holds, PSN is convex, and the sort value is indeed a decreasing function of spares level.

If M is any set of spares, we will denote by $M(i)$ the number of spares of $ORU(i)$ in the set M, by $A(M)$ the resulting station availability, and by $C(M)$ the cost of procuring the spares in M. We have:

$$A(M) = \prod_{i} PSN_i[\, M(j)+1 \,] \qquad \text{[Eq. A-15]}$$

$$C(M) = \sum_{i} c_i M(i), \qquad \text{[Eq. A-16]}$$

where c_i is the cost of ORU_i.

If we increase the level of ORU_j from $M(j)$ to $M(j)+1$ to form a new spare set M', then

$$\begin{aligned} ln\, A(M') &= \sum_{i \neq j} ln\, PSN_i[\, M(i) \,] + ln\, PSN_j[\, M(j)+1 \,] \qquad \text{[Eq. A-17]} \\ &= \sum_{i} ln\, PSN_i\, [\, M(i) \,] + ln\, PSN_j[\, M(j)+1 \,] - ln\, PSN_j[\, M(j) \,] \\ &= ln\, A(M) + c_j\, r[\, j, M(j)+1 \,]. \end{aligned}$$

That is, adding a spare s with cost $c(s)$ to the set M gives a new availability $A(M')$, with $ln\, A(M') = ln\, A(M) + c(s)\, r(s)$.

In general, adding any number of spares to M to form M' results in a new availability and the similar relationships

$$ln\, A(M') = ln\, A(M) + \sum_{s \in M' - M} c(s) r(s), \qquad \text{[Eq. A-18]}$$

where $M' - M$ denotes the difference of the sets M' and M, the collection of spares that were added.

Now suppose that the set M was obtained via marginal analysis, and let N be any other set of spares with lower or equal total cost, $C(N) \leq C(M)$. To show M is optimal, we must show that $A(N) \leq A(M)$ or, equivalently, $ln\, A(N) \leq ln\, A(M)$.

Let $X = N \cap M$, the intersection of N and M. Then X contains the spares common to both sets M and N. By the above, we have

$$ln\, A(M) = ln\, A(X) + \sum_{s \in M - X} c(s) r(s) \qquad \text{[Eq. A-19]}$$

$$ln\, A(N) = ln\, A(X) + \sum_{s \in N - X} c(s) r(s). \qquad \text{[Eq. A-20]}$$

The marginal-analysis technique dictates that M contains all of the highest sort values. Therefore, since $M - X$ and $N - X$ are disjoint, we know that the lowest sort value $r(M)$ of spares in $M - X$ is greater than the greatest sort value $r(N)$ of a spare in $N - X$. Further, since $C(M) \geq C(N)$, $C(M - X) \geq C(N - X)$. Thus,

$$\begin{aligned} ln\, \mathrm{A(M)} &= ln\, A(X) + \sum_{s \in M - X} c(s) r(s) \qquad \text{[Eq. A-21]} \\ &\geq ln\, A(X) + r(M) \sum_{s \in M - X} c(s) \\ &\geq ln\, A(X) + r(M)\, C(M - X) \\ &\geq ln\, A(X) + r(N)\, C(N - X) \\ &\geq ln\, A(X) + r(N) \sum_{s \in N - X} c(s) \\ &\geq ln\, A(X) + \sum_{s \in N - X} c(s) r(s) \\ &= ln\, A(N). \end{aligned}$$

Thus, M is an undominated set of spares, and the optimality of marginal analysis is proved.

APPENDIX B

REPAIR BUDGET: METHODS, ASSUMPTIONS, AND DATA

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The M-SPARE repair budget estimates center around a single ratio: an orbital replaceable unit's (ORU's) repair-to-procurement-cost ratio. M-SPARE multiplies that ratio by the ORU's procurement cost to obtain the ORU's repair cost. It then multiplies the repair cost by the annual number of ORU repair actions (total failures minus condemnations) to obtain the annual repair budgets. The model uses that simple ratio because more detailed repair data for the station are not yet available. After examining available repair data from existing NASA systems, we decided that use of the repair ratio was the best means for estimating repair budgets:

- The ratio puts realistic bounds on the problem. A large ratio (e.g., 85 to 100 percent) is not practical because if the ORU repair costs that much, procuring a new ORU would be the better course of action.
- The ratio is sensitive to the procurement cost of the ORU; more expensive ORUs cost more to repair.
- The ratio method is based upon historical NASA data.

In this appendix, we describe how and why we determined the M-SPARE default repair ratio of 28 percent. First, we present the historical NASA data from the Spacelab (a laboratory that flies in the shuttle bay) and NASA's Orbiters (i.e., the shuttles). We then show how we calculated the ratio and how a single ratio seems to represent a good indicator of repair costs across components even when procurement cost varies dramatically.

REPAIR DATA

Table B-1 presents the original equipment manufacturer's (OEM's) repair data for the Spacelab and the shuttle divided into three basic categories: direct labor costs (proportional to the number of ORUs repaired), fixed labor costs (an annual OEM fee independent of the number of ORUs repaired), and material costs. Those data are taken from readily available sources or are general estimates of NASA experts and are not the result of an extensive data search. We used only OEM repair data since it

is not known whether a Kennedy Space Center (KSC) NASA depot will perform station repair.

TABLE B-1

COMPARING SPACELAB AND SHUTTLE REPAIR COSTS

Cost component	FY93 ($000)		Percent of budget	
	Spacelab[a]	Shuttle[b]	Spacelab[a]	Shuttle[b]
Labor (direct)	2,175	26,800	78	49
Labor (fixed)	524	18,300	18	33
Material	100[c]	10,000[c]	4	18
Sum	2,799	55,100	100	100
No. ORU/LRU repaired	24	524		
$000/repair FY93	117	105		
$000/repair FY92	112	100		

Note: LRU = line replaceable unit.
[a] Spacelab information from seven OEMs.
[b] Shuttle OEM information (FY93).
[c] Rough estimates from telephone conversations.

For the Spacelab, the information came from a sample of seven U.S. OEM depots (see Table B-2). The "total" line in Table B-2 specifies the data used in Table B-1 for all the OEMs. The direct labor cost of $2,175,000 in Table B-2 equals the average repair cost times the number of ORUs repaired at each OEM. The fixed labor cost in Table B-2 is the retention cost for management of bonded storage, maintenance of technical documentation and test equipment, and program management ($524,000). Material cost includes parts used in the repair actions ($100,000). The number of ORUs repaired for the year was 24.

For the shuttle, the information came from the estimated repair requirements for FY93, which are closely linked to historical information. The direct labor costs are the estimated OEM costs and do not include the NASA depot or Downey facility. The fixed labor cost equals the annual subcontracting agreements from some 77 OEMs (NASA terms those costs "Phase A" costs) plus the capability retention costs for OEMs no longer making shuttle components (those costs ensure that the

TABLE B-2

KSC SPACELAB FLIGHT HARDWARE – U.S. DEPOT COSTS

U.S. depot/vendor	Retention costs (FY93 $000)[a] (firm)	Unit repair costs (FY93 $000)[b] (estimate)	FY92 repaired	Direct costs (costs × repaired)
Airesearch	30.0	40.0	2	80
Brunswick	131.0	30.0	1	30
Carleton	153.0	30.0	0	0
Hamilton standard	23.0	90.0	6	540
ODETICS	127.0	157.0	4	628
		96.0	7	672
Honeywell	24.0	67.5	2	135
IBM-OWEGO	35.5	45.0	2	90
Total	523.5	555.5	24	2,175
Average cost	74.8	69.4		90.6

[a] Depot retention costs include management of bonded storage, maintenance of technical documentation and test equipment, and program management.

[b] Unit repair costs do not include parts used in the repair. Estimate the seven U.S. depots consume a total of $100,000 per year.

OEM retains the skilled labor necessary to repair components, and NASA terms them "Phase B" costs). Two-thirds of the shuttle fixed labor costs fall into the Phase B category. The total LRUs repaired equal the sum of reparable and nonreparable LRU parts rework replacements (PRR).

The two NASA systems show very different breakouts of the three budget categories as a percentage of the total budget (see Table B-1). That is not surprising since the two NASA systems are very different in function, number of systems, types of repair capability, and accounting methods. For instance, the shuttle is a launch vehicle, and its engines require more material-intensive repair than a laboratory. Also, since the shuttle is shifting most of its repair capability to the NASA facility at KSC and thus decreasing its direct costs, fixed retention costs for the OEM go up. Even with those differences, for FY93 the Spacelab and the shuttle average repair costs per component (ORU or LRU) are very similar at $117,000 and $105,000, respectively. Consequently, we decided to move away from estimating the three

repair categories since they varied so and instead use the average repair cost that is more consistent between the NASA systems.

We initially used that average repair cost per component times the number of repairs to produce repair budgets; however, that method resulted in inconsistent repair budgets for certain groups of station ORUs. For instance, sometimes the model operates on relatively inexpensive ORUs, and the use of a straight repair cost created budgets close to the cost of procuring new ORUs for every repair action. Thus, we needed a repair cost estimator sensitive to ORU procurement costs yet still capable of keeping the average ORU repair cost around $100,000. That estimator is the repair ratio.

THE REPAIR-TO-PROCUREMENT RATIO

The repair-to-procurement ratio is the average repair cost divided by the average procurement cost. NASA estimates the procurement cost for Spacelab ORUs is between $300,000 and $500,000. (NASA shuttle did not have an analogous procurement cost for the repaired OEM LRUs.) We next estimated the station ORU procurement costs, which are very comparable to the Spacelab costs. The station average procurement cost is about $400,000 (FY92) when weighted by the ORU's estimated number of repairs in FY02. The station procurement cost used preliminary station data across work packages. By dividing the average Spacelab repair cost ($112,000 in FY92) by an appropriate average procurement cost ($400,000 in FY92), we produce the M-SPARE default repair ratio of 28 percent.

The final M-SPARE default value we needed to estimate was the labor percentage. The labor percentage splits the annual repair budget into repair cost estimates for labor and for material. The model multiplies the total repair cost by the labor percentage to estimate the labor component and by one minus the labor percentage to estimate the material component. We estimated the default value by taking the average of the labor percentages (fixed and direct) for Spacelab and the Shuttle – roughly 90 percent. Thus, M-SPARE uses the 28 percent repair ratio and 90 percent labor costs as its default values (see Chapter 6 to set those options).

HOW GOOD IS A SINGLE REPAIR RATIO?

Now that we have a repair ratio, the next step is to determine how well it indicates repair costs across all ORUs. Since NASA could not easily access the repair

and the procurement cost at a component level, we used data from the U.S. Air Force. We examined B1 bomber data because some of that system's LRUs are comparable in cost to NASA's expensive components. Table B-3 displays the repair ratio (the sum of the unit repairs divided by the sum of the procurement costs) for three LRU subsets. If we examine all LRUs, the average procurement cost is $49,000 and the repair ratio is 11.6 percent. If we examine only LRUs that cost more than $20,000, the average procurement cost increases, but the repair ratio stays basically the same. Even when we examine only the most expensive ORUs with an average cost of $313,000, the repair ratio remains at 11 percent. This analysis indicates that though the procurement costs of components may change, the repair ratio on average stays fairly constant.

TABLE B-3

STRONG CORRELATION BETWEEN UNIT REPAIR AND PROCUREMENT COSTS

(Example: B1 bomber)

Subsets of B1 LRUs by procurement cost	Average procurement costs ($000)	Approximate ratio of unit repair to procurement costs (%)
All LRUs	49	11.6
LRUs greater than $20,000	150	11.1
LRUs greater than $100,000	313	11.1
Air Force rule of thumb		10 - 20

CONCLUSION

Estimating aggregate dollar repair requirements by using a single ratio across all ORUs seems appropriate until more detailed data become available. The ratio is sensitive to an ORU's procurement price, it allows the user to place bounds on repair cost, and it uses actual NASA data. A possible future enhancement to that methodology may include a ratio based upon the type of ORU (mechanical or electrical), a ratio that varies over time to reflect the transition from OEM to a centralized KSC depot, and a separate estimate for shop replaceable units and material costs.

APPENDIX C

GLOSSARY

GLOSSARY

ASCII	=	American Standard Code for Information Interchange
CAGE	=	Commercial and Government Entity
CRC	=	cumulative replaced condemnations
DOS	=	Disk Operating System
EPS	=	electric power system
FSCM	=	Federal Supplier Code for Manufacturers
IBM	=	International Business Machines
KSC	=	Kennedy Space Center
LC	=	LogCycle
LM	=	launch month
LMI	=	Logistics Management Institute
LRU	=	line replaceable unit
MB	=	mean broken
MO	=	Mean number of Orbit failures for the next logistics cycle
M-SPARE	=	Multiple Spares Prioritization and Availability to Resource Evaluation
MTBF	=	mean time between failures
NASA	=	National Aeronautics and Space Administration
OEM	=	original equipment manufacturer
ORU	=	orbital replaceable unit
PC	=	personal computer
PLT	=	procurement lead time
POP	=	Program Operating Plan
POS	=	probability-of-sufficiency

PRR	=	parts rework replacements
PSN	=	probability of a spare when needed
QPA	=	quantity per application
RAM	=	random access memory
RMAT	=	Reliability and Maintainability Assessment Tool
SIMSYLS	=	simulation of manned space station logistics support
SRU	=	shop replaceable unit
SSF	=	Space Station Freedom
VMR	=	variance-to-mean ratio

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The Logistics Management Institute developed a methodology that estimates the optimal orbital replaceable unit (ORU) spares inventory for NASA's Space Station Freedom. NASA is using this methodology to select a spares inventory that maximizes station availability, i.e., the probability that no critical system is inoperative for lack of an ORU spare over the resupply cycle. Spares are ranked in order of decreasing benefit per cost (the improvement provided to station availability per dollar) and added, in that order, to the inventory until a target resource expenditure or availability is reached. The methodology also develops optimal spares inventories constrained by the spares weight the shuttle can carry, the spares volume the station can store, or a combination of resources.

To implement our methodology, we developed the Multiple Spares Prioritization and Availability to Resource Evaluation (M-SPARE) model that operates on a personal computer. M-SPARE presents the maximum availability for an entire range of resource expenditures. The model also converts annual spares requirements over any period of the station's life into funding estimates for the next 9 years. To address other spares-related costs, the model also estimates repair budgets. In this guide, we describe the M-SPARE methodology, operation, and analytical capabilities.

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