NASA Technical Memorandum 4628

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Recommended Techniques for Effective Maintainability

A Continuous Improvement Initiative of the NASA Reliability and Maintainability Steering Committee
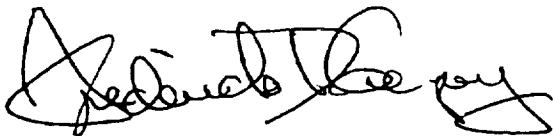
December 1994

PREFACE

Current and future NASA programs face the challenge of achieving a high degree of mission success with a minimum degree of technical risk. Although technical risk has several elements, such as safety, reliability, and performance, a proven track record of overall system effectiveness ultimately will be the NASA benchmark. This will foster the accomplishment of mission objectives within cost and schedule expectations without compromising safety or program risk. A key characteristic of systems effectiveness is the implementation of appropriate levels of maintainability throughout the program life cycle.

Maintainability is a process for assuring the ease by which a system can be restored to operation following a failure. It is an essential consideration for any program requiring ground and/or on-orbit maintenance. The Office of Safety and Mission Assurance (OSMA) has undertaken a continuous improvement initiative to develop a technical roadmap that will provide a path toward achieving the desired degree of maintainability while realizing cost and schedule benefits. Although early life cycle costs are a characteristic of any assurance program, operational cost savings and improved system availability almost always result from a properly administered maintainability assurance program. Past experience on NASA programs has demonstrated the value of an effective maintainability program initiated early in the program life cycle.

This memorandum provides guidance towards continuous improvement of the life cycle development process within NASA. It has been developed from NASA, Department of Defense, and industry experience. The degree to which these proven techniques should be imposed resides with the project/program, and will require an objective evaluation of the applicability of each technique. However, each applicable suggestion not implemented may represent an increase in program risk. Also, the information presented is consistent with OSMA policy, which advocates an Integrated Product Team (IPT) approach for NASA systems acquisition. Therefore, this memorandum should be used to communicate technical knowledge that will promote proven maintainability design and implementation methods resulting in the highest possible degree of mission success while balancing cost effectiveness and programmatic risk.

Frederick D. Gregory
Associate Administrator for
Safety and Mission Assurance

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DEVELOPING ACTIVITY

The development of this technical memorandum has been overseen by the NASA Reliability and Maintainability (R&M) Steering Committee, which consists of senior technical representatives from NASA Headquarters and participating NASA field installations. This Committee exists to provide recommendations for the continuous improvement of the R&M discipline within the NASA community, and this manual represents the best technical "advice" on designing and operating maintainable systems from the participating Centers and the Committee. Each technique presented in this memorandum has been reviewed and approved by the Committee.

CENTER CONTACTS

Appreciation is expressed for the dedication, time, and technical contributions of the following individuals in the preparation of this manual. Without the support of their individual Centers, and their enthusiastic personal support and willingness to serve on the NASA R&M Steering Committee, the capture of the maintainability techniques contained in this manual would not be possible.

All of the NASA Centers are invited to participate in this activity and contribute to this manual. The Committee members listed below may be contacted for more information pertaining to these maintainability techniques.

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I. INTRODUCTION

A. PURPOSE

Maintainability is a process for assuring the ease by which a system can be restored to operation following a failure. Designing and operating cost effective, maintainable systems (both on-orbit and on the ground) has become a necessity within NASA. In addition, NASA cannot afford to lose public support by designing less than successful projects. In this era of shrinking budgets, the temptation to reduce up front costs rather than consider total program life cycle costs should be avoided. In the past, relaxation of R&M requirements to reduce up front costs has resulted in end-items that did not perform as advertised and could not be properly maintained in a cost effective manner. Additional costs result when attempts are made late in the design phase to correct for the early relaxation of requirements.

The purpose of this manual is to present a series of recommended techniques that can increase overall operational effectiveness of both flight- and ground-based NASA systems. Although each technique contains useful information, none should be interpreted as a requirement. The objective is to provide a set of tools to minimize the risk associated with:

- Restoring failed functions (both ground and flight based)
- Conducting complex and highly visible maintenance operations
- Sustaining a technical capability to support the NASA mission utilizing aging equipment or facilities.

This document provides (1) program management considerations - key elements of an effective maintainability effort; (2) design and development considerations; (3) analysis and test considerations - quantitative and qualitative analysis processes and testing techniques; and (4) operations and operational design considerations that address NASA field experience. Updates will include a section applicable to on-orbit maintenance with practical experience from NASA EVA maintenance operations (including ground and on-orbit operations and ground-based simulations). This document is a valuable resource for continuous improvement ideas in executing the systems development process in accordance with the NASA "better, faster, smaller, and cheaper" goal without compromising mission safety.

B. CONTROL/CONTRIBUTIONS

This document will be revised periodically to add new techniques or revisions to the existing techniques as additional technical data becomes available. Contributions from aerospace contractors and NASA Field Installations are encouraged. Any technique based on project/program experience that appears appropriate for inclusion in this manual should be submitted for review. Submissions should be formatted identically to the techniques in this memorandum (Figure 1) and sent to the address below for consideration.

> National Aeronautics and Space Administration
> Code QS
> 300 E Street S.W.
> Washington, DC 20546

Organizations submitting techniques that are selected for inclusion in this manual will be recognized on the lower portion of the first page of the published item. Contacts listed earlier in this document should be used for assistance. If additional information on any technique is desired, the contacts listed earlier in this document can be utilized for assistance.

C. MAINTAINABILITY TECHNIQUE FORMAT SUMMARY

The maintainability techniques included in this manual are Center-specific descriptions of processes that contribute to maintainability design, test, analysis and/or operations. Each technique follows a specific format so users can easily extract necessary information. The first page of each technique is a summary of the information contained, and the rest of the technique contains the specific detail of the process. Figure 1 shows the baseline format that has been used to develop each technique.

Technique Title, page number
*Technique XXX-XX ***

TECHNIQUE FORMAT

<u>Technique</u>: *A brief statement defining the design technique and how it is used.*

<u>Benefits</u>: *A concise statement of the technical improvement and/or impact on resource expenditure realized from implementing the technique.*

<u>Key Words</u>: *Any term that captures the theme of the technique or provides insight into the scope. Utilized for document search purposes.*

<u>Application Experience</u>: *Identifiable programs or projects that have applied the technique within NASA and/or industry.*

<u>Technical Rationale</u>: *A brief technical justification for the use of the technique.*

<u>Contact Center</u>: *Source of additional information, usually sponsoring NASA Center.*

<u>Technique Description</u>: *A technical discussion that is intended to give the details of the process. The information should be sufficient to understand how the technique should be implemented.*

<u>References</u>: *Publications that contain additional information about the technique.*

** Each technique within a section is identified using one of the following acronyms specific to that section followed by the associated sequential technique number.
- **PM**: Program Management
- **DFE**: Design Factors and Engineering
- **AT**: Analysis and Test
- **OPS**: Operations and Operational Design Considerations

Figure 1: Technique Format Definitions

Program Management

A fundamental key to program and mission success is the development of systems that are reliable and affordable to operate and maintain with today's limited resources. Early definition of both hardware and software requirements that provide the capability for rapid restoration when failures occur is essential. While incorporation of a maintainability program may require some additional early investment, the resulting benefits will include operational cost savings and improved system availability. The techniques included in this section are intended to provide management personnel with an understanding of all information necessary to develop, foster, and integrate a successful maintainability program that will enhance mission success and lower overall costs. Each technique provides high-level information on a specific subject, and can be tailored or expanded to achieve optimum application.

Technique	Programmatic provisions for ease of maintenance greatly enhance hardware and software system operational effectiveness for both in-space and ground support systems.

BENEFITS OF IMPLEMENTING MAINTAINABILITY ON NASA PROGRAMS

Include the principles of maintainability early in the development process to realize significant benefits in all program life cycle phases.

Benefits	Implementation of maintainability principles can reduce risk by increasing operational availability and reducing lifecycle costs. Provisions for system maintainability also yields long term benefits that include decreased maintenance times, less wear and tear on project personnel, and extended useful life of ground and in-space assets.
Key Words	System maintainability, program management, lifecycle costs, availability, concept development, human factors
Application Experience	International Space Station Program, Hubble Space Telescope, SRB's, Shuttle GSE, Space Acceleration Measurement System, and others.
Technical Rationale	Maintainability requirements for programs that require ground and/or in-space maintenance and anomaly resolution have to be established early in the program to be cost effective. Lack of management support to properly fund maintainability activities up-front can result in increased program risk. Including maintainability in the design process will greatly reduce the number of operational problems associated with system maintenance, improve the availability of the system, and reduce program costs.
Contact Center	**All NASA Field Installations**

Benefits of Implementing Maintainability
on NASA Programs
Technique PM-1

Over the years, NASA has successfully launched manned spacecraft to the moon, sent unmanned probes into the outer reaches of the sc' system, and developed reusable space tems for earth orbitable missions. NASA also performs valuable atmospheric research and development of ground systems, all of which contain complex hardware and ftware that must be maintained during all ases of operations and in multiple environments. However, in this age of shrinking budgets, doing more with less is becoming the overall programmatic theme. NASA space flight programs are being driven towards more automated, compact designs in which fewer support resources will be available than in past programs.   This technique will outline the benefits of implementing well-defined and user-friendly principles of maintainability on all NASA programs, regardless of the operational scenario. Emphasis is placed on how and why a maintainability program can enhance the effectiveness of a system and its overall operation. It must be noted, however, that maintainability of unmanned deep space systems provides a different set of challenges.

Ma tainability is defined in NASA Handbook 5300.4(1E), "Maintainability Program Requirements for Space Systems," as: "A measure of the ease and rapidity with which a system or equipment can be restored to operational status following a failure," and is consistent with NHB 7120.5, "Management of Major Systems and Projects." It is a characteristic of equipment and installation, personnel availability in the required skill levels, adequacy of maintenance procedures and test equipment, and the physical

environment under which maintenance is performed. Applying maintainability principles will enhance the systems readiness/availability through factors such as visibility, accessibility, testability, simplicity, and interchangeability of the systems being maintained. Using maintainability prediction techniques and other quantitative maintainability analyses can greatly enhance the confidence in operational capabilities of a design. These predictions can also aid in design decisions and trade studies where several design options are being considered. Also, cost savings and fewer schedule impacts in the operational phase of the program will result due to decreased maintenance time, minimization of support equipment, and increased system availability. Another benefit is a decrease in management overhead later on in the life cycle as a result of including maintainability planning as a full partner in early maintenance/logistics concept planning and development.

PROGRAMMATIC BENEFITS

Maintainability Program Implementation
Project management is responsible for implementing maintainability on a program via development of specific requirements for cost effective system maintenance in the early phases of the life cycle. Trade studies of the impacts of maintainability design on life cycle costs are used to evaluate the balance between cost of designing to minimize maintenance times and the associated increase in system availability resulting from the decrease in maintenance times. Usually, the up-front cost of designing-in maintainability is much less than the cost savings realized over the operational portion of the life cycle.

Several programs have opted to accept the short-term cost savings by deleting maintainability requirements in the design phase, but the associated increase in

maintenance and support costs incurred during operations would have been significant. An example of this is the Space Station Program, which had deleted requirements for on-orbit automated fault detection, isolation and recovery (FDIR), saving the program up-front money. However, the alternative concept was to increase the mission control center manpower during operations for ground based FDIR, but this presented a significant cost increase when averaged over the life cycle. Another positive example is the Hubble Space Telescope Program. Maintainability concepts were included early in the life cycle, where maintenance planning and optimum ORU usage in design saved the program significant costs when on-orbit repairs became necessary. Figure 1 accentuates the cost tradeoffs between introducing maintainability concepts into a program and the time at which they are introduced. These tradeoffs can mean the difference between a successful maintainability program and a costly, less effective one.

Figure 1: Effect of Implementing Maintainability Program vs. Phase

The NASA systems engineering process should require that the system be designed for ease of maintenance within it's specified operating environment(s), and should ensure that the proper personnel (design and operations maintainability experts) and funds are committed to development of the process to achieve maximum program benefit. Program schedule will be affected by lack of system maintainability because necessary ground support will increase, maintenance times will be higher, necessary maintenance actions will increase, EVA will be at a premium, and system availability will be lower. Table 1 highlights key program benefits.

Maintenance/Logistics Concept Development
Development of the maintenance and logistics concepts for a program early in the life cycle must include the maintainability characteristics of the design. The maintenance concept is a plan for maintenance and support of end-items on a program once it is operational. It provides the basis for design of the operational support system and also defines the logistics support program, which will determine the application of spares and tools necessary for maintenance. The use of other logistic resources, such as tools and test equipment, facilities and spare parts, will be optimized through including maintainability planning as a key operational element. Derivation of these plans early on in the life cycle solidifies many operational aspects

Table 1: Maintainability Programmatic Benefits

• Enhanced System Readiness/ Availability
  - Reduced Downtime
  - Supportable Systems
  - Ease of Troubleshooting and Repair
• System Growth Opportunities
  - Hardware/Software Modifications
  - Interchangeability
  - Modular Designs
  - Decreased Storage Considerations
• Reduced Maintenance Manpower
• Reduced Operational Costs
• Compatibility with other Programs
• Reduced Management Overhead

of the program, thus allowing for integrated design and support planning development.

MAINTAINABILITY DESIGN BENEFITS

Visibility
Visibility is an element of maintainability design that provides the system maintainer visual access to a system component for maintenance action(s). Even short duration tasks such as NASA space shuttle orbiter component inspection can increase downtime if the component is blocked from view. Designing for visibility greatly reduces maintenance times.

Accessibility
Accessibility is the ease of which an item can be accessed during maintenance and can greatly impact maintenance times if not inherent in the design, especially on systems where on-orbit maintenance will be required. When accessibility is poor, other failures are often caused by removal/ disconnection and incorrect re-installation of other items that hamper access, causing rework. Accessibility of all replaceable, maintainable items will provide key time and energy savings to the system maintainer.

Testability
Testability is a measure of the ability to detect system faults and to isolate them at the lowest replaceable component(s). The speed with which faults are diagnosed can greatly influence downtime and maintenance costs. For example, deficiencies in Space Shuttle Orbiter testability design have caused launch delays, which translate to higher program costs. As technology advances continue to increase the capability and complexity of systems, use of automatic diagnostics as a means of FDIR substantially reduces the need for highly trained maintenance personnel and can decrease maintenance costs by reducing the erroneous replacement of non-faulty equipment. FDIR systems include both internal diagnostic systems, referred to as built-in-test (BIT) or built-in-test-equipment (BITE), and external diagnostic systems, referred to as automatic test equipment (ATE), test sets or off-line test equipment used as part of a reduced ground support system, all of which will minimize down-time and cost over the operational life cycle.

Simplicity
System simplicity relates to the number of subsystems that are within the system, the number of parts in a system, and whether the parts are standard or special purpose. System simplification reduces spares investment, enhances the effectiveness of maintenance troubleshooting, and reduces the overall cost of the system while increasing the reliability. For example, the International Space Station Alpha program has simplified the design and potentially increased the on-orbit maintainability of the space station, thus avoiding many operational problems that might have flown with the Freedom Program. One example is the Command and Data Handling Subsystem, which is the data processing backbone for the space station. Formerly, the system consisted of several different central processing units,

of several different central processing units, multiple level architecture, and several different network standards. The new design comprises only one network standard, one standard CPU, and a greatly reduced number of orbital replaceable units (ORU's). Maintainability design criteria were definite factors in the design changes to this space station subsystem.

Reduced training costs can also be a direct result of design simplification. Maintenance requires skilled personnel in quantities and skill levels commensurate with the complexity of the maintenance characteristics of the system. An easily maintainable system can be quickly restored to service by the skills of available maintenance personnel, thus increasing the availability of the system.

Interchangeability
Interchangeability refers to a component's ability to be replaced with a similar component without a requirement for recalibration. This flexibility in design reduces the number of maintenance procedures and consequently reduces maintenance costs. Interchangeability also allows for system growth with minimum associated costs, due to the use of standard or common end-items.

Human Factors
Human factors design requirements also should be applied to ensure proper design consideration. The human factors discipline identifies structure and equipment features that impede task performance by inhibiting or prohibiting maintainer body movement, and also identifies requirements necessary to provide an efficient workspace for maintainers. Normally, the system design must be well specified and represented in drawings or sketches before detailed anthropometric evaluation can be effective.

However, early evaluation during concept development can assure early application of anthropometric considerations. Use of these evaluations results leads to improved designs largely in the areas of system provisions for equipment access, arrangement, assembly, storage, and maintenance task procedures. The benefits of the evaluation include less time to effect repairs, lower maintenance costs, improved supportability systems, and improved safety.

Summary
Implementation of maintainability features in a design can bring about operational cost savings for both manned and unmanned systems. The programmatic benefits of designing system hardware and software for ease and reduction of maintenance are numerous, and can save a program, as seen with NASA's Hubble Space Telescope. Maintenance in a hostile, micro-gravity environment is a difficult and undesirable task for humans. Minimal exposure time to this environment can be achieved by implementing maintainability features in the design. The most successful NASA programs have been those which included maintainability features in all facets of the life cycle. Remote system restoration by redundancy management and contingency planning is particularly essential to assuring mission success on projects where manned intervention is either undesireable or impractical.

References

1. NASA Handbook 5300.4(1E) *"Maintainability Program Requirements for Space Systems,"* March 10, 1987, NASA Headquarters.

2. NASA Handbook 7120.5, *"Management of Major Systems and Projects,"* November 1993, NASA Headquarters

3. Air Force Design Handbook 1-9
"Maintainability (for Ground Electronic Systems)," Second Edition, Revision 7, February 25, 1988, United States Air Force Aeronautical Systems Division.

4. *"Maintainability Engineering Design and Cost of Maintainability,"* Revision II, January 1975, Rome Air Development Center.

5. *Reliability, Maintainability, and Supportability (RMS) Guidebook,* Second Edition, 1992, Society of Automotive Engineers G-11 International RMS Committee.

6. MIL-STD-470B *"Maintainability Program for Systems and Equipment,"* May 30, 1989, Department of Defense

Technique	Identify program management considerations necessary when implementing maintainability principles for NASA spaceflight, atmospheric, or ground support programs.
MAINTAINABILITY PROGRAM MANAGEMENT CONSIDERATIONS *Establish and implement a comprehensive, integrated maintainability program for any project that requires maintenance during its operational life cycle.*	
Benefits	Early and effective planning and implementation of a maintainability program can significantly lower the risk of reduced system operational effectiveness resulting from maintainability design shortfalls. This reduces maintenance time/support, which directly relates to reduced operating costs and increased system operational time.
Key Words	Maintainability Management, Maintenance Concept, Logistics Support, Quantitative Requirements, Maintainability Planning
Application Experience	Hubble Space Telescope, SRB's, Shuttle GSE, and Space Acceleration Measurement System.
Technical Rationale	Decisions by program management to establish maintainability requirements early in the program will provide design impetus towards a system with higher operational availability at lower operational costs. Lower downtime and less complicated maintenance actions will be needed when maintenance is required.
Contact Center	**NASA Headquarters**

Maintainability Program Management
Considerations
Technique PM-2

This technique outlines management considerations to observe when applying the principles of maintainability on a program at NASA. It also provides information on how to realize cost savings and reduced system downtime. This information complements PM-1, "Benefits of Implementing Maintainability on NASA Programs," by providing guidelines for establishing a maintainability program once the benefits have been understood.

Program management is responsible for establishing proper integration of maintainability early in program development and ensuring adequate control of the application of the maintainability discipline throughout the development program. Figure 1 provides flow diagram for an effective Maintainability program beginning with development of its goals and objectives, followed by development of the program/system maintenance concept and the Maintainability Program Plan, and establishment of program control and evaluation during design, production (manufacturing) and operations. The order of these program development elements is important, as each affects the next step in the process.

(1) ESTABLISH MAINTAINABILITY AS
PART OF THE OVERALL SYSTEMS
ENGINEERING AND OPERATION
PLANNING PROCESS.

Set Goals and Objectives
One of the missions of the maintainability program is to measure the ability of an item to be retained or restored to a specified condition when maintenance is performed. The degree of maintainability designed into a system should
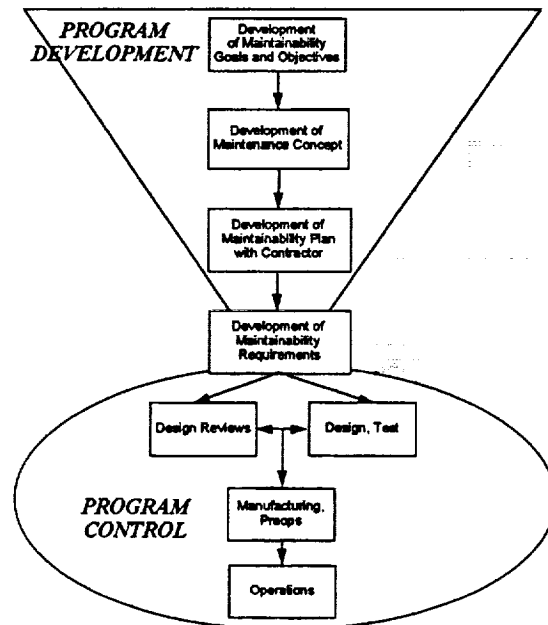
Figure 1: Maintainability Program Development

reflect the function (mission) of the system/subsystem and the impact on operational objectives of the program if the system is non-operational for any length of time. System availability (the ability of the system to operate whenever called upon to do so) is very important, and maximum availability should be a goal of the program. Program maintainability goals and objectives must be developed with cost and schedule in mind; however, careful consideration must also be given to the technical and operational goals of the program. These qualitative goals and objectives are developed by analyzing the system operating cycle, the physical and maintenance support environments, and other equipment characteristics consistent with mission and cost objectives.

Attention must also be given to existing support programs to avoid needless duplication during development of new

support systems. Development of the maintainability goals and objectives will lead to derivation of the maintenance concept, maintainability plan, and definition of maintainability requirements discussed in the following paragraphs.

Establish Interfaces with Other Engineering Disciplines
Maintainability engineering is a system engineering discipline that combines system analysis and equipment design with a knowledge of safety, reliability, human factors, and life-cycle costing to optimize the maintenance characteristics of system design and to provide an awareness of interface problems. Its goal is to optimize the combination of design features,

repair policies, and maintenance resources to the desired level of maintainability at acceptable life-cycle costs. The many interfaces and feedback paths between maintainability engineering and other product development and operational disciplines are shown in Figure 2.

While maintainability personnel must be intimately involved in the product development process and provide inputs to design through design techniques and analysis, it is program management's responsibility to develop and support the relationship between maintainability and the rest of the system engineering disciplines. This support is key to establishment of a
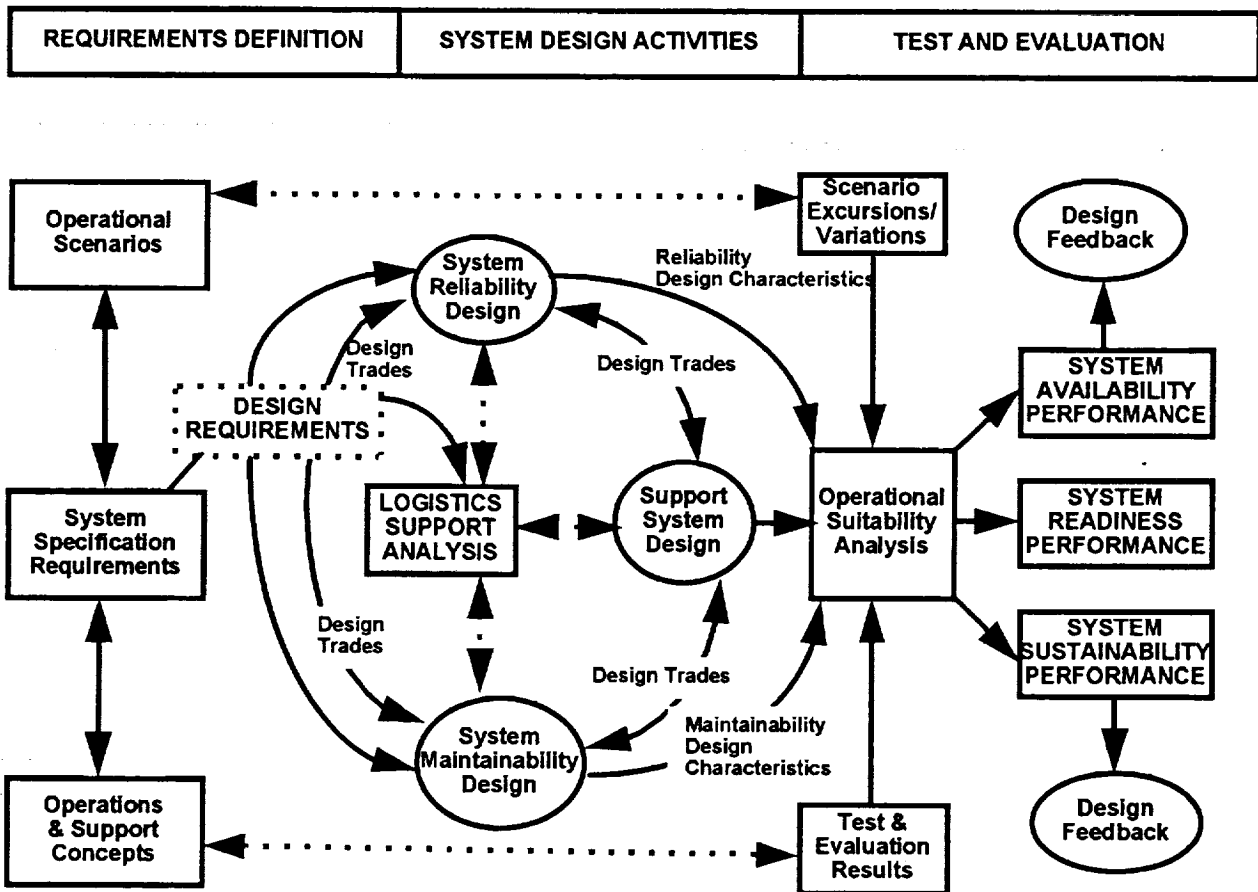

Figure 2: System Reliability, Maintainability and Support Relationships (typical)

concurrent engineering process. These relationships must be mirrored in the Maintainability Program Plan.

(2) DEVELOP MAINTENANCE AND LOGISTICS CONCEPTS EARLY IN THE CONCEPTUAL PHASE OF THE PROGRAM.

The program maintenance concept provides the basis for establishing overall maintainability design requirements on the program, and contains detailed planning on maintenance policy.

It defines overall repair policy, organizational and depot maintenance, system availability, repair vs. replacement policy, level of replacement, skill level requirements, sparing philosophy, diagnostic/testing principles and concepts, contractor maintenance responsibilities, payload maintenance responsibilities, and crew time allocations for maintenance (PM-3 provides details on each of these elements). Development of the maintenance concept is based on initial maintainability analysis and program inputs such as mission profile, system availability and reliability requirements, system mass properties constraints, and personnel considerations. The maintenance concept may be developed from the ground up, or may come from a similar successful program, tailored to meet the needs of the new program. New technology may also dictate the maintenance concept, e.g. maintainable items may be scrapped instead of repaired because the cost of repair outweighs the replacement cost.

Definition of logistics and support concepts is a function of the maintenance concept. The operational environment of the system, the level of support personnel defined by the maintenance concept, and cost and schedule are important drivers for the logistics/support programs.

These elements are also important contributors to system maintainability in that logistics planning can define how much system down time is required during maintenance operations.

For example, downtime can be held to a minimum if spares are co-located with the system during operations. It is important that Program management closely monitor all logistics development to ensure inclusion of maintenance and logistics concepts early in the program. Both concepts drive the development of lower-level requirements.

Assess Existing Resources
Another important aspect of planning for a new program is assessment of the existing logistic and support infrastructure. As an example, the infrastructure of the NSTS system at KSC comprises the launch pad, numerous assembly and support buildings, and support personnel and equipment. These are important factors to consider when planning for new programs that will use KSC as the central operations base. If some of the existing structures and equipment can be used by the new program, then the developmental and operational costs of the program will be reduced. During early planning stages, management should also look at how the new program can adapt to the existing support infrastructure, and what equipment and personnel may be used to eliminate unnecessary costs.

Establish a Maintainability Program Plan
The maintainability program plan is the master planning and control document for the maintainability program. It provides detailed activities and resources necessary to attain the goals and objectives of the maintainability program. It must be developed with the program contractor(s) if they exist, or if the program is in-house, all developmental and

operational disciplines must be represented. The plan must be consistent with the type and complexity of the system or equipment and must be integrated with the systems engineering process. It identifies how the contractor/program office will tailor the maintainability program to meet requirements throughout the three major program phases : Development, Production, and Operations/ Support. Typically it contains the following elements shown in Table 1:

Table 1. Elements of the Maintainability Program Plan

- Duties of each organizational element involved in the accomplishment of the maintainability tasks cited in the product specification or statement of work.

- Interfaces between maintainability and other project organizations, such as design engineering, software, reliability, safety, maintenance, and logistics.

- Identification of each maintainability task, narrative task descriptions, schedules, and supporting documentation of plans for task execution and management

- Description of the nature and extent that the maintainability function participates in formal and informal design reviews, and authority of maintainability personnel in approval cycle for drawing release.

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(3) PROVIDE UNIFORM QUALITATIVE AND QUANTITATIVE MAINTAINABILITY REQUIREMENTS.

Maintainability design requirements are established from the Maintainability Program Plan and the derived maintenance concept.

These requirements are intended as rules system designers follow to meet overall program goals and objectives. They include mission, operational environment, and system concepts. They must be baselined early and not changed unless absolutely necessary.

The requirements can include both quantitative and qualitative values of maintainability parameters. Quantitative maintainability requirements are usually the result of maintainability allocations based on system availability and operational timing requirements, with allocations made at each level down to the replaceable module, assembly or component level as needed. Examples of quantitative requirements are shown in Table 2:

Table 2. Examples of Quantitative Requirements

- Maintenance manhours per operating hour (MMH/OH)
- Mean-Time-To-Repair (MTTR)
- Mean-Time-To-Restore-System (MTTRS)
- Fault detection and isolation of sub-systems task times
- End item change out time
- Unit removal/installation times
- Availability

They may be established at any, or all, levels of maintenance and can help define maintenance criticalities and reduction of necessary system components. Qualitative requirements are used to accomplish two purposes. First, they address maintainability design features which are vital in achieving the maintainability goals, but cannot be measured. For example, elimination of safetywire/lockwire, standardization of

fasteners, use of captive fasteners, and color-coding of electrical wiring are some basic qualitative maintainability requirements used on orbital programs. Second, qualitative requirements are used to meet customer/program requirements and enhance the maintainability characteristics of the system. Examples include specification of common handtools only for organizational and intermediate levels of maintenance, and designing so that only one skill level is required for all organizational level maintenance personnel.

(4) EXERCISE PROGRAM CONTROL AND EVALUATION.

The maintainability program must be an integral part of the systems engineering process and all design and development activities. Activities include design reviews, development and implementation of methods for assessing maintainability effectiveness, dissemination of maintainability data, and proper implementation of program test and evaluation. Subcontractor/supplier control is also a key areas for program evaluation and monitoring.

Summary
Program management's participation in the development and implementation of sound maintainability practices on NASA programs is extremely important. Whether the program contains ground based systems, or is orbital and beyond, maintainability plays a key role in system operations, providing for increased system effectiveness and availability, and lower life cycle costs. The steps outlined above are guidelines towards success, and can be tailored depending on the type of program. However, the importance of a concurrent engineering approach and the existence of intimate professional relationships between maintainability personnel and other systems engineering disciplines can not be overstated,

and existence of these examples will enhance the chance of program success (based on historical experience).

References

1. NASA Handbook 5300.4(1E), *"Maintainability Program Requirements for Space Systems,"* March 10, 1987, NASA Headquarters.

2. Air Force Design Handbook 1-9, *"Maintainability (for Ground Electronic Systems),"* Second Edition, Revision 7, February 25, 1988, United States Air Force Aeronautical Systems Division.

3. *"Maintainability Engineering Design and Cost of Maintainability,"* Revision II, January, 1975, Rome Air Development Center.

4. Reliability, Maintainability, and Supportability (RMS) Guidebook, Second Edition, 1992, Society of Automotive Engineers G-11 International RMS Committee.

Related Techniques

Technique PM-1, "Benefits of Implementing Maintainability on NASA Programs".

Technique PM-3: "Maintenance Concept for Space Systems."

Technique	Develop a maintenance concept early in the program life cycle to provide a basis for full maintainability support. It should be used to influence systems design to ensure that attributes for ease of maintenance, minimization of repair and down time, and logistics support will be present in the final design.

MAINTENANCE CONCEPT FOR SPACE SYSTEMS

Develop a maintenance concept to specify system/equipment maintainability requirements

Benefits	Effective development of a maintenance concept can enhance the effectiveness of maintenance support planning and aid both logistics planning and design of a maintainable system. The maintenance concept can also provide assessments of cost savings for maintenance activities and resources allowable at each maintenance level.
Key Words	Maintenance Concept, Spares Requirement, Logistics Support, Maintenance Plan, Maintainability Requirements.
Application Experience	Space Acceleration Measurement System (SAMS), Combustion Module-1 (CM-1) Shuttle/Station Experiment.
Technical Rationale	The need to identify quantity, cost, types of spares, and related servicing techniques required to sustain a space system mission capability is a prime driver in developing maintainability requirements for a space system at the onset of its design. A system maintenance concept should be developed to define the basis for establishing maintainability requirements and to support design in the system conceptual phase. The maintenance concept provides the practical basis for design, layout, and packaging of the system and its equipment. The number of problems associated with product support and maintenance of space systems can be reduced, if not eliminated, by applying the principles prescribed in the system's maintenance concept.
Contact Center	**Lewis Research Center (LeRC)**

Maintenance Concept for Space Systems
Technique PM-3

The maintenance concept provides the basis for overall maintainability design requirements for the program, and contains detailed planning of maintenance policy for the operational system. It establishes the scope of maintenance responsibility for each level (echelon) of maintenance and the personnel resources (maintenance manning and skill levels) required to maintain a space system. Early development and application of the maintenance concept in structuring the maintainability plan can eliminate or reduce occurrence of problems that may interrupt system operation.

The maintenance concept for a new system must be systematically formulated during the early conceptual design phase of a program to minimize maintenance problems during the operational phase. This proactive approach is being used on Space Station-based experiment development programs at LeRC to incorporate current Space Station Program support principles, prescribed Space Acceleration Measurement System (SAMS) and Combustion Module One (CM-1) operational and repair policy, and identified sparing requirements.

Elements
This maintenance concept will aid in logistics planning and will guide design by providing the basis for establishment of maintenance support requirements in terms of tasks to be performed, frequency of maintenance, preventive and corrective maintenance downtime, personnel numbers and skill levels, test and support equipment, tools, repair items, and information. Inputs to the maintenance concept should include: a mission profile, system reliability and availability requirements, overall size and weight constraints, and crew considerations. The concept should support the following design elements as they apply to a manned

orbital space program where on-orbit and ground maintenance is planned.

Repair Policy
The repair policy should consider the support to be provided at the maintenance echelons (levels) summarized in Table 1.

Table 1. Echelons of Maintenance

	Organizational Maintenance	*Depot Maintenance*
Where Performed	On-orbit	NASA Center or Contractor
System Maintainer	Flight Crew	Center Engineers and Technicians
Basis	Repair and retain equipment	Repair and return equipment to stock inventory
Type of work accomplished	Inspect equipment	Repair at module, ORU, and component level
	Remove and replace modules and ORU's	Repair and maintain ground support equipment
	Adjust equipment	Calibrate equipment

Organizational Maintenance
Organizational maintenance is maintenance performed by the using organization (e.g., flight crew) on its own equipment. This maintenance consists of functions and repairs within the capabilities of authorized personnel, skills, tools, and test equipment. Organizational level personnel are generally occupied with the operation and use of the equipment, and have minimum time available for detailed maintenance or diagnostic checkout; consequently, the maintenance at

this level is restricted to periodic checks of equipment performance. Cleaning of equipment, front panel adjustments, and the removal and replacement of certain plug-in modules and Orbital Replaceable Units (ORUs), referred to as black boxes, are removed and forwarded to the Depot Level.

Depot Maintenance
Depot maintenance is maintenance performed at NASA Centers or contractor facilities for completely overhauling and rebuilding the equipment as well as to perform highly complex maintenance actions. The support includes tasks to repair faulty equipment to the part level, if deemed necessary. This level of maintenance provides the necessary standards for equipment calibration purposes, and also serves as the major supply for spares.

System Availability
Operational Availability (A$_o$) is defined as the probability that at an arbitrary point in time, the system is operable, i.e., is "up." It is a function of the frequency of maintenance, active maintenance time, waiting time, logistics time, administrative time, and the ready time of the system, and is expressed as:

$$A_o = \frac{UPTIME}{TOTALTIME} \qquad (1)$$

Where:

UPTIME = the total time a system is in an operable state, and

TOTAL TIME = the combination of uptime and downtime, in which downtime is the time in which a system spends in an inoperable state.

Repair vs. Replacement Policy
Normally, on-orbit repair should not be performed on any plug-in modules or ORUs. If any on-orbit repair actions are planned, they should be clearly identified in the concept. At the organizational level, failed items should be either discarded or sent to the NASA Center or contractor for exchange and repair in accordance with repair/discard policies identified in the system requirements. Corrective maintenance, limited to replacement of faulty ORUs and plug-in modules, should be specified to be performed during the mission period. Prime equipment should be designed to have ready access for maintenance. Quick-opening fasteners should also be specified.

Level of Replacement
The design for proper level of ORU definition should consider compatible failure rates for hardware parts within the same ORU. Relative ranking of ORU's through reliability and maintainability considerations and mission criticality analysis can also contribute toward the proper level of replacement definitions. The required level of replacement should be specified at the plug-in module and ORU levels. Maintenance and support of a system should involve two-tier maintenance echelons. The first level provides for repair of the end-item on-orbit by replacing select faulty or defective plug-in modules and ORUs identified through use of specified diagnostic procedures. Faulty ORUs should then be evacuated to the second level of the maintenance echelon (depot level), which will be at a NASA Center for repair if deemed necessary. The particular NASA center/ facility should act as the depot for repair of faulty items.

Skill Level Requirements
Hardware should be designed to aid on-orbit and ground maintenance, inspection, and repair. Special skills should not be required to maintain a system. The following design

features should be incorporated:

• Plug-in module and ORU design to minimize installation/removal time and requirements for hand tools, special tools, and maintenance skills.

• Plug-in modules and ORUs should be designed for corrective maintenance by removal and replacement.

• Plug-in module and ORU designs requiring preventive maintenance should be optimized with respect to the access, maintenance hours, and maintenance complexity.

• Software and its associated hardware should be designed so that software revisions/corrections can be easily installed on-orbit with minimum skill level requirements.

• Flight crew training for payload flight operation should identify hands-on crewmember training, at the NASA center where the system is built, to familiarize crewmembers with the removal/replacement of hardware.

Spares Philosophy

Two basic types of spares should be required to support a maintainable system: development spares and operational spares. Development spares are those that must be identified and acquired to support planned system test activities, integration, assembly, check-out and production. Operational spares are those spares that must be acquired to support on-going operations on-orbit.

The quantity of development spares required for each system, and the total quantities to sustain the required availability during the planned test activities, integration, assembly, and check-out test should be determined according to the following:

• Custom-made components/parts
• Long-lead time items

The quantity of spares required for each system and the total quantities to sustain the required operational availability on-orbit should be determined according to the following:

• Items that are critical to system operation
• Items that have high failure rate
• Items that have limited life

In the initial spares provisioning period and to the maximum extent practical, spares should be purchased directly from the actual manufacturer; i.e., lowest-tier subcontractor, to eliminate the layers of support costs at each tier. The initial provisioning period should cover early test and evaluation, plus a short period of operation, to gain sufficient operational experience with the system. This will provide a basis for fully competitive acquisition of spares.

Spares with limited shelf life should be identified and should be acquired periodically to ensure that adequate quantities of spares are available when needed. Spares with expired shelf lives should be removed and replaced.

Procurement of spares should be initiated in sufficient advance of need to account for procurement lead time (administrative and production lead time).

The location of the spares inventory (on-orbit and on-ground) should be a function of the on-orbit stowage allocation capabilities and requirements. A volume/weight analysis should be conducted to determine the quantity and types of spare items necessary to sustain satisfactory operational availability. The volume/weight analysis shall

assure available or planned payload volume and weight limits, and planned or available on-board stowage area.

Breakout should be addressed during initial provisioning and throughout the replenishment process in accordance with NMI 5900.1, Reference 1. Breakout is the spares procurement directly from the original equipment manufacturer, prime contractor, or other source, whichever proves most cost-effective. A spare item requirement list should be maintained by procurement and technical personnel.

Diagnostic/Testing Principles and Concepts

The system should meet the following failure detection requirements as a minimum:

• The system should have the capability to detect, isolate and support the display of failures to the plug-in module level. Crew observations may be used as a method of failure detection of the following: visual displays, keyboards/buttons, general lighting, speakers.

• System design should provide the capability for monitoring, checkout, fault detection, and isolation to the on-orbit repairable level without requiring removal of items.

• Manual override and/or inhibit capability for all automatic control functions should be provided for crew safety and to simplify checkout and troubleshooting.

• All failures of the system should be automatically detected and enunciated either to the flight crew or the ground crew.

• Accesses and covers should be devoid of sharp corners/edges and be equipped with grasp areas for safe maintenance activities.

• Systems/subsystems/items should be designed

to be functionally, mechanically, electrically, and electronically as independent as practical to facilitate maintenance.

The concept should also describe operating/testing techniques to identify problems and consider the complexity of the various types of items in the space system and associated maintenance personnel skills (for all software, firmware, or hardware). The techniques will identify maintenance problems. In all cases of fault simulation, the safety of personnel and potential damage to system/equipment should be evaluated in the concept. The concept should request that a safety fault tree analysis be the basis for determining simulation. Also, a Failure Modes, Effects, and Criticality Analysis should be used to evaluate and determine fault simulation. Some of the fundamental maintenance actions to be evaluated, monitored, and recorded are as follows:

• Preparation and visual inspection time
• Functional check-out time
• Diagnostic time: fault locate and fault isolate
• Repair time: gain access, remove and replace, adjust, align, calibrate, and close access
• Clean, lubricate, service time
• Functional check-out of the repair action

Responsibilities for Contractor Maintenance

The prime contractor's maintainability program should provide controls for assuring adequate maintenance of purchased hardware. Such assurance is achieved through the following:

• Selection of subcontractors from the standpoint of demonstrated capability to produce a maintainable product.

- Development of adequate design specifications and test requirements for the subcontractor-produced product.

- Development of proper maintainability requirements to impose on each subcontractor.

- Close technical liaison with the subcontractor (both in design and maintainability areas) to minimize communication problems and to facilitate early identification and correction of interface or interrelation design problems.

- Continuous review and assessment to assure that each subcontractor is implementing his maintainability program effectively.

Responsibilities for Payload Maintenance

Director of field installations responsible for launch preparation, maintenance, or repair activities should be responsible for maintenance planning and for providing the resources necessary to support the efficient identification of maintenance related problems in accordance with system requirements. These responsibilities include:

- Implementing a system that will identify, track, and status problems related to routine maintenance activities attributable to the design characteristics of flight hardware and software.

- Providing information for use in a data collection system to improve the accuracy of quantitative maintainability and availability estimates. This information can be used to identify failure trends influencing reliability growth characteristics during design and to communicate "lessons learned" from ground maintenance experience.

- Recommending to the Program Manager, responsible for design and development of flight hardware/ software, areas for design improvement to increase the efficiency in

ground processing or maintenance operations. The rationale for supporting these recommendations should include factors such as reduction in ground turnaround time and operational support costs.

Allocation of Crew Time for Maintenance Actions

Crew time for maintenance should be identified in accordance with system complexity, reliability, and criticality of the items to the system and mission requirements. Analytical methods exist which can be used to prioritize and allocate crew time for maintenance actions.

References

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Design Factors and Engineering

The objective of the Maintainability function is to influence system design such that the end product can be maintained in a cost effective operational condition with minimum downtime. In order for the Maintainability discipline to provide maximum influence to a program, design principles to obtain these objectives must be implemented early in the design phase. Techniques that have proven to be beneficial on previous programs are presented in this section as design recommendations for future programs.

Technique	Provide guidelines for the design of maintainable equipment for compatibility with dexterous robots by outlining selection criteria for associated fasteners and handling fixtures.

SELECTION OF ROBOTICALLY COMPATIBLE FASTENERS AND HANDLING MECHANISMS

Optimization of robotics design via selection and use of compatible resources will reduce system downtime and increase availability

Benefits	The application of these guidelines to the design process will increase the effectiveness of dexterous robots by allowing for optimized design of robotics components used during maintenance tasks. In addition, because Extra Vehicular Activity (EVA) tasks performed with robots must be simplified to accommodate robotics dexterity (which is intrinsically inferior to that of a human crew member), robotically compatible designs will facilitate the simplified (less time consuming) EVA tasks. This equates to less system downtime and higher availability for both ground and on-orbit systems.
Key Words	Robotically compatible; maintenance; fasteners; handling fixtures
Application Experience	International Space Station Program
Technical Rationale	The following selection guidelines enable design engineers to identify the criteria required for robotics compatibility and to tailor their specifications to different robotics systems and environments. They provide general concepts for using robotically compatible fasteners and handling fixtures that have been applied on the Space Station program and states the advantages of these concepts.
Contact Center	**Johnson Space Center (JSC)**

Selection of Robotically Compatible Fasteners and Handling Mechanisms
Technique DFE-1

Before designing an ORU or other component for robotics compatibility, the feasibility of such an effort must first be assessed. Some items (e.g., thermal blankets), because of their flexibility, cannot be manipulated by robotics systems. The assessment should show (1) if the ORU or component can be manipulated by a robot, (2) if not, whether a major redesign of the item will be required to make it robot compatible, and (3) what effect the redesign will have on weight and cost (a factor that can be determined by simple analyses).

Reference 1 describes a preliminary analysis that might be used to determine the feasibility of designing for robotics compatibility. Once it is determined that the item can be designed to be manipulated by a robot, it must then be determined how the design relates to and affects the design of (1) other components in the system, (2) the system's layout, and (3) the robotics system with which it will interface.

Figure 1, which illustrates the process for redesigning for robotics compatibility as detailed in Reference 1, shows the sequence by which the design of items higher in a process flow impact the design of the lower items. Although the sequence may be altered, the alteration may result in increased costs, in schedule delays, and in less flexibility in applying robotics compatibility. The bidirectional arrows indicate processes that should be performed using an integrated approach that considers the impacts the ORU, system, and robot design have on each other. Once the above mentioned analysis is performed and design of the robotically compatible fasteners or handling fixtures is begun, the objectives then must be to:

- Provide for alignment.
- Avoid jamming and binding.
- Withstand the loads that may be imparted by the robotics systems.
- Provide adequate access.
- Simplify the operation.
- Assist ORU alignment and softdock and harddock functions. "Softdock" is defined as the initial temporary attachment between two or more pieces of equipment to prevent inadvertent release prior to permanent attachment.

Reference 2 lists a number of guidelines and requirements that may be applicable to designing for robotics compatibility of Space Station hardware. Reference 3 lists a number of different robotically compatible fasteners and handling fixtures for Space Station use. The purpose of this technique, however, is to assist designers in applying the stated concepts to their system ORU's and not to list contractual requirements. The six design objectives for fastener and handling fixture design requirements are addressed in the following section.

FASTENER AND HANDLING FIXTURE DESIGN REQUIREMENTS

Provide for alignment
Alignment provisions may be implemented as (1) markings, (2) alignment guides, and (3) design of the robotics system and its control system. Only the second of these options, alignment guides, is addressed in this section. Markings and robotics system designs are described in References 1, 2, and 3.

Fasteners
There are more options available for aligning fasteners than there are for handling fixtures. For example, fasteners are captive and are an integral part of an ORU. Therefore, if the ORU contains proper alignment features and is
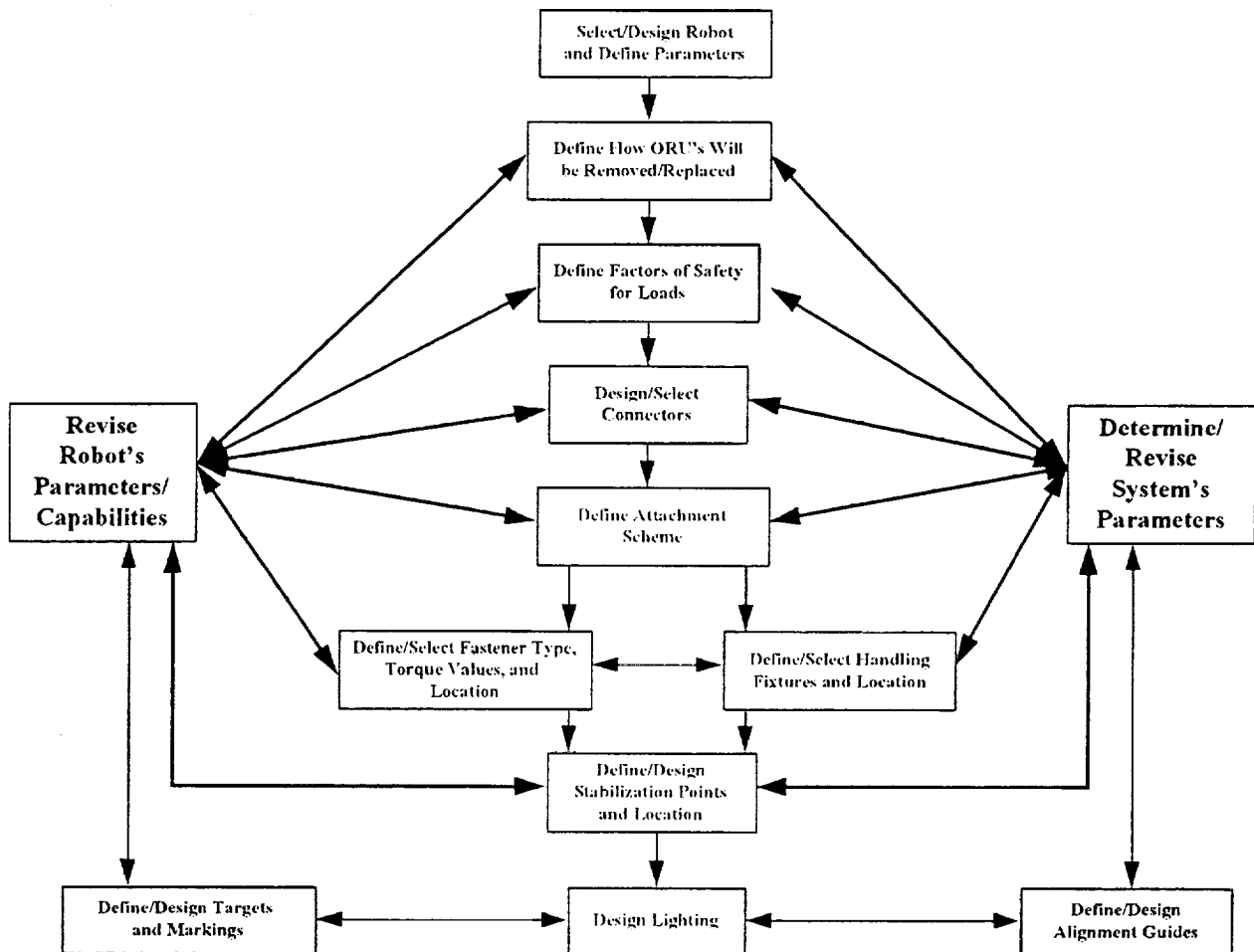
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                    ┌─────────────────────┐
                    │  Select/Design Robot │
                    │ and Define Parameters│
                    └─────────────────────┘
                               │
                    ┌─────────────────────┐
                    │  Define How ORU's Will│
                    │ be Removed/Replaced  │
                    └─────────────────────┘
                               │
                    ┌─────────────────────┐
                    │ Define Factors of Safety│
                    │      for Loads       │
                    └─────────────────────┘
                               │
                    ┌─────────────────────┐
                    │    Design/Select     │
                    │     Connectors       │
                    └─────────────────────┘
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                    ┌─────────────────────┐
                    │  Define Attachment   │
                    │       Scheme         │
                    └─────────────────────┘
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┌─────────────┐   ┌─────────────┐
│ Revise   │   │ Determine/ │
│ Robot's   │   │ Revise   │
│ Parameters/ │   │ System's   │
│ Capabilities│   │ Parameters │
└─────────────┘   └─────────────┘

┌──────────────────────┐   ┌──────────────────────┐
│ Define/Select Fastener Type,│   │ Define/Select Handling│
│   Torque Values, and │   │ Fixtures and Location│
│   Location   │   └──────────────────────┘
└──────────────────────┘

┌──────────────────────┐
│   Define/Design   │
│ Stabilization Points │
│   and Location   │
└──────────────────────┘

┌──────────────────────┐   ┌──────────────────────┐   ┌──────────────────────┐
│ Define/Design Targets│   │   Design Lighting   │   │   Define/Design   │
│   and Markings   │   │   │   │   Alignment Guides   │
└──────────────────────┘   └──────────────────────┘   └──────────────────────┘

Figure 1. Process for Robotics Compatibility Design

properly aligned and inserted, the fasteners will be properly aligned as well. However, since handling fixtures are grappled independent of the insertion and alignment of the ORU, the incorporation of alignment features is confined to the fixture and end effector. The ORU alignment feature design, which is discussed in References 2 and 3, is an important

consideration, since it can lessen fastener complexity. The alignment techniques being used for Space Station fasteners are described below.

Alignment of Tool to Fastener Head

Robotic testing has shown that, provided there is proper visual contrast between the fastener head and the surrounding structure, a 7/16- inch fastener with a flat head can be easily captured by the robotics end effector (nut driver). Earlier concepts specified or recommended rounded heads because it was believed the rounded head would accommodate greater misalignment tolerances. It was found, however, that a flat-headed fastener provided the robot with the same misalignment tolerances as the same fastener with a rounded top.

Alignment of Fastener to Nut

The bolt is aligned to a nut by tapering the end (pilot) of the bolt and by having a cone or countersink around the nut. For fasteners that form an assembly or that are, in Space Station terminology, "attachment mechanisms," there are housings which contain tapered "fingers."

Handling Fixtures

The two alignment techniques for Space Station handling fixtures are described below.

V-slot Insertion

The V-slot insertion technique is used with the microfixture and H handle, which interface with the Special Purpose Dextrous Manipulator (SPDM) end effector or the ORU tool changeout mechanism (OTCM). The OTCM fits as a V into the grooves of the H handle closes its V-shaped grooves around the corners of the microinterface (see reference 2 for a detailed description). The positional misalignment tolerance allowed for the H fixture is approximately 0.5 inch with angular misalignment tolerance of about ±2°. The

microfixture allows positional misalignments of about 0.3 inch and angular misalignments of about ±3°.

Cylinder-over-cone

The microconical tool slips over and attaches collets to the microconical interface, which is shaped like a cone. The allowable translational and angular misalignment tolerances for the microconical tool are 0.25 inch and ±1°, respectively.

AVOID JAMMING AND BINDING

Fasteners

Once alignment is accomplished and the fastener begins to enter the nut, there is still the possibility of cross-threading. Cross-threading can be avoided by aligning the nut using the unthreaded portion on the bolt, and it can also be avoided by using an expandable thread diameter nut; i.e., a Zipnut. A Zipnut consists of three separate segments within a housing that, when assembled, form the internal threads of a nut. The segments are held against the threads of a bolt or screw by springs that force them to a minimal diameter, and a ramp that allows them to separate or come together, depending on the direction in which the bolt is inserted. When a bolt is inserted, the segments are allowed to slide back and away, allowing the bolt to slide through without obstruction. This type of nut is described in detail in Reference 2.

Handling Fixtures

When using robotically compatible handling fixtures which apply the slot in the V-groove concept as described above (i.e., the microinterface or X handle), care must be taken that the corners are rounded. This precaution must be taken to keep the handle from binding to the end effector, as happened in the JSC robotics laboratories with the first H handle concept which had sharp corners.

The corners of the H handle (renamed the X handle) were rounded, and the binding effect was thus eliminated.

WITHSTAND LOADS THAT MAY BE IMPARTED BY ROBOTICS SYSTEMS FOR FASTENERS AND HANDLING FIXTURES

SSP 30000, table 3-3, "Factors of Safety," specifies that for metallic flight structures, the general factor of safety is a yield of 1.25 and an ultimate of 2.00.

PROVIDE ADEQUATE ACCESS

Fasteners
Adequate access for fasteners is provided by designing a proper layout of the system as described in reference 3. The fastener selection (or fastening scheme) can be influenced by the robotics access if more than 1 degree of freedom is required by the robot to engage and disengage the fastener. A lever, for example, requires more than 1 degree of freedom and therefore requires significantly more access space to operate than that required to engage a bolt. In addition, the higher the torque value, the larger the end effector (motor), lessening the allowable robotics access space. For Space Station, no levers will be used by robots.

Handling Fixtures
Certain small Space Station ORU's are being placed so close to each other that inadequate access space is provided for the robot to open its jaws around the interface. The problem was resolved by using the microconical interface that snaps around the interface in a "stabbing" motion. By using a tool that does not require jaws to open around an interface; i.e., the microconical tool, the required access space is significantly reduced.

Simplify the Operation Fasteners
The robotics operation can be simplified by the following methods:

Use Captive Fasteners
Use of captive fasteners is the best method for simplifying robotics operation. This eliminates the need for the robot to carry and insert the fasteners and thus increases the probability of mission success.

Reduce Number of Operations
The type of fastener selected can reduce the number of operations required. For example, using the Zipnut eliminates the need for rotation, since the bolt can be slid through the nut and then tightened with a single rotation.

Choose Proper Forms of Fastening
Forms of fastening that require the robot to use more than 1 degree of freedom should be eliminated. Levers, for example, not only will increase the access space requirements (as described previously), but may also necessitate force moment accommodation and more complex control software.

Avoid Fasteners Requiring Excessive Torque
To engage fasteners that require excessive torque (i.e., 50 foot-pounds or over), the robot must stabilize itself with one arm, constricting the allowable configurations for removing and replacing the ORU. This necessitates additional hardware for robot stabilization. In general, care must be taken when using robotic systems for fasteneing due to the reaction forces that will be present.

Reduce Sizes and Types of Fastener Heads
Using different sizes and types of fastener heads will reduce the number of tools required by the robot.

Handling Fixtures
The grasping of the interface can be simplified by allowing the robot to grasp the interface from a number of different orientations. For

example, the microinterface and the microconical interface can be grasped from two different orientations of the OTCM relative to the handling fixture, while the X handle can only be grasped from one orientation. There may be some instances, however, in which it would be advisable to limit the allowable orientations. For example, if the robot can grasp an ORU from only one orientation, there is less chance that the ORU will be improperly inserted in its base plate.

ASSIST ORU ALIGNMENT AND SOFTDOCK AND HARDDOCK FUNCTIONS

Fasteners
When designing robotically compatible ORU's, the alignment guides and softdock features may be incorporated as part of the ORU, or fasteners with these features may be designed or selected. Softdock fasteners are thus more complex and are called "attachment mechanisms" in the Space Station Program. Alignment and softdock functions are described below.

Alignment Functions
If alignment features are lacking for the ORU, they can be incorporated via the tapering of pins, or fingers, located on the housings of the attachment mechanisms.

Softdock Functions
For the Space Station Freedom Program, attachment mechanisms achieve softdock either through the use of detents that are housed on an outer casing of the attachment mechanisms or via the Zipnut method. The Zipnut is ramped such that if an attempt is made to separate the bolt from the nut, the segments are pulled together allowing the bolt to be removed via rotation only. The Zipnut thereby functions as an excellent softdock attachment.

Handling Fixtures
Alignment and softdock functions are described below.

Alignment Functions
The location of the handling fixture can significantly impact ORU alignment. The further the handling fixture is from the ORU's center of gravity, for example, the more difficult it is for the robot to maintain a line of insertion that will be perpendicular to its attachment plate.

Other factors to be considered when placing handling fixtures are the size of the ORU, the location and type of alignment guides, and the placement of fasteners. These items are discussed in Reference 3 because of their dependence on ORU features.

Softdock Function
Softdock features may be used to prevent an ORU from "floating away" prior to its being fastened. This may also be achieved by fastening the ORU without releasing the handling fixture. The three above mentioned handling fixtures for Space Station have holes in their centers for fasteners, which allows the OTCM to grasp the ORU, insert it, and then drive the bolt with its nut driver without ever releasing the ORU handle.

References

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2. *Robotics Systems Interface Standards, Volume 2, Robotics Interface Standards* (Draft), SSP 30550.

3. *The Design Process for Achieving Robotics Compatibility*, Contractor Report No. <TBD>.

Technique	Minimize the occurrence and effect of Built In Test (BIT) false alarms by applying principles and techniques that are intended to reduce the probability of false alarms and increase the reliability of BIT in avionics and other electronic equipment.

FALSE ALARM MITIGATION TECHNIQUES

Use techniques such as voting schemes, continuous monitoring, and decentralized architectural design to minimize the occurrence and effects of Built-in-Test (BIT) false alarms

Benefits	Effectively implementing BIT techniques automatically reduces the number of BIT false alarms. Decreasing the number of BIT false alarms increases a system's availability and decreases the maintenance man-hours required. The overall result is a reduction of the system's life cycle cost.
Key Words	Anomalies, Built-In-Test, False Alarms, Circuit Monitoring
Application Experience	International Space Station Program, National Space Transportation System
Technical Rationale	The reliability of a system's BIT can be determined in part by the number of false alarms it experiences. If the BIT can not accurately identify and report the occurrence of failures then the test has failed its mission. Testability must be treated with the same level of importance as other design disciplines. BIT reliability must be considered just as critical as any other performance requirement. A system can not perform its mission if its components are constantly being removed for false maintenance.
Contact Center	**Johnson Space Center**

False Alarm Mitigation Techniques
Technique DFE-2

In order to mitigate false alarms, a system's Built In Test (BIT) circuitry must be able to cope with a limited amount of anomalous performance. NASA Handbook 5300.4 (1E) defines a false alarm as "an indicated fault where no fault exists." Based on this definition, this technique is concerned only with BIT indications of system malfunction which cause unnecessary maintenance actions. The inability of a system to detect or report the occurrence of a failure, a "fails to alarm condition", is not a false alarm and is not addressed.

BIT should be designed to distinguish between actual failures and anomalies which must be tolerated due to adverse operating conditions or that are normal anomalies within acceptable limits. To accomplish this, the following principles and techniques must be mandated in the system specifications, requirement documents, and design policies and implemented in the system design.

Voting Scheme
One technique is called the "Voting Scheme." With the voting scheme, all test data are analyzed by three or more different computers. A failure is declared only when a majority of the computers detect the same failure. An example of this type of architecture is the Space Shuttle Orbiter Avionics System. The five General Purpose Computers (GPCs) are all interconnected to the same 28 serial data channels. The GPCs perform all system-level processing and require a majority agreement on all test signals. This technique requires an extensive use of resources but is extremely effective at mitigating false alarms. A less complicated version of this is the use of double or triple redundant monitors. Having two or more sensors in series increases the reliability of more sensors in series increases the reliability of

the test data reported while only requiring a single computer or processor.

Continuous Monitoring
Continuous monitoring with BIT filtering can be used in place of the voting scheme. With this technique, BIT results are based on a integration of successive measurements of a signal over a period of time instead of a single check of the signal. The monitoring of the signal does not have to be continuous but only sampled over the time period. The filtering involves comparing the current reading of a signal with past and future readings of the same signal. This filtering allows for the disregarding of sporadic out-of-limit measurements. Only when a signal is out-of-limits for a predefined time limit or a sequence of tests identify the same failure, should the BIT flag be set.

To maximize the effectiveness of continuous monitoring, the BIT data must be recorded. Once recorded, the data need to be summarized and evaluated so that trends can be tracked and weaknesses identified. To help manage all this data, controls should be implemented. The number of signals monitored and the maximum sample rate can be limited. The time span over which data are collected should be set at a reasonable period, and the type of data accumulated should be restricted. Finally, computing techniques can be used that do not require the storage of old data. Once the information is gathered, a failure log should be created.

This failure log is the basis for future modifications to the system's BIT. To improve the BIT, every instant of anomalous performance not related to an identified failure mode should be analyzed and the root causes identified. Some form of corrective action must be taken to avoid recurrence. If a design change cannot be made, then the BIT must be

modified to accommodate the non-failure causing anomaly.

The need for modification requires BIT to be flexible. Test parameters and limits must be easily changed. The operator should be able to control or even change the test sequence. This flexibility allows the necessary changes in the BIT to be made if false alarms start occurring. For example, the Space Station's Command and Data Handling System uses programmable Deadman Timers in the multiplexer/ demultiplexer (MDM's) and standard data processor (SDP's). The response intervals of the timers can be adjusted by the system controller to accommodate changes in system configuration or mode of operation. However, the BIT software must be changed without disturbing the system operation. For this to be possible, the BIT software must be independent of the operating software.

Decentralized Architecture
Another technique for mitigating false alarms is the use of a distributed or decentralized BIT architecture. With this approach the BIT is implemented so that a "NO GO" on a given test directly isolates the implied failure to a replaceable unit. Locating most of the BIT internal to a unit greatly reduces the possibility of incorrect isolation of a failure. Although the decentralized BIT concept consists primarily of unit level tests, some system level testing is still required.

An excellent technology for combining unit level testing with system level testing is boundary scan. Boundary scan is the application of a partitioning scan ring at the boundary of integrated circuit (IC) designs to provide controllability and observability access via scan operations. In Figure 1, an IC is shown with an application logic section, related input and output, and a boundary scan path consisting of a series of boundary scan cells (BSC), one BSC per IC function pin. The BSCs are interconnected to form a scan path between the host IC's Test Data Input (TDI) pin and Test Data Output (TDO) pin, for serial access.

During normal IC operation, input and output signals pass freely through each BSC, from the Normal Data Input (NDI) to the Normal Data Output (NDO). However, when the boundary test mode is entered, the IC's boundary is partitioned in such a way that test stimulus can be shifted in and applied from each BSC output (NDO). The test response can then be captured at each BSC input (NDI) and shifted out for inspection. Internal testing of the application logic is accomplished by applying test stimulus from the input BSCs and capturing test response at the output BSCs. External testing of wiring interconnects and neighboring ICs on a board assembly is accomplished by applying test stimulus from the output BSCs and capturing test response at the input BSCs. This application of a scan
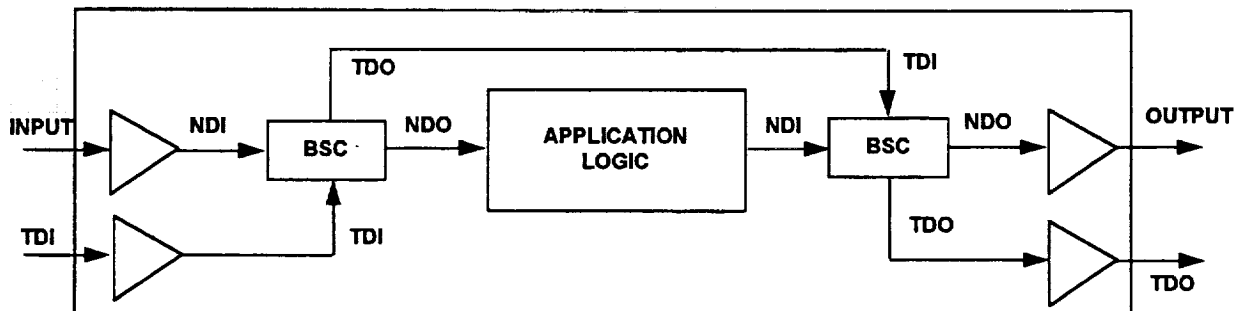
Figure 1: Built In Test Architecture

path at the boundary of IC designs provides an embedded testing capability that can overcome test access problems. The unit level tests can also be combined for a subsystem or system level verification (Figure 2). More details on applying these techniques are in IEEE Standards 1149.1 "Boundary Scan" and 1149.5 "System and Maintenance Bus."

Finally, high-reliability components should be used in the design. The reliability of the BIT hardware should at least equal or exceed that of the hardware it is testing. The BIT software also needs to be thoroughly tested and verified to ensure that it will not be a source of false alarms. Accordingly, adequate amounts of effort and resources must be allocated during the design phase. The designer should not be unduly limited by memory size, component count, or any other allocated resource.

These guidelines are not all inclusive. The false alarm problem is very complex. Each system is unique and must be approached differently. The best approach is simply to eliminate each factor as it is identified.

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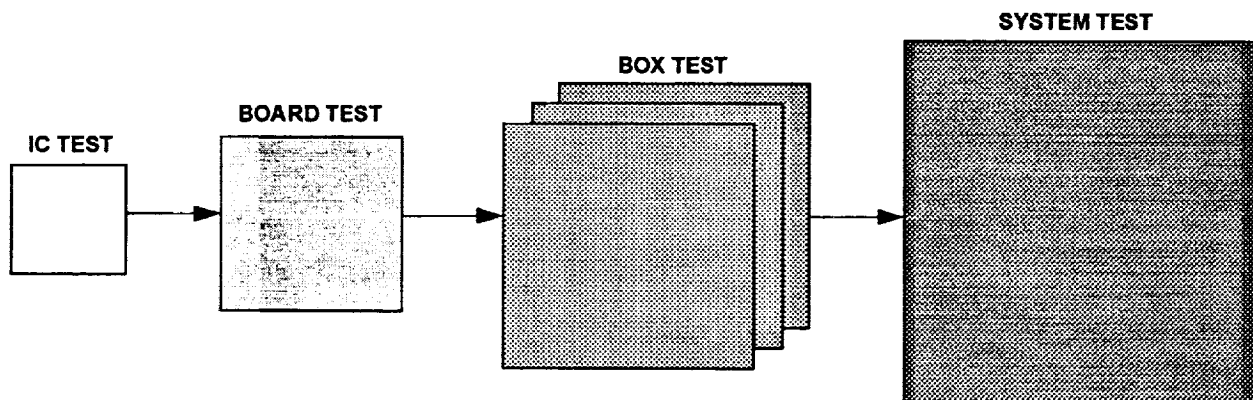
Figure 2: Typical Test Regimen for Space Systems

Analysis
And
Test

Maintainability analysis is a very important part of the design process in which aspects of the maintenance concept are quantified and design decisions are made based on results. Hardware and Software testing not only verifies that the item(s) in question will perform within the specific environment, but also allows for maintenance items to be identified and verifies maintainability design features. The techniques contained within this section describe a wide range of analysis and test processes used within the NASA community and should provide a vehicle for education, communication, and continuous improvement.

Technique	Simulate on-orbit space maintenance activities by using a neutral buoyancy facility to assist in making design decisions that will ensure optimum on-orbit maintainability of space hardware.

NEUTRAL BUOYANCY SIMULATION OF ON-ORBIT MAINTENANCE

Neutral buoyancy simulation provides an effective means for making maintainability design decisions and verifying maintenance actions

Benefit	Neutral buoyancy simulation can provide valuable information for designing-in accessibility, modularity, simplicity, and standardization. It can also provide cost-effective, specific design information on the effectiveness of crew stability aids, crew maneuvering aids, specialized tools, and operational timeliness. Maintainability criteria that can be established by utilizing this process include: component accessibility; fasteners accessibility, systems installation; and the configuration and operation of crew stability aids and tools.
Key Words	Neutral Buoyancy Simulation, Maintainability Design Criteria, Space Maintenance Activities, On-Orbit Maintainability, Simulated Weightless Environment, Orbital Maintenance Special Tools, ORU
Application Experience	Skylab, Hubble Space Telescope, Space Shuttle Orbiter, International Space Station, Apollo
Technical Rationale	Equipment and crew interface testing in a simulated weightless environment at an early development stage in NASA programs is an accurate means of assessing hardware and tool design features and determining crew capabilities and requirements. While other forms of weightlessness simulations (e.g., parabolic flight, motion base, and computer models) have proven effective in specific applications, underwater simulations have proven particularly beneficial in hardware development, crew/hardware interface design, and operations planning, since they can accommodate a large worksite volume and extended test times.
Contact Center	**Marshall Space Flight Center (MSFC)**

Neutral Buoyancy Simulation of On-Orbit Maintenance
Technique AT-1

The neutral buoyancy facility at MSFC has been used since 1968 to effectively simulate the weightlessness of space, and has assisted in the establishment of maintainability design criteria, particularly in extravehicular activity (EVA). Use of full-scale neutral buoyancy simulations has also allowed for direct human participation in test operations, as well as for access to the large body mock-up hardware developed for EVA simulations. These methods are a very effective way of simulating on-orbit environments for the purpose of verifying and solidifying operations and maintenance procedures.

Other neutral buoyancy facilities used for NASA hardware development and test and crew training are the Weightless Environment Test Facility (WETF) at Johnson Space Center, the Neutral Buoyancy Research Facility at the University of Maryland, College Park, Maryland and the neutral buoyancy facility at McDonnell Douglas, Huntington Beach, California.

Neutral Buoyancy Characteristics

The MSFC neutral buoyancy facility has the following overall characteristics:

- Six-console control room.

- Three-person, double-lock hyperbaric chamber.

- Floating crane for underwater movement of hardware (one 2000-pound hoist, one 500-pound hoist).

- Removable roof section to accommodate large hardware.

- T.V. monitors, communications with test subjects, audio/video taping capability, pressure and depth displays of test subjects, and lightning warning systems.

- Support of up to four Shuttle space suited crew members.

- Umbilical-supplied underwater primary life support systems.

- Operational Remote Manipulator Systems (RMS).

- Air-lock for emergency test subject evacuation.

The neutral buoyancy tank within the facility is a 1.3 million-gallon water tank that measures 40 ft. deep and 75 ft. in diameter. The water temperature is maintained at a range of 88 to 92 degrees Fahrenheit and a pH of 7.50. Cathodic protection systems are used to inhibit corrosion. The tank accommodates up to four pressure-suited test subjects simultaneously. Extravehicular Mobility Units are available for four test subjects. The tank can accommodate test durations of up to 6 hours.

HST Simulations

Underwater simulations in the neutral buoyancy facility strongly influenced the maintainability design criteria for the Hubble Space Telescope (HST) and its components; particularly with regard to visibility, accessibility, and simplicity. One of the primary considerations in maintainability of space hardware is the accessibility of components and systems by crew members during EVA. To be maintained in space, the components of a hardware item must be seen and reached by a pressure-suited astronaut or be within range of the appropriate tools.

Altogether, some 70 Orbital Replacement Units (ORUs) on the HST can be replaced on-orbit. Some of the largest ORUs are batteries, computers, reaction wheel assemblies, science instruments, fine guidance sensors, and wide field planetary cameras. One of the telephone-booth-sized science experiments weighs over 700 pounds. These items are mounted in equipment bays around the perimeter of the spacecraft. The bays open with large doors so components can be readily inspected and handled. Using neutral buoyancy simulations, design features of these components were validated, verified, and refined to ensure that the ORU features of modularity, accessibility, and simplicity were inherent in the design. Other features included a series of crew stability aids; including handrails, portable handles, tether attachments, and foot restraints. Neutral buoyancy simulation studies also determined the placement of foot restraints on both the HST and the RMS arm for maximum accessibility. These design features give the crew mobility and stability during unstowing, transporting, and stowing ORUs.

Door latch design criteria were also addressed in neutral buoyancy simulations involving the HST. All internally stowed ORUs except the Radial Science Instrument are concealed by doors that must be opened and closed by a crew member before ORUs are installed or removed.

Simulations and Design Influence
A design criterion that has become increasingly important in on-orbit maintenance and which has been studied using neutral buoyancy simulation is standardization of the EVA interface to ORUs. The practice of standardization became a key issue in HST development with the decision to mount ORUs with 7/16-

inch double height hex head bolts in three types of fittings: J-hooks, captive fasteners, and keyhole fasteners. Neutral buoyancy simulations have proven that the use of standardized bolt heads, clearances, and torque limits reduces the complexity of ORU maintenance in space. To achieve electrical connector standardization, neutral buoyancy simulation studies have evaluated such criteria as connector geometry (wing-tab presence, length, and diameter) and surface texture (knurls, ridges, and irregular shapes). Response variables studied included ease of alignment, firmness of grip, and level of torque required to lock the connectors. Studies of this type led to the development of a standard for blind-mate, scoop-proof, low-force, and subminiature connectors. If accepted as a standard, these connectors would be used in the Upper Atmosphere Research Satellite, Explorer Platform, International Space Station, and in robotic manipulators.

Human factors studies have been a significant part of neutral buoyancy simulation tests with large space structures. For example, experiments have been conducted to determine the effect of fatigue on productivity during lengthy EVA structural assembly operations. An experienced test subject assembled a 36 element tetrahedral truss structure repeatedly for 4 hours, while the subject's heart rate and general conditions were monitored. These neutral buoyancy simulations demonstrated EVA productivity to be significantly higher in space than in comparable conditions simulated in ground tests. Assembly time for structural assembly tasks was approximately 20 percent less in actual flight. The Experimental Assembly of Structures in EVA (EASE) project, an experiment flown on Space Shuttle mission STS 61-B, revealed that a flexible structure can be

assembled in underwater conditions with a learning curve of 78 percent. It was determined that learning rate is independent of the strength, coordination, or size of the test subject; or the fit of the pressure suit.

Structural configurations have been used at the MSFC neutral buoyancy simulator to obtain human factors data. In one experiment, six-element tetrahedrons were used to obtain data on learning and on the relative value of a variety of assembly aids. The structural elements in these tetrahedrons were 11-foot-long tubes of PVC plastic, 4 inches in diameter. Sleeve-locking connectors were used to join the beams at the nodes of the structure, or "joint cluster." Much more complex structures were used to collect information on fatigue, and on crew members' ability to deal with complicated configurations and hardware. A single 36-element tetrahedral truss served as a baseline structure for comparing single-person assembly with two-person assembly, for quantifying productivity changes due to the use of various assembly aids, and for evaluating other structural configurations.

Results of structural assembly experiments have shown that test subject learning rate is much higher in the weightless conditions of neutral buoyancy than in conditions on dry land. The most time-consuming task during assembly operations is aligning the beams. This large time consumption is due to the kinematics of water drag. Fatigue is not a significant factor in the assembly process if the subjects pace themselves. None the less, the following considerations must be taken when running a simulation to avoid problems:

- Assign two safety divers per test subject to manage the umbilical and monitor the test subjects performance.

- When possible, conduct paper computer simulations, and one-g dry run simulations prior to neutral buoyancy simulations.

Principal Limitations

The principal limitations of neutral buoyancy simulations include: (1) the need to design hardware to accommodate the effects of water corrosion, (2) varying water pressure with depth, and (3) frictional resistance of the water to body and equipment movement.

The impact of not taking full advantage of the neutral buoyancy simulation capabilities at MSFC and other locations could mean entering a space mission without full knowledge of the effects of weightlessness on mission tasks, particularly in EVA's. Maximum emphasis should be placed on conducting simulations with the highest fidelity possible to ensure mission success. Failure to do so results in a greater probability of incurring safety hazards, anomalies, increased maintenance resources (man-hours), and hardware damage.

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Technique	Predict the mean time to repair (MTTR) of avionics and ground electronics systems at any level of maintenance (on orbit, intermediate or depot level) using analytical methods . This technique assumes a constant failure rate, and should be used accordingly.

MEAN TIME TO REPAIR PREDICTIONS

Use mean-time-to-repair predictions for early life cycle assessment of system maintenance requirements and as a good metric for trade study alternatives

Benefits	The predictions can be used to highlight those areas of a system that exhibit poor maintainability in order to justify improvement, modification, or a change of design. They also permit the user to make an early assessment of whether the system predicted downtime and logistic requirements are adequate and consistent with the system operational requirements and allocations.
Key Words	Maintainability Parameter, Mean Time To Repair (MTTR), Space Prediction, Failure Rate, Maintenance Action
Application Experience	International Space Station Program
Technical Rationale	This MTTR prediction technique is a fast, simple, accurate and effective approach for providing a design baseline for repair times. Design and product assurance engineers can use the MTTR data to effectively define sparing, logistics and maintenance programs for a pending design.
Contact Center	**Johnson Space Center (JSC)**

Mean Time to Repair Predictions
Technique AT-2

In general, the MTTR of a system is an estimated average elapsed time required to perform corrective maintenance, which consists of fault isolation and correction. For analysis purposes, fault correction is divided into disassembly, interchange, reassembly, alignment and checkout tasks. The repair time of a maintainable unit generally consists of both a large number of relatively short-time repair periods and a small number of long-time repair periods. The former would correspond to the more usual case where the failed unit is replaced by a spare at the operational site on detection of a failure. The long downtimes would occur when diagnosis is difficult or removing a defective part is complicated due to, for instance, rusted/stripped mounted nuts. Having a collection of such field data provides the design engineer an opportunity to assess the Mean Time To Repair (MTTR) of the current system as it matures, or to predict the MTTR of a new system according to its features with the current system.

MTTR is a useful parameter that should be used early in planning and designing stages of a system. The parameter is used in assessing the accessibility/locations of system components; for example, a component that often fails should be located where it can easily be removed and replaced. The estimated MTTR may also dictate changes in system designs in order to meet the turn-around time criteria for critical systems, such as communication and life support systems on the Space Station. In addition, the parameter helps in calculating the life cycle cost of a system, which includes cost of the average time technicians spend on a repair task, or how much Extravehicular Activity (EVA) time is required for astronauts to repair a system.

MTTR is defined as the average time necessary

to troubleshoot, remove, repair, and replace a failed system component. An interval estimator for MTTR can be developed from the mean of the sample data, within a lower and a upper limit with a confidence bound. For example, from a sample data set, one can find with 90-percent confidence that the range 3.2 to 4.2 will contain the population mean. Unfortunately, the exact MTTR of a system can never be found due to data uncertainties.

Log-Normal Distribution
The distribution most commonly used to describe the actual frequencies of occurrence of system repair time is the log normal because it reflects short duration repair-time, a large number of observations closely grouped about some modal value, and long repair-time data points. The general shape of log normal distribution is shown in Figure 1.

Without getting involved in the derivation of the distribution equations which can be found in any statistical textbook, the following example will illustrate how MTTR of a replaceable unit may
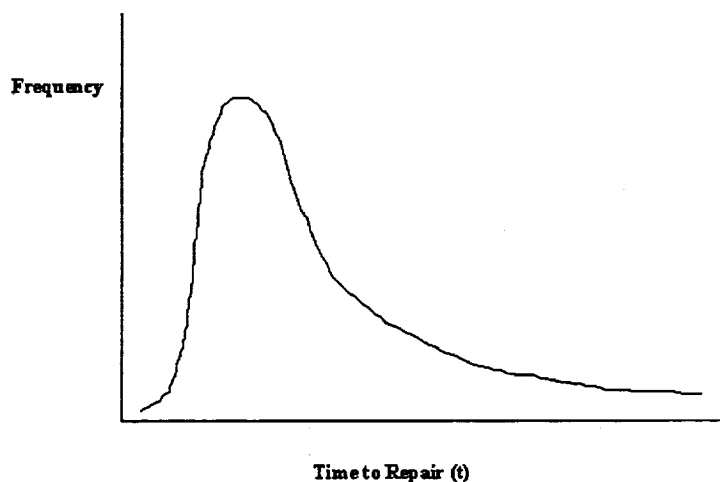
Figure 1: Lognormal Distribution

be calculated from a finite observed set of data.

Example 1: The repair times t_i for an orbital replaceable unit (ORU) are observed to be 1.3, 1.5, 1.7, 1.8, 2.2, 2.6, 3.0, 3.1, and 3.9 hours. Using log normal distribution to estimate the MTTR of the unit.

Solution:

$$t_i' = \ln t_i \tag{1}$$

Utilizing statistical methods, the Maximum Likelihood Estimator (MLE), or the best estimated value of the mean is:

$$\overline{t'} = \frac{1}{n}\sum_{i=1}^{n} t_i' \tag{2}$$

Then, $\overline{t'} = 0.79124$

The Maximum Likelihood Estimator of the variance is:

$$s'^2 = \frac{1}{n-1}\sum_{i=1}^{n} (t'_i - \overline{t'})^2 \tag{3}$$

Then, $s'^2 = 0.1374$

$$\mu = MTTR = e^{(\overline{t'} + \frac{s'^2}{2})} \tag{4}$$

$$= e^{(0.79124 + \frac{0.1374}{2})} =$$

Therefore, the mean of the log normal distribution of this example is:
and its variability of time to repair is:

$$= MTTR \sqrt{(e^{s'^2} - 1)} \tag{5}$$

$$= 2.36\sqrt{(e^{0.1374} - 1)} = 0.90 \ h$$

How to Implement the MTTR Process

Accurately estimating the MTTR of a new system is more than applying the derived formulas on field data of any existing systems. The designer must know the overall maintenance concept and operating conditions of the new system; for example, how and where the system is going to be operated and how its failed units will be swapped out. With this background, the designer can proceed to approximate the maintenance procedure of the new system, then select an existing system that has been exposed to similar operating conditions and that has a mature set of operating data. After the similarity between the two systems is assessed, the designer then can determine certain conversion factors needed to make the existing system data more applicable to the new system. Once this is done, the predictions for the new system are more meaningful and accurate.

Elements of MTTR

The MTTR prediction of a system begins at the replaceable unit level (RUL) where a defective unit is removed and replaced in order to restore the system to its original condition. Then the system MTTR predictions are accomplished by integrating the MTTR's of maintainable units. The following defines the elements used in the MTTR prediction of a system:

Fault Isolation: Time associated with those tasks required to isolate the fault to the item.

Disassembly: Time associated with gaining access to the replaceable item or items identified during the fault correction process.

Interchange: Time associated with the removal and replacement of a faulty replaceable item or suspected faulty item.

Reassembly: Time associated with closing up the equipment after interchange is performed.

Alignment: Time associated with aligning the system or replaceable item after a fault has been corrected.

Checkout: Time associated with the verification that a fault has been corrected and the system is operational.

Constant failure rates: The rate of failures that result from strictly random or chance causes. This type of failure occurs predominantly in the useful life period of a unit.

K factor: For on-orbit tasks, a conversion factor may be applied to convert elemental task times performed in 1-g environment to Micro-gravity environment. The conversion factor may be derived from data of past similar programs or from the neutral buoyancy testing.

Ground Rules and Assumptions
In the prediction, certain ground rules and assumptions apply:

- Mean Time To Repair (MTTR) does not include the maintenance overhead, which is generally non-related task time such as time to fill out a requisition, time to go get tools, break-time, time waiting for parts, etc.

- Worksite time is the only variable considered.

- All equipment experiences a constant failure rate.

- All tasks are performed sequentially by one crew member unless otherwise noted.

- Maintenance is performed in accordance with established maintenance procedures and appropriately trained personnel.

- The prediction depends upon the use of recorded reliability and maintainability data and experience that have been obtained from comparable systems and components under similar conditions of use and operation.

System Level Prediction
At the system level, MTTR is calculated by summing the product of the replaceable items' MTTR's and their corresponding failure rates; the result is then divided into the sum of all replaceable items' failure rates. Mathematically, it can be expressed as:

$$\mu_{system} = MTTR_{system}$$

$$= \frac{1}{\lambda} \sum_{i=1}^{n} \lambda_i\, MT$$

Where λ_i = failure rate of to be repair

(6)

$$\lambda = \sum_{i=1}^{n} \lambda_i$$

and system variance:

$$\sigma_{sys}^2 = \left(\frac{1}{\lambda}\right)^2 \sum_{i=1}^{n} \lambda_i^2\, \sigma_i^2$$

As an example, assume the three ORUs of a system have the following MTTR'S, Variance (V), and failure rates (λ):

	MTTR	V	$\lambda(10^{-6})$	MTTR*λ
ORU 1	4.5	0.5	12.7	57.15
ORU 2	2.3	0.7	500.0	1150.00
ORU 3	11.4	0.56	2.2	25.08
Total:			514.9	1232.23

Apply the above formula to calculate the system MTTR:

$$MTTR_{system} = \frac{1}{514.9}(1232.$$

and its variance:

$$\sigma_{system}^2 = \frac{1}{(514.9)^2}(0.5 \times 12 \qquad (7)$$

$$+ 0.7 \times 500^2 + 0.56 \times 2$$

The results of the above example indicate that the most often failed unit will essentially drive the MTTR and variance of a system.

Overall, the prediction is a straight forward process and is useful in estimating a system's MTTR. Even with a limited set of data, if the prediction is used early in the design phase, the derived value should help in shaping a preliminary design guideline for the system. In addition, the prediction can also verify logistics and maintainability requirements at some later stage.

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Technique	Estimate or predict the future availability of a system, function, or unit where availability is defined as the probability that the system, function, or unit will be in an operable state at a random time. Availability may be assessed for a single component, a repairable unit, a replaceable unit, a system of many replaceable units, or a function performed by multiple systems.

AVAILABILITY PREDICTION AND ANALYSIS

Availability analysis provides a measure which can be used to optimize system readiness within cost and schedule constraints

Benefits	Availability prediction and assessment methods can provide quantitative performance measures that may be used in assessing a given design or to compare system alternatives to reduce life cycle costs. This technique increases the probability of mission success by ensuring operational readiness. Analyses based on availability predictions will help assess design options and can lead to definition of maintenance support concepts that will increase future system availability, anticipate logistics and maintenance resource needs, and provide long term savings in operations and maintenance costs based on optimization of logistics support.
Key Words	Availability, Achieved Availability, Inherent Availability, Operational, Stochastic Simulation, Maintainability, RMAT, Markov Model
Application Experience	International Space Station Program
Technical Rationale	Availability estimation is a valuable design aid and assessment tool for any system whose operating profile allows for repair of failed units or components. These systems include those that operate on earth such as control centers, system test facilities, or flight simulation systems/facilities. Applying availability prediction and analysis techniques is also an extremely valuable process for guiding the development of maintenance concepts and requirements.
Contact Center	**Johnson Space Center (JSC)**

Availability Prediction and Analysis
Technique AT-3

Availability can be predicted or estimated using various methods and measures. Availability is a characteristic of repairable or restorable items or systems, and assumes that a failed item can be restored to operation through maintenance, reconfiguration, or reset. It is a function of how often a unit fails (reliability) and how fast the unit can be restored after failure (maintainability). A foundation to support both the establishment of reliability and maintainability (R&M) parameters and trade-offs between these parameters is created by availability prediction and analyses. Availability can be estimated for components, items, or units, but overall spacecraft system or ground system availability estimation is based on the combinations and connectivity of the units within the system that perform the functions, i.e., the series and redundant operations paths.

Availability Measures
One basic measure of availability, called inherent availability, is useful during the design process to assess design characteristics. The measure involves only the as-designed reliability and maintainability characteristics and can be calculated using the estimated mean-time-between-failure (MTBF) and mean-time-to repair (MTTR) parameters. The predicted or estimated measure of inherent availability is calculated as:

$$A_i = \frac{MTBF}{MTBF + MTTR} \tag{1}$$

The MTTR time in the inherent availability

calculation does not include such times as administrative or logistic delay time, which generally are beyond the control of the designer, and does not include preventive maintenance time. However, effective trade-offs using the basic times and parameters are possible. Trade-off techniques and some sample uses are included in Reference 1, Section 5.5.

Another measure of availability, achieved availability or A_a, can be expressed as:

$$_a = \frac{OT}{OT + TCM + TP} \tag{3}$$

where OT is the total time spent in an operating state, TCM is the total corrective maintenance time that does not include before-and-after maintenance checks, supply, or administrative waiting periods; and TPM is the total time spent performing preventive maintenance. A_a is more specifically directed toward the hardware characteristics than the operational availability measure, which considers the operating and logistics policies.

A third basic measure of availability, operational availability, considers all repair time: corrective and preventive maintenance time, administrative delay time, and logistic support time. This is a more realistic definition of availability in terms providing a measure to assess alternative maintenance and logistics support concepts associated with the operation of a system or function. It is usually defined by the equation:

$$\frac{Uptime}{Uptime + Downtime} = \frac{Upti}{Total} \tag{2}$$

where Uptime is the total time a system is in an operable state, and Downtime is the total time the system is in an inoperable state.
The sum of Uptime and Downtime, or Total Time, is usually known, specified as a requisite operating time, or is a given time to perform a critical function. Downtime often is broken down into a variety of subcategories such as detection and diagnosis time, time waiting for repair parts, actual unit repair or replacement time, test and checkout time, etc. Table 1 shows the basic difference between the availability measures defined above.

Table 1: Commonly Used Availability Measures

Availability Measure	*Function of:*	*Excludes:*
Inherent (A_i)	hardware design	ready time, preventative maintenance downtime, and administrative downtime
Achieved (A_a)	hardware design but also includes active, preventative, and corrective maintenance downtime	logistics time and administrative downtime
Operational (A_o)	Product of actual operational environment including ready time, logistics time, and administrative downtime	All inclusive

System or Function Availability Estimation

System/function availability estimates may be derived in a limited fashion by algebraically combining mean value estimates of the system units, or more rigorously by using computer-aided simulation methods.

Mean Value Estimation

Mean value estimation of system availability is usually performed by algebraically combining component, LRU, and ORU availabilities calculated using equation (1). When the system is composed of a number of components, LRU's, or ORU's, the failure of any one of which results in the system being down, the system availability is calculated from the product of these units' availability. When the system involves item redundancy, redundant block availability estimates can be calculated using simple Boolean mathematical decomposition procedures similar to reliability block diagram solution methods. See Reference 1, Section 10.4.

Computer-Aided Simulation

Availability prediction using computer-aided simulation modeling may use either a stochastic simulation or a Markov model approach. Stochastic simulation modeling uses statistical distributions for the system's reliability, maintainability, and other maintenance and delay time parameters. These distributions are used as mathematical models for estimating individual failure and restoration times and can include failure effects and other operational conditions. A computer program generates random draws from these distributions to simulate when the system is up and down, maintains tables of failures, repairs, failure effects, etc., and tracks system or function capability over time. These data may then be used to calculate and output system operational availability estimates using equation (2).

Stochastic Simulation Methods

Discrete event stochastic simulation programs are recommended to perform operational availability predictions and analyses for large, repairable systems such as the space station or large ground systems and facilities. These methods simulate and

monitor the availability status of defined systems or functions that are composed of a collection of Replaceable Units (RUs). The following process is generally used:

(1) Generate simulated future failure times for each designated RU based on predicted RU reliability distributions and parameters.

(2) Step through simulated operating time, and when failure events are encountered, evaluate the failure impact or function status given the specific failures encountered.

(3) Repair or replace the failed RU using a maintenance policy and procedure based on the availability of required maintenance resources, priority or criticality of the failure, or the current system or function status. Once an RU is repaired or replaced, the system or function status is reset appropriately, and a future failure time for the RU is again generated.

Generation of simulated failures and maintenance actions for RUs requires as input the estimated RU time-to-failure distribution model parameters and factors that define the frequency of other scheduled or unscheduled maintenance. The maintenance actions can include equipment failures, preventive maintenance tasks, and environmentally or human-induced failures.

To evaluate the effect of a simulated failure on the function's operational capability at a particular point in time, minimal cut sets of failure events that define the system or function failure conditions can be used. Minimal cut sets of failure events can be generated from reliability block diagrams or fault tree analysis of the functions, and then

used during a simulation run to dynamically determine queuing priorities based upon functional criticality and the current level of remaining redundancy after the simulated failure occurs.

Maintenance is simulated by allocating available maintenance resources and spare parts to the awaiting maintenance action (or waiting for resources to become available). Groups of maintenance actions may also be packaged into shifts of work. If the system under consideration is in a space environment, both external (extravehicular activity or EVA) or internal (intravehicular activity or IVA) can be considered.

When the stochastic simulation method is used, each run of the simulation model (called an iteration) will yield a single value of the availability measure that depends on the chance component or unit failures and repairs that happened during that iteration. Therefore, many iterations are required to cover as many potential failure situations as possible, and to give the analyst a better understanding of the variation in the resulting availability as a function of the variations in the random failure and repair process. The number of iterations required for accurate availability measure results will depend on the iteration to iteration variation in the output measure. Experience has shown that in system availability simulations with a large iteration-to-iteration variation, 200 to 1000 iterations or more may be required to obtain a statistically accurate estimate of the average system availability.

For example, the Reliability and Maintainability Assessment Tool (RMAT) is a stochastic computer-aided simulation method like that described that has been used at Johnson Space Center for assessing the maintainability and availability characteristics

of the Space Station. The output of the RMAT includes the percent of total (or specified mission) time each defined space station function spends in a "down" state as well as the percent of time each defined function is one failure away from functional outage (is zero failure tolerant). Using RMAT, analysts at JSC have been able to perform trade studies that quantify the differences between alternative Space Station configurations in terms of their respective operational availability and maintainability measure estimates.

The same simulation methods (such as RMAT) that provide for operational availability measures will also provide maintenance resource usage measures such as maintenance manpower needs and spare part requirements. With this capability, JSC has been able to estimate the maintenance manpower needs, including EVA requirements, of various Space Station alternative configurations.

Markov Model Approach
A Markov process, or state-space analysis is a mathematical tool particularly well suited to computer simulation of the availability of complex systems when the necessary assumptions are valid. This analysis technique also is well adapted to use in conjunction with Fault Tree Analysis or Reliability Block Diagram Analysis (RBDA). Examples of the use of Markov process analysis may be found in Reference 1 or in such standard reliability textbooks as Reference 2.

Failure to use availability predictions and analysis during the design process may lead to costly sub-optimization of the as-designed system reliability and maintainability characteristics. Where operations and support costs are a major portion of the life

cycle costs, availability prediction and analysis are critical to understanding the impact of insufficiently defined maintenance resources (personnel, spare parts, test equipment, facilities, etc.), and maintenance concepts on overall system operational availability and mission success probabilities. These analyses can therefore greatly reduce the life cycle costs associated with deploying and supporting a space or ground system.

References

1. MIL-HDBK-338; *Electronic Reliability Design Handbook*, Reliability Analysis Center, Rome, NY, 1989.

2. O'Connor, J.T.; *Practical Reliability Engineering*, John Wiley & Sons Ltd., Chichester, 1991.

Technique	Employ statistical Monte Carlo methods to analyze availability, life cycle cost (LCC), and resource scheduling by using the Availability Cost and Resource Allocation (ACARA) program, which is a software tool developed at Lewis Research Center .
AVAILABILITY, COST, AND RESOURCE ALLOCATION (ACARA) MODEL TO SUPPORT MAINTENANCE REQUIREMENTS *Utilize computer simulation to analyze availability, life cycle cost, and resource scheduling*	
Benefits	The ACARA program is an inexpensive tool for conducting maintainability, reliability and availability simulations to assess a system's maintenance requirements over a prescribed time interval. Also, availability parameters such as equivalent availability, state availability (percentage of time at a particular output state capability), and number of state occurrences can be computed.
Key Words	Maintainability Modelling, Availability, Computer Simulation
Application Experience	International Space Station Program, LeRC Micro-gravity Experiments
Technical Rationale	The development of the Space Station and other space systems (i.e., Space Station payloads and experiments) requiring long-term maintenance support dictates maintenance planning with emphasis on an understanding of the level of support required over a given period of time. The program is written specifically for analyzing availability, LCC, and resource scheduling. A combination of exponential and Weibull probability distribution functions are used to model component failures, and ACARA schedules component replacement to achieve optimum system performance. The scheduling will comply with any constraints on component production, resupply vehicle capacity, on-site spares, crew manpower and equipment.
Contact Center	**Lewis Research Center (LeRC)**

Availability, Cost, and Resource Allocation (ACARA) Model to Support Maintenance Requirements
Technique AT-4

The ACARA program models systems represented by reliability block diagrams comprising series, parallel, and M-of-N parallel redundancy blocks. A hierarchical description of the system is needed to identify the subsystems and blocks contained in the system. Given a reliability block diagram (RBD) representation of a system, the program simulates the behavior of the system over a specified period of time using Monte Carlo techniques to generate block failure and repair intervals as a function of exponential and/or Weibull distributions. ACARA interprets the results of a simulation and displays tables and charts for the following:

• Performance, i.e., availability and reliability of capacity states

• Frequency of failure and repair.

• Lifecycle cost, including hardware, transportation, and maintenance.

• Usage of available resources, including maintenance man-hours.

ACARA Inputs
A RBD must be prepared for ACARA to simulate a system's availability. The RBD depicts a system, and the arrangement of the blocks depicts a performed function.

RBD does not necessarily depict physical connections in the actual system, but rather shows the role of each block in contributing to the system's function. The blocks are sequentially numbered as B1, B2, B3, etc. and subsystems are numbered as S1, S2, etc, which are defined from the inside out. Figure 1 shows an example of a system with its corresponding blocks and subsystems. Beginning with the innermost set of blocks, each parallel or series set of blocks is
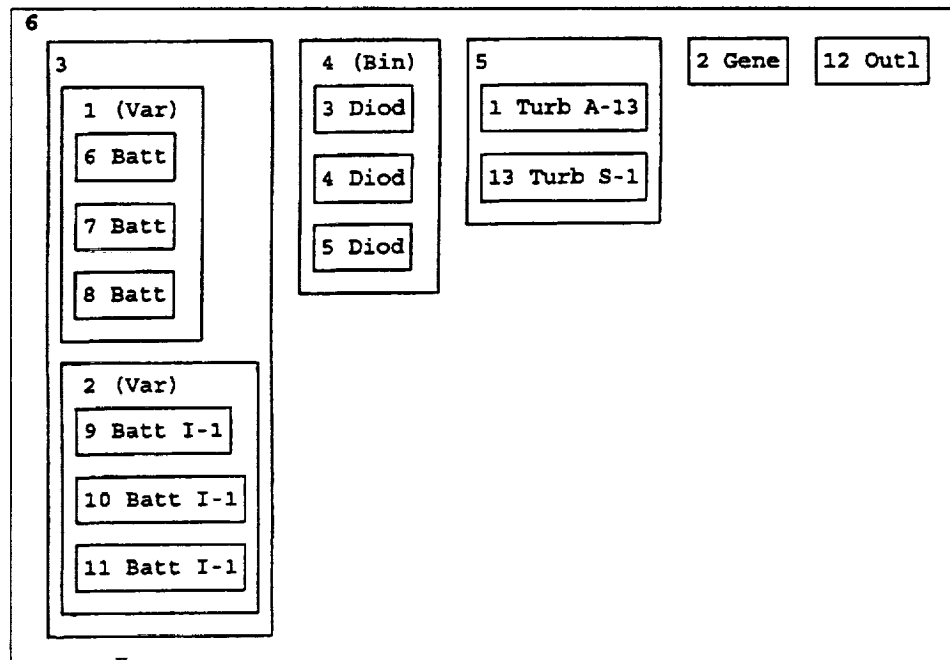
Figure 1: Diagram of Blocks and Subsystems

partitioned into a subsystem which in turn may combined with other blocks or subsystems.

The system shown in Figure 1 contains 6 subsystems:

- Subsystems 1 and 2 are both variable M-of-N parallel arrangement of batteries. These subsystems respectively contain Blocks 6 through 8 and Blocks 9 through 11.

- Subsystem 3 consists of Subsystems 1 and 2 in parallel.

- Subsystem 4 is a binary M-of-N parallel arrangement of diodes, Blocks 3 through 5.

- Subsystem 5 is a parallel arrangement of two turbines, Blocks 1 and 13.

- Subsystem 6 comprises the entire system and is a series arrangement of Subsystems 3 through 5 and Blocks 2 and 12.

Modeling Time-to-Failure
The ACARA program uses the Weibull distribution function to model the time-to-failure for the system. The shape and scale factors are adjusted to modify the form of the distribution. Uniform random numbers from 0 to 1 are generated and substituted for the reliability, R. ACARA uses the early failure(i.e., infant mortality), random failure, and wearout failure (life-limiting failure) models. These models are adjusted by user-defined parameters to approximate the failure characteristics of each block.

Random failure is modelled by the Weibull distribution function where the shape factor is equal to 1 (equivalent to the exponential distribution) and the scale

parameter is equal to the Mean Time Between Failure (MTBF).

Wearout failure is also modeled by the Weibull function. The shape factor must be 1 or more. If the block with an initial age (i.e., it is not brand new) is installed, its initial age is subtracted from its first time-to-failure due to wearout. Likewise, if it undergoes a failure-free period, this period is added to its first time-to-failure.

ACARA generates time-to-failure events using one or a combination of these models and assigns the minimum resulting time for each block as its next failure event. The early failure model is canceled by assigning to the block type an early failure probability of zero; random failure, by an excessively large MTBF; and wearout failure, by an excessively large mean life.

ACARA also simulates redundant pairs of active and standby blocks. A standby block is installed as dormant and its time-to-failure is initially modelled by random failure, in which the MTBF is multiplied by its characteristic "Dormant MTBF Factor." Then, the corresponding active time-to-failure is modelled by early, random, and wearout failure until the active block is replaced.

Modeling Down Time
The downtime for a failed block depends in part upon the availability of spares and resources. These spares may be local spares, i.e., initially located at the site. If a local spare is available when the block fails, the block is immediately replaced and downtime will depend only on the mean-time-to-repair (MTTR). If no local spares are available, ACARA will schedule a replacement according to the schedule production quantities for that block type, the constraints

on mass, volume, and delay associated with the manifesting and loading spares to the resupply vehicle. ACARA also checks the constraints on the maintenance agents to determine when the block can be replaced.

Once all the above conditions are met to allow the block to be replaced, ACARA then estimates the time required to replace it. The time-to-repair depends upon the MTTR's for that block type. MTTR's may be specified for up to three separate maintenance agents. Examples of maintenance agents are crew, equipment, and robotics. ACARA assumes that the maintenance actions occur simultaneously, so that the block's repair time is determined by the maintenance agent having the maximum MTTR. During the simulation, the time-to-repair may either be set equal to the maximum defined MTTR or to be determined stochastically. Refer to Reference 1 for a complete guide on the use of ACARA and the explanation for entering data and the output of graphs and information. ACARA may be obtained from the Computer Software Management and Information Center (COSMIC) at the University of Georgia, (706) 542-3265.

References

1. Stalnaker, Dale K., *ACARA User's Manual*, NASA-TM-103751, February 1991.

2. Hines, W.W. and Montgomery, D.C., *Probability and Statistics in Engineering and Management Science*, 2nd Ed., John Wiley & Sons, 1980

Technique	Apply a univariate failure prediction algorithm using a signal processing technique to rocket engine test firing data to provide an early failure indication. The predictive maintenance technique involves tracking the variations in the average signal power over time.
ROCKET ENGINE FAILURE PREDICTION USING AN AVERAGE SIGNAL POWER TECHNIQUE *Use performance prediction algorithms during rocket engine tests for identification of incipient failures*	
Benefits	This technique will therefore reduce unnecessary failures attributed to the traditionally used redline-based system. The average signal power algorithm can be used with engine test firing data to provide significantly earlier failure indication times than the present method of using redline limits. Limit monitoring techniques are not capable of detecting certain modes of failures with sufficient warning to avoid major hardware and facility damage.
Key Words	Rocket Engines, Failure Detection, Detectability
Application Experience	Space Transportation System (STS)
Technical Rationale	Detection of anomalous behavior is critical during the operation of the Space Shuttle Main Engine (SSME). Increasing the detectability of failures during the steady-state operation of the SSME will minimize the likelihood of costly engine damage and maintenance. The average power signal algorithm is superior to the time series algorithm because more parameters contribute to the first simultaneous failure indication times. This increases the agreement between several parameters, thus increasing the likelihood that an engine anomaly has occurred. This method also reduces the number of false failure indications that can prematurely shut down the engine during testing or operation.
Contact Center	**Lewis Research Center (LeRC)**

Rocket Engine Failure Detection Using An Average Signal Power Technique
Technique AT-5

For discrete random processes, probabilistic functions are used to describe the behavior of the rocket engine system. The Power Spectral Density (PSD) is computed to describe how the variation of the random process is distributed with frequency. For stationary signals, the PSD is bandlimited to $\pm 1/(2T)$, where T is the sampling interval in seconds.

Average Signal Power Calculations

The PSD is defined as the discrete-time Fourier transform of an autocorrelation function. (The derivation of the autocorrelation function is shown in Reference 1.) When the autocorrelation function is evaluated at zero lag, then an expression for the average signal power (ASP) of a random stationary process results:

$$P = r_{xx}[0] = \int_{-\frac{1}{2T}}^{+\frac{1}{2T}} P_{xx} \qquad (1)$$

$P_{xx}(f)$ = discrete - time
            Fourier transfor
$r_{xx}[0]$ = inverse discret
            Fourier transfor

The average signal power for several SSME parameters is determined by calculating the autocorrelation at zero lag for the parameters provided in Table 1. The assumption is made that the signal is stationary over the computation interval. The average signal power calculations are performed over 2-second, 50-percent overlapping window for nominal test firings at both 104- and a 109-percent-rated power levels. A smaller time increment must be used to improve the failure detection capability of the algorithm.

The average plus three standard deviations of the average signal power are computed for all the nominal firings at both engine power levels. These values are combined to calculate the thresholds (see Reference 1).

A safety factor ranging from 1.5 to 3.5 is needed to ensure no false failure indications are computed for the nominal firings. The range of safety factors reflected signal behavior variations that occurred over seven nominal A2 firings. When used in the failure detection mode, failure of the average signal power of a parameter to fall outside its threshold results in a failure indication. Also shown in Table 1 are the thresholds calculated from the SSME nominal test firings based on the average signal power algorithm along with the associated safety factors.

Table 1: Signal Threshold and Safety Factor for SSME's

Parameter	Average Power	
	Threshold	Safety Factor
Mixture Ratio	0.00112	1.5
MCC Coolant Discharge	200	1.5
MCC Hot Gas Injector Pressure	125	1.5
LPOP Shaft Speed	1598	2.5
LPFP Discharge Pressure	2509	1.5
HPFP Discharge Pressure	436	1.5
Fuel Preburner Chamber Pressure	232	1.5

PBP Discharge Pressure	911	1.5
HPOP Discharge Pressure	268	1.5
PBP Discharge Temperature	0.04	3.0
MCC Pressure	47	1.5
HPFP Inlet Pressure	4	1.5
HPOP Inlet Pressure	6	1.5
HPFT Discharge Temperature A	32	2.0
HPFT Discharge Temperature B	38	2.5
HPOT Discharge Temperature A	154	3.5
HPOT Discharge Temperature B	104	3.5
HPFP Shaft Speed	550000	3.5

Algorithm Implementation

A system identification and signal processing software package on a RISC workstation provides the average signal power algorithm. Command and Data Simulator (CADS) data from a predetermined number of SSME test firings are used to establish the failure indication thresholds.

Several system conditions must be considered to ensure that the algorithm does not erroneously indicate an engine fault. These conditions include sensor failure, propellant tank venting and pressurization, and propellant transfer. Sensor failure detection techniques must be exercised before, or concurrently, with safety monitoring algorithms in order to eliminate the possibility of a sensor failure being interpreted as an engine problem. Typically, all parameters exhibiting sensor problems are removed prior to the application of the algorithm.

Failure indication thresholds are established by applying the average signal power algorithm to a set number of nominal tests. For the SSME four anomalous firings and one nominal firing were tested using the thresholds shown in Table 2. An example of the application of the average signal power algorithm to a SSME anomalous test firing is shown in Figures 1 and 2. Figure 1 illustrates the interval over which the average signal power was computed for a single parameter, HPFP discharge pressure and one test firing. Figure 2 displays the resulting average signal power, as a function of time. As shown, the threshold for the average signal power algorithm has been exceeded.

Figure 1: Application of the Average Signal Power Algorithm to the HPFP Discharge Pressure
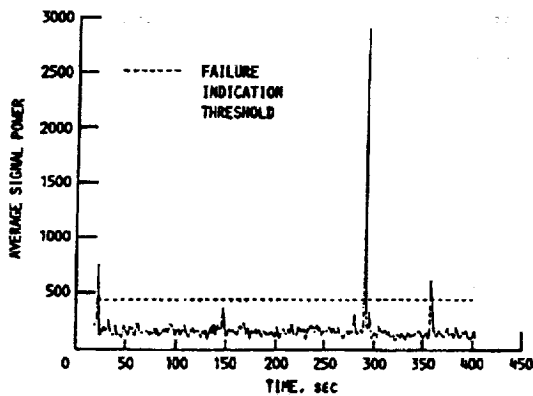
Figure 2: Average Signal Power for that Interval with the Failure Indication Threshold

Nomenclature:

HPFP   high pressure fuel pump
HPFT   high pressure fuel turbine
HPFTP high pressure fuel turbopump
HPOP   high pressure oxidizer pump
HPOT   high pressure oxidizer turbine
LPFP   low pressure fuel pump
MCC   main combustion chamber
PID   parameter identification
SSME   space shuttle main engine

Reference

Meyer, C.M., Zakrajsek, J.F., *Rocket Engine Failure Detection Using System Identification Techniques*, <u>AIAA Paper 90-1993</u>, July 1990.

Operations
And Operational
Design Considerations

This section provides a rich source of ideas to any organization that is involved in either spaceflight operations or design to support those operations. The techniques reflect actual spaceflight operations experience and related field experience that can be used to achieve continuous improvement. They can provide a mechanism for feedback from operators of flight hardware to system designers to make the systems easier, safer, and less costly to operate. Also, they provide the design engineer with valuable information on the latest technology advances in the operations environment. These techniques also can serve as a communications tool for operations personnel, allowing for transfer of knowledge and enhancement of professional development. The techniques contained herein are the most up-to-date NASA operational processes, process improvements, and feedback to design engineers, all of which are dedicated to making NASA systems as maintainable and cost efficient as possible.

Technique	Engage in refurbishment activities to rebuild and prepare for reuse of the Solid Rocket Boosters (SRB's) after each Space Shuttle Orbiter launch. These refurbishment activities include: (1) inspection, (2) reworking of anomalies to specification, (3) material review board (MRB) acceptance or scrapping, (4) cleaning, (5) corrosion protection and prevention, (6) scheduled part replacement, (7) test and checkout, and (8) preparation for storage or return to flight buildup.
SRB REFURBISHMENT PRACTICES *Maintainability concepts can be applied on reusable launch vehicle systems through design of an efficient refurbishment process*	
Benefits	Refurbishment of SRB components is cost effective and conserves resources. This allows for reuse of SRB's, thus saving money for the program versus building new SRB's for each launch.
Key Words	Refurbishment, Maintainability Design Criteria, Salt Water Protection, Galvanic Corrosion, Sealant, Electronic Component Vibration Testing
Application Experience	Space Shuttle Solid Rocket Booster (SRB), Space Shuttle Solid Rocket Motor (SRM).
Technical Rationale	Through the past decade of maintaining the SRB by refurbishing the structures and components; MSFC and its contractors have developed and implemented successful refurbishment specifications and procedures that have proven their effectiveness. For example, failure to adhere to the proven practice of refurbishing recovered hardware from salt water impact can result in unacceptable performance, scrapping of otherwise usable hardware, expenditure of unnecessary resources, and possible schedule delays.
Contact Center	**Marshall Space Flight Center (MSFC)**

SRB Refurbishment Practices
Technique OPS-1

Solid Rocket Booster (SRB) Refurbishment encompasses the activities required to return the reusable SRB component to a flightworthy condition after SRB ignition, liftoff, and flight; separation from the external tank; descent (free fall and parachute); ocean impact; and retrieval. When the decision was made to recover and reuse the SRB hardware, a design team was organized to formulate the maintainability criteria for a reusable booster. The SRB Flow Chart for Maintainability is shown in Figure 1. The maintainability design team produced the Solid Rocket Booster Maintainability Design Criteria Document [1], a document that was used by designers as they conceived each design feature, performed the necessary tradeoffs of the design parameters, and made other design and product engineering decisions. The design team included maintainability as a design goal and incorporated the desired maintainability features into components of the end item throughout the design process. Maintainability factors that were considered during the design of the SRB are shown in Table 1.

Table 1. SRB Maintainability Factors

1. *Accessibility*
2. *Commonality of Fasteners*
3. *Electrical Subsystem Installation and Removal*
4. *Thrust Vector Control (TVC) Subsystem Installation and Removal*
5. *Ordnance Installation and Removal*
6. *Markings and Color Coding*
7. *Unitization of Subsystems*
8. *Irreversibility of Connectors*
9. *Tool and Equipment Design*
10. *Spares Provisioning*

Design Process Considerations

Table 2 lists typical maintenance actions that were considered during the design process. The SRB was designed to withstand launch, water impact, and towback environments, incorporating the capability of 10 flights for the parachutes; 20 flights for electrical/electronic components, Thrust Vector Control (TVC) components, and SRM components; and 40 flights for the structures. SRB structures are typically welded and/or mechanically fastened aluminum except for the external tank attach ring, which is mechanically fastened steel.
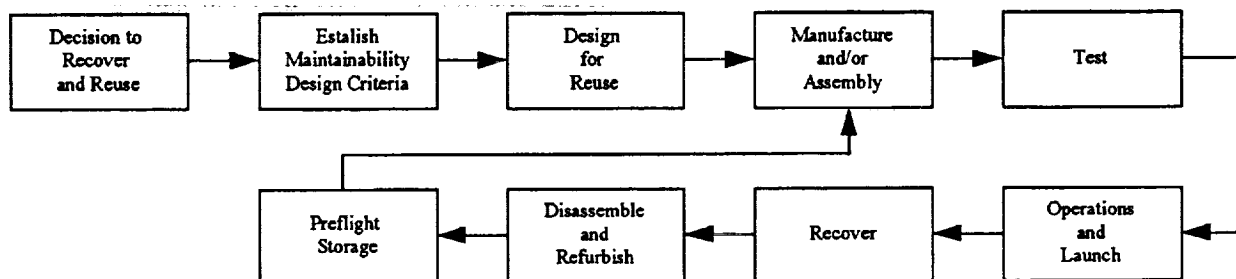

Figure 1. SRB Flow Chart for Maintainability

Table 2. Maintenance Actions

> 1. Inspection
> 2. Troubleshooting
> 3. Calibration and Adjustment
> 4. Repair

All aluminum structural assemblies are first painted and then coated with an ablative insulation. The SRM segments are forged D6AC steel. All structural components are cleaned and/or alodined as appropriate, before being primed and top coated with paint. The mechanically fastened aluminum and steel structural components are designed to be protected from salt water intrusion by applying sealant between adjoining surfaces, installing the fasteners with sealant, torquing the fasteners, and applying a fillet of sealant along the edge of brackets where they join the main structure. The electronic/electrical components exposed to salt water are sealed, and the external surfaces of these components are painted. The TVC hydraulic system is a closed-loop system that does not permit the intrusion of sea water. The SRM segments' external surfaces are protected with an epoxy paint finish, and the internal surfaces are protected by the propellant insulator that is bonded to the inside surfaces of the SRM segments. Areas not protected with paint or bonded-on insulation are protected with a water-repellent grease.

Specific Improvements

Typical areas of the SRB that have been redesigned or modified as a result of trouble areas found during recovery and refurbishment are discussed below:

1. Galvanic corrosion occurred in the aft skirt of the first few SRB's recovered. To prevent this from recurring the design team added a zinc coating to selected metal components, and bolted anodes (Zinc bars) to some components of the TVC system.

2. The aft skirts of the first few SRB'S experienced water impact damage. The corrective action included the addition of gusset reinforcements to the structural rings. Foam was sprayed on the interior of the aft skirt to protect the reinforcement rings and the TVC components. Impact force with the water was reduced by increasing the diameter of the main parachutes from 115 feet to 136 feet. The larger parachutes decreased the SRB's water impact velocity from 88 ft/sec to 75.5 ft/sec (60 mph to 51.5 mph, respectively).

3. During initial teardown and inspection, water and corrosion were found between the mating surfaces of structural members. To correct this problem, the sealant application specifications were modified to require the sealant to be applied to both surfaces before joining.

4. To eliminate potential water entry into the forward skirt, the following areas were modified or redesigned:

a. The aft seal on the forward skirt was changed from a rectangular to a "D" configuration to allow better contact between the forward skirt and the forward dome of the SRM.

b. A fillet of sealant was added between the access door and the surrounding structure after final close-out of the forward skirt.

c. Sealant was added to the mating surfaces and the installation bolts of the separation nut housing for the main parachute attach fittings.

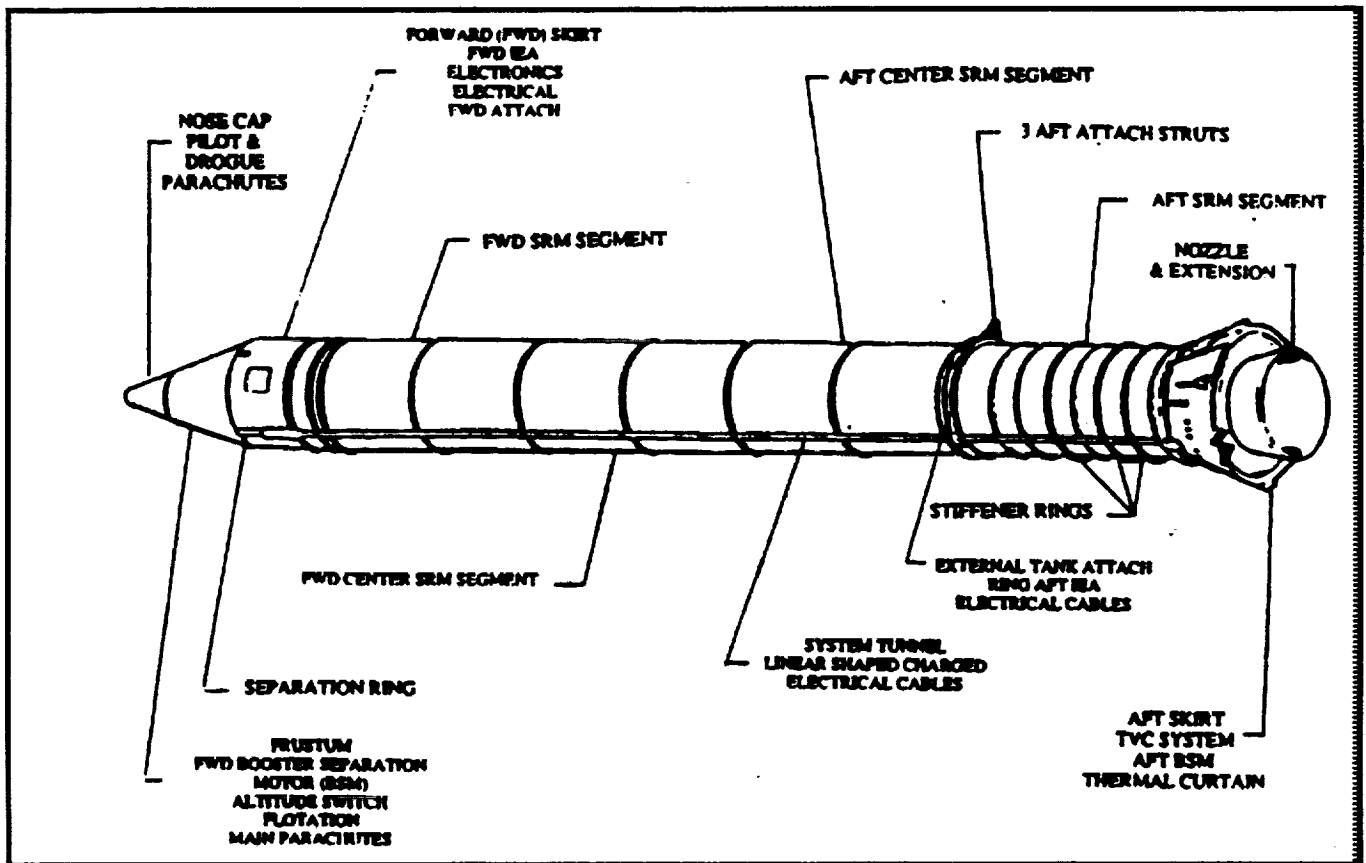5. The following practices improved

Figure 2. SRB Flight Configuration

maintainability, parachute deployment, and parachute inflation:

a. To avoid abrasive damage that occurred during main parachute deployment, foam and ablative material were added to portions of the frustum and the main parachute support structure.

b. To avoid damage to the parachutes during deployment, the parachutes are now packed in a circular pattern rather than the previous zig-zag pattern.

c. The opening at the top of the main parachute canopy was decreased in diameter to allow quicker inflation of the parachute.

6. After every flight electronic components

were being returned to the vendor for refurbishment. After refurbishment, acceptance test procedures (ATP) were performed, including vibration and thermal testing. The vibration level of these tests caused the remaining life of the component to be reduced. To prevent the excessive expenditure of components' lifetime (except for the range safety system components) vibration and thermal testing has been eliminated during normal turnaround.
The constant improvement of electronic parts by the manufacturer presents a unique problem to the SRB refurbishment effort because the improved parts are often not interchangeable with their predecessors.
A sufficient quantity of spare parts must be procured to meet logistics requirements until the components are redesigned to use the improved parts.

Typical Refurbishment Procedures

Figure 2 depicts the SRB flight configuration. After approximately 125 seconds into the Shuttle flight, the SRB'S are jettisoned from the external tank. During reentry, the nose cap is jettisoned (it is not recovered), deploying the drogue parachute. After the SRB is stabilized in a vertical position, the frustum is jettisoned and descends into the ocean. Its descent is held to a safe velocity by the drogue parachute. In the meantime, the jettisoning of the frustum deploys the three main parachutes, lowering the remaining portion of the SRB into the ocean. Once in the ocean, the parachutes (which are jettisoned at water impact) and the frustum are removed by the recovery team and positioned onto the recovery vessel. A plug is inserted into the SRM nozzle throat and the SRB is dewatered. Removal of the water from the SRB allows the SRB to be positioned from a vertical position to a horizontal position. The SRB is then towed to the disassembly area dock.

At dockside, the SRB is lifted from the water and placed on dollies. The SRB pyrotechnics are disarmed, the TVC fuel system is depressurized, and an assessment team inspects and documents anomalies that may have occurred during flight. Then the SRB is washed with a detergent solution in a semiautomated wash facility. The aft skirt is removed and routed to the TVC disassembly facility. Table 3 lists a typical flow sequence for major structure refurbishment. After the aft skirt is removed, the remainder of the SRB is routed to the disassembly facility.

As the SRB components are removed, they are identified by attaching a metal tag with their part number and dispositioned per the *Predisposition List for SRB Flight Hardware*[2]. The SRB component is then

Table 3. Typical Structure Refurbishment Flow

1. Tow SRB from water impact area to dock
2. Remove SRB from ocean, Rinse with potable water.
3. Place SRB on transporter.
4. Safe SRB Ordnance and Hydrazine Systems.
5. Assessment Team Inspection
6. Wash SRB with detergent solution and rinse.
7. Remove aft skirt assembly.
8. TVC refurbishment facility.
9. Remove TVC Components.
10. Disassembly area: remove components.
11. Critical dimension check.
12. Thermal protection system removal, robotic hydrolaser.
13. Inspect, Visual and NDE (XRAY and Ultrasonics).
14. Rework, Touch-up paint (repaint every fifth use.)
15. Inspect and identify.
16. Preflight storage.

routed to the refurbishment area where a prepared refurbishment procedure document is attached to the part. The part is reworked to conform to the Refurbishment Engineering Specification. This specification lists the requirements for refurbishing each component to flightworthy condition before it is returned to storage.

The SRM segments are disassembled in the disassembly facility at dockside, placed on rail cars, and transported to the SRM contractor located in Utah. At the contractor's plant, the segments are off-loaded and routed to refurbishment areas. All segments that are to be reused must meet the requirements of specification STW7-2744[3]. If segment dimensions fall outside the acceptable requirements of this specification, an individual analysis is required to determine the effect on the structural and sealing capability before reusability is determined. All documented

*Table 4. Types of Hardware That Have
Been Successfully Refurbished*

1. *Major Structures (Frustrum, Forward Skirt,
   Aft Skirt, External Tank Attach (ETA) Ring,
   Solid Rocket Motor (SRM) Segments, etc.*
2. *Electronic Components: Integrated Electronic
   Assembly (IEA), Integrated receiver Decoder
   (IRD), etc.*
3. *Electrical Cables.*
4. *TVC Components Auxiliary Power Unit
   (APU), Hydraulic Pump, Hydraulic Reservoir,
   Fuel Service Module (FSM), etc.*

nonconformances are reviewed to determine
if the condition of the hardware has changed.
The most critical areas to be reviewed are
case membrane thickness, vent port and leak
port threaded areas and sealing surfaces, and
aft segment stiffener stubs. No surface
defects (corrosion, pitting, scratches,
noncrack-like flaws, etc.) deeper than 0.010
inch are permitted. All segments are
hydrotested to 1.125 times the Maximum
Expected Operating Pressure and magnetic-
particle inspected.

References

1. NASA/MSFC: *Solid Rocket Booster
   Maintainability Design Criteria
   Document,* SE-019-022-2H,
   NASA/Marshall Space Flight Center, AL.

2. USBI: *Predisposition List for SRB
   Flight Hardware,* 10PLN-0027, USBI,
   United Technologies, Huntsville, AL.

3. Thiokol: *Space Shuttle SRM
   Refurbished Case Acceptance Criteria,*
   STW7-2744, Thiokol Corporation, Space
   Operations, Brigham City, Utah.

4. NASA/MSFC: *Sealing of Faying
   Surfaces Subject to Sea Water Exposure*

on the SRB Excluding the SRM,
10A00526, NASA/ Marshall Space Flight
Center, AL.

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   Subject to Sea Water Exposure on the
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   NASA/Marshall Space Flight Center, AL.

6. NASA/MSFC: *Protective Finishes for
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   the SRM,* 10A00528, NASA/Marshall
   Space Flight Center, AL.

7. NASA/MSFC: *Solid Rocket Booster
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   Plan,* SE-019-040-2H, NASA/Marshall
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   STW7-2863, Thiokol Corporation,
   Space Operations, Brigham City, Utah.

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    Finalization Requirements for Nozzle
    Metal Hardware,* STW7-3450, Thiokol
    Corporation, Space Operations, Brigham
    City, Utah.

11. Thiokol: *Space Shuttle SRM,
    Acceptance Criteria, New and Modified
    Case,* STW7-3489, Thiokol Corporation,
    Space Operations, Brigham City, Utah.

12. Thiokol: *Space Shuttle SRM,
    Acceptance Criteria for Refurbished*

Igniter Chambers and Igniter Adapter,
STW7-3861, Thiokol Corporation, Space
Operations, Brigham City, Utah.

13. Thiokol: *Refurbishment and Acceptance
    Criteria for Redesigned Barrier-Booster
    Assembly,* STW7-3888, Thiokol
    Corporation, Space Operations, Brigham
    City, Utah.

14. Thiokol: *Manufacturing Plan for Space
    Shuttle Redesigned Solid Rocket Motor
    (RSRM) Project,* TWR-10341(CD),
    Prepared for NASA by Thiokol
    Corporation. Brigham City, Utah.

15. USBI: 10MNL-0028, *Solid Rocket
    Booster Pictorial Representations
    Handbook,* USBI, United Technologies,
    Huntsville, AL.

16. USBI: *Frustum/Aft Skirt Disassembly
    Requirements,* 10REG-0032, USBI,
    United Technologies, Huntsville, AL.

17. USBI: *Refurbishment Engineering
    Specifications For Space Shuttle Solid
    Rocket Booster Assembly Project,*
    10SPC-0131, USBI, United
    Technologies, Huntsville, AL.

Technique	Protect the receptacles/plug ends of demated electrical connections with covers provided by manufacturer or with generic plastic caps or if covers are unavailable, leave in downward facing position.

ELECTRICAL CONNECTOR PROTECTION

Protect demated electrical connectors with plastic caps or manufacturer's covers instead of double bagging

Benefits	Moisture collects in the bag when the double-bag-and-seal method is used. This can lead to corrosion of the connector or possible electrical shock when the connector is reused. The use of plastic caps or manufacturer's covers will prevent moisture buildup, thus alleviating potential hardware damage or injury.
Key Words	Connector, Electrical
Application Experience	Space Transportation System (STS)
Technical Rationale	If the proper method of protection is not used when connectors are demated, there is the possibility of electrical shock to personnel connecting receptacles/plug ends, and increased surface corrosion rate due to environmental effects.
Contact Center	**Kennedy Space Center (KSC)**

Electrical Connector Protection
Technique OPS-2

This practice can be implemented in two
ways:

- Provide instructions in operations and
  maintenance documents for protecting
  the connector after use. (A step should
  be included to inspect the connectors
  for corrosion/debris and provide
  direction for corrosion/debris removal,
  necessary.) If ESD is a concern, do
  not use generic plastic caps as they can
  be ESD generators. ESD-approved
  caps should be used.

- Provide placard or tag on or near
  connector, stating method to leave
  connector after use.

Reference

KSC-DE-512-SM, Rev. B, *Guide for Design
Engineering of Ground Support Equipment.*

Technique	When designing robotic systems for removal and application of thermal protection materials, pay close attention to support fixture indexing, precision positioning, optimum sequencing, and protection against robotic cell environmental conditions. By integrating proven hardware and software practices with equipment and facility design and operation, the effectiveness of robotic systems is ensured.
	ROBOTIC REMOVAL AND APPLICATION OF SRB THERMAL SYSTEMS *Use robotic systems to improve productivity of the launch vehicle refurbishment process*
Benefits	Adherence to proven robot cell design and operational practices will result in improved consistency, speed, safety, precision, and reliability and increased cost-effectiveness of robotic systems over manual or semi-automated processes.
Key Words	Robot, robotic removal of insulation, robotic application of insulation, robot cell design, and robot operational practices.
Application Experience	Space Shuttle Solid Rocket Booster (SRB)
Technical Rationale	SRB refurbishment operations at KSC have resulted in the successful robotic insulation removal and application of 68 SRB aft skirts and other SRB elements. The facility schematic depicted in the description shows the SRB aft skirt in its most environmentally critical operation, insulation removal. This facility has been in operation for 5 years and, under routine maintenance, has been operational since its inception. Similar reliable operation has been experienced in the robotic application of insulation.
Contact Center	**Marshall Space Flight Center (MSFC)**

Robotic Removal and Application of SRB
Thermal Systems
Technique OPS-3

When the SRB is recovered from the ocean, disassembled for refurbishment, and reused on subsequent Space Shuttle flights, several layers of insulating materials and protective coatings must be removed and then re-applied. Experience has shown that the use of robotic systems for insulation removal and application will improve productivity in most operations by a factor in excess of 10 to 1. Originally, the application of the SRB insulation was a semi-automatic operation. The nine ingredients (see Table 1) were measured by hand, placed in a large blender and mixer, and mixed to a uniform consistency required for spraying. This mixture was pressurized and delivered to the

Table 1. Ingredients in the SRB Insulation

1. *2215 Adhesive parts A & B**
2. *Ground Cork*
3. *Glass Ecco Spheres*
4. *Phenolic Micro Balloons*
5. *Chopped Glass Fibers 1/4 inch long*
6. *Milled Glass Fibers 1/8 inch long*
7. *Bentone 27*
8. *Ethyl Alcohol*
9. *Methylene Chloride/per Chloroethylene*

*   *The original adhesive that contained shell*
     z Catalyst was a carcinogenic

spray gun, which was attached to a pedestal mounted robot in the spray cell. The SRB structures were prepared by hand, i.e., sanded, cleaned, inspected, and areas masked that did not require insulation. The SRB structure was mounted on a portable turntable, which was coordinated with the operation of the robot and spray gun. Then

the SRB structure and the turntable were positioned into the spray cell. A technician (with breathing air and protective equipment) was required in the spray cell during actual spraying to take thickness measurements, assist in unplugging the spray gun, and remove the wet insulation, if it did not meet specifications. The cured insulation had to meet a flatwire tensile test of 50 to 100 pounds and a toleranced thickness requirement. Adjustments were made to the delivery system and the insulation reapplied until it met specifications. Preparation of the structure for spraying and insulation required many man-hours.

After automating and robotizing the application of the insulation, the insulation ingredients are automatically measured, blended, mixed, pressurized and delivered to the spray gun, which is mounted on a gantry robot. The gantry robot allows spraying inside the structures without the need to rotate the structure for access. The robot is programmed to automatically attach an end-effector to perform the following operations: sanding, cleaning, inspection, masking, spraying, and thickness measurements. Automating and robotizing the application of insulation eliminated the need for a technician in the spray cell and eliminated many of man-hours of hand work. .

At the start of the SRB refurbishment program, the insulation was removed manually. This required a technician to manually hold a hydrolaser pressurized to 8,000 to 10,000 psi. This created a backwash of 72 pounds force that the technician had to overcome using two 2-men crews rotated every 15 minutes. Any insulation left after this operation was removed by hand using nonmetallic chisels and mallets. Manual removal of the insulation from the two aft skirts required
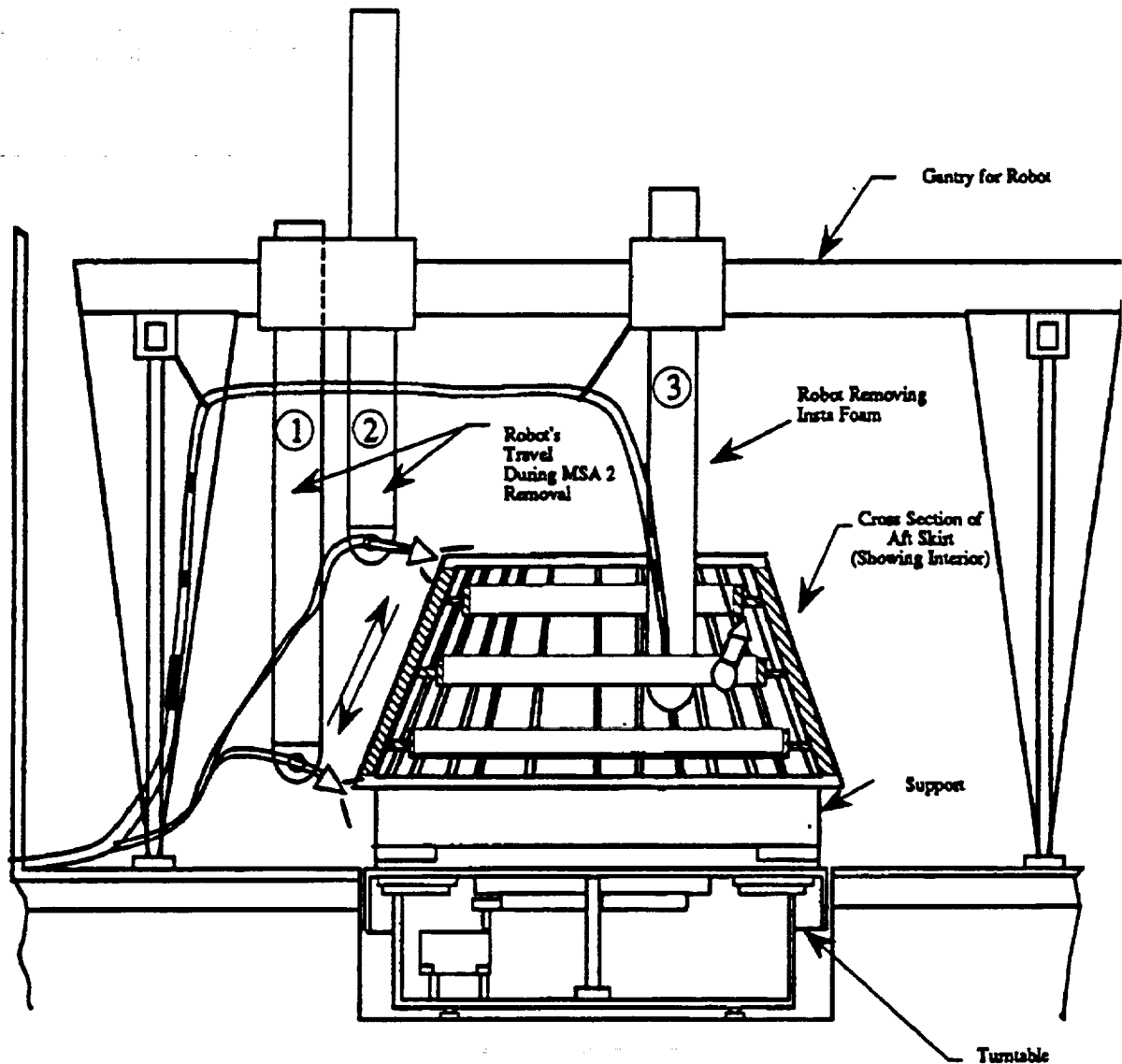
Figure 1. Example Robot Facility: SRB Insulation Removal

① Robot Arm Position for External Insulation Removal (MSA-2)
② Robot Arm Position for External Insulation Removal (MSA-2)
③ Robot Arm Position for Internal Insulation Removal (Insta-Foam)

approximately 400 man-hours.

Procedures for Robotic Removal

Robotizing the removal of the insulation reduced the man-hours for two aft skirts to approximately 64 man-hours. The hydrolaser is mounted on a gantry robot which is located in the removal cell. The pressure to the hydrolaser has been increased to 12,000 to 15,000 psi. Technicians have been eliminated from the hazardous environment. The robot is controlled by computer. A turntable (also controlled by computers) is mounted flush with the floor. After removal of the insulation, the robot is programmed to clean the hydrolaser cell.

Table 2 lists typical reasons for using automated robot cell to apply and remove SRB insulation. Table 3 is a list of the 13 best practices in the design of robotic systems for removal and application of insulation. The most predominant consideration was the high pressure water spray and debris environment encountered in the hydrolaser insulation removal process. Operational maintenance, as well as design, is important in maintaining a safe and

Table 2. Typical Reasons for Using Robots

1. Man out-of-the-loop for hazardous and toxic environments.
2. Efficient; robot does not get tired.
3. Will do whatever it is programmed to do and will do it repeatedly.
4. Will handle various end effectors for sanding, cleaning, inspection, spraying, and thickness measurements.

efficient operation. Potable water is used to reduce corrosion in the pumps, valves, and lines. The use of de-ionized water should be

considered in areas where the water has a high mineral content. Since the water used in the insulation removal process is recycled, the water must be filtered prior to reuse to

Table 3. Best Practices for Robotic Systems

1. Gear Specifications to the environment and the application (i.e., adaption to a solvent or water spray and debris-laden environment).
2. Pay close attention to the ergonomics for operators (i.e., convenience of controls, visibility, manual override, and teaching procedures).
3. Provide sufficient space in robotic facilities for support equipment, mechanisms, personnel, and operational control stations.
4. Design-in automated shutdown to be activated in the event of excessive flow, pressures, temperatures, or inadvertent ingress of personnel.
5. Consider the use of vision systems for alignment, completion status, inspection, and thickness measurements.
6. Provide overload sensing and tactile feedback for delicate operations.
7. Retain manual capability for emergency and backup operations.
8. Establish precise automatic indexing of fixtures with workpiece and robot to minimize setup time.
9. Provide electrical grounding of all system elements.
10. Purchase over-rated equipment. Use only 75% or less of the capacity in the initial design to provide growth potential and operational/maintenance margins.
11. Protect robot elements from solvents in the environment to ensure continued robot lubrication.
12. Train and use dedicated personnel for robotic operations.
13. Establish preventive maintenance requirements during the design phase based on designed-in ease of maintenance features (i.e., proper panel access, calibration test ports, equipment clearances, etc.).

prevent erosion and corrosion of pumping and spray equipment.

For the SRB insulation system removal, the water is filtered to contain particles no greater than 5 microns. On a quarterly basis, or every 100 operating hours, high pressure water pumps are inspected and overhauled if necessary to repair or replace the pump head, pistons, or brass sleeves. Preventive maintenance is performed regularly.

Facility Requirements

A robotic facility of the type used for SRB insulation removal and application must allow operator visibility of the process and careful design for personnel safety and access provisions. During the noisy removal process, personnel within a 50 ft. radius are required to wear ear protection. Operators entering the area during or immediately after spray operations are required to wear protective suits with self-contained breathing apparatus to prevent inhalation or contact with toxic fumes.

Facility design must be carefully coordinated with robot design and robotic operations planning. A concurrent engineering approach is desirable in the design of robotic systems to ensure use of the correct robot, operating in an optimally designed facility, for the target application. A team of engineers and technicians representing all applicable disciplines should be assigned full time to the project throughout design and operations. Three levels of drawings of the robot/facility complex representing: (1) components, (2) subsystems, and (3) the integrated system should proceed through 30, 60, and 90 percent design reviews. Three-dimensional solid modeling simulations using computer-aided design techniques will dramatically speed up the design process. (See the MSFC Guideline titled, "Concurrent Engineering Guideline for Aerospace Systems," in NASA TM 4322, "NASA Preferred Reliability Practices for Design and Test"). The facility must contain support equipment, pumping systems, material storage, control stations, and personnel dressing and clean-up.

Particular attention should be paid to debris handling. Sloped concrete subfloors provide for easy debris collection and clean-up. Automated cell clean-up techniques should be considered for material removal operations.

Special Design Considerations

Robotic systems lend themselves to the effective application of automated emergency shutdown, automatic end-effector changeout, overload sensing, tactile feedback, and manual override. These features should be designed into the robotic system at the outset with participation of the robot vendor. Setup time can be minimized by providing pre-engineered or automatic indexing and relative positioning between the work piece, support tooling or equipment, and robot. While mechanical systems should be over-designed for extra margins of safety against wear and malfunctions, care should be taken not to grossly overdesign control system memory, particularly if a bubble memory is used. This could result in slower robot control system operation.

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MM B8611, *SRB Insulation Manufacturing
Manual (Forward Assembly)*
MM B8616, *SRB Aft Skirt Assembly-MSA-2
TPS Operations Manual*
MM B8630, *MSA-2 Tunnel Cover Assembly
Operations Manual STP 513, Cleaning
Sprayable MSA-2 Insulation Spray*
STP 621, *MSA Control Room Operation*
STP 622, *Installation and Removal of Robot
End Effector Adapters*
STP 634, *Sprayable MSA-2 Insulation
Control Room and Mix Operations*
TP 741, *MSA-2 Spray System Preparation -
ARF*
SESP (Safety Engineering Standard
Procedure) 23405, *Safety Requirements for
Robot Systems*

Technique	Prior to venting a hydrogen (H_2) system, initiate a gaseous helium (GHe) sweep purge to evacuate air from the vent line. After venting operations are complete, initiate a second GHe sweep purge to evacuate the vent system of residual H_2. Use a flapper valve or check valve on the vent line to prevent air intrusion into the line during low or intermittent flow conditions.

GHe PURGING OF H₂ SYSTEMS

Purge a hydrogen system with gaseous helium to greatly reduce the chances of catastrophic events during venting

Benefits	This practice greatly reduces the possibility of a vent line fire and/or explosion during H_2 venting operations. It is impractical to supply the large quantities of GHe required to create a non-flammable H_2/He mixture during H_2 venting operations. The upper flammability limits of a gaseous H_2/air mixture is lower with no GHe present. This technique also provides substantial safety benefits.
Key Words	Purge, Hydrogen, H_2, Helium, GHe
Application Experience	National Space Transportation System (NSTS)
Technical Rationale	Use of dilution purges when venting explosive gases such as hydrogen is not necessarily desirable. • Mixtures of H_2/He do not become non-flammable until the mixture is 91% He. • For "fuel rich" hydrogen/helium mixtures in air, the flammability limit increases with increasing He content, until 85% He mixture is obtained.
Contact Center	**Kennedy Space Center (KSC)**

GHe Purging of H₂ Systems
Technique OPS-4

This technique recommends initiating a GHe sweep purge to evacuate air from a vent line prior to venting a H₂ system. After the initial venting operation is complete, a second GHe sweep purge should be conducted to evacuate the vent system of residual H₂. The upper flammability limits of a gaseous H₂/air mixture is lower with no GHe present (see Figure 1). A flapper valve or check valve used on the vent line will prevent air intrusion into the line during low or intermittent flow conditions.

This practice should be included in all new systems operating procedures and changes initiated to applicable existing procedures. System design should be reviewed to include the following as recommended by NASA TM X-52454 (Lewis Research Center):

- Include a check valve/flapper valve or other suitable mechanism to exclude air from vent stacks at low or intermittent flow conditions.

- Extend vent stacks 15 ft. above a building roof.

- Discontinue use of ordinary hydrocarbon flame arresters which are incapable of quenching a H₂ flame.

- Provide a minimum of a 3-volume exchange (pulse purges) to sweep system prior to introducing hydrogen.

Five to 10 volume exchanges to purge a vent system is a commonly acceptable industry practice.

Reference

H. Hannah, LSOC 32-30, *FCSS Hazardous Commodity Purge Study*, dated September 1991.

HAZARDOUS COMMODITY PURGES
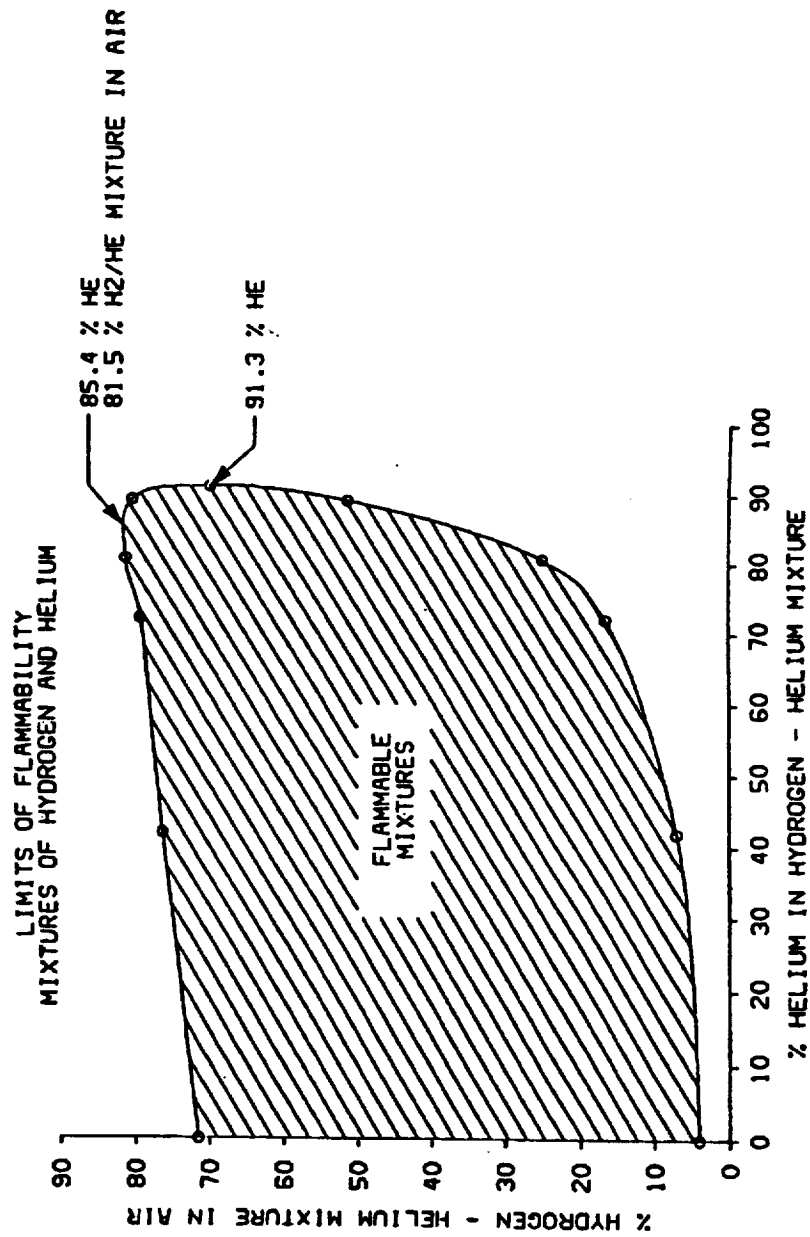
Figure 1. Limits of Flammability-Mixtures of H_2 and He

Technique	Use solid state Programmable Logic Controllers (PLC's) in system/equipment design to control and monitor systems and processes.
PROGRAMMABLE LOGIC CONTROLLERS *Use of programmable logic controllers results in ease of maintenance through modularity, replaceability, and ability to troubleshoot*	
Benefits	System/equipment design using PLC's is a prime example of the application of maintainability design objectives. PLC's are designed with ease of maintenance and troubleshooting as a major function. When virtually all components are solid state, maintenance is reduced to the replacement of a modular, plug-in type component. Fault detection circuits and diagnostic indicators, incorporated in each major component, can tell whether the component is working properly. With the programming tool, any programmed logic can be viewed to see if input or outputs are on or off.
Key Words	Controller, Programmable
Application Experience	Space Transportation System (STS), Facilities and Ground Support Systems.
Technical Rationale	Conventional relay-based control systems are more subject to failure and cannot handle complex processing as efficiently as PLC'S. Use of PLC's in system design will reduce failure rates and subsequent downtime, ultimately saving a program money.
Contact Center	**Kennedy Space Center (KSC)**

Programmable Logic Controllers
Technique OPS-5

PLC'S provide control capabilities not possible in the past. Control systems incorporating programmable controllers are now able to operate machines and processes with an efficiency and accuracy never before achievable with conventional relay-based control systems. Usually, PLC architecture is modular and flexible, allowing hardware and software elements to expand as the application requirements change. If an application outgrows the limitations of the PLC, the unit can easily be replaced with a unit having greater memory and input/output capacity, and the old hardware can be reused for a smaller application.

PLC attributes make installation easy and cost effective. Their small size allows PLC'S to be located conveniently, often in less than half th   pace required by an equivalent relay contro. panel. On a small scale changeover from relays, the PLC'S' small and modular construction allows it to be mounted near the relay enclosure and pre-wired to existing terminal strips. Actual changeover can be made quickly by simply connecting the input/output devices to the pre-wired terminal strips. Table 1 lists some features available and benefits of PLC'S.

In large installations, remote input/output stations are placed at optimum locations. The remote station is connected to the processor by a pair of twisted wires. This configuration results in a considerable reduction of material and labor cost that would have been associated with running multiple wires and conduits.

PLC Components and Operation
PLC'S, regardless of size, complexity, or cost, contain a basic set of parts. Some of the parts are hardware; others are software

Table 1. Typical Programmable Logic Controller Features/Benefits

Features	Benefits
Solid State Components	High reliability
Programmable Memory	Simplifies changes Flexible control
Small Size	Minimal space requirements
Microprocessor Based	Communications capability Higher level of performance Higher quality products Multi-function capability
Software Timers/Counters	Eliminate hardware Easily changed presets
Software Control Relays	Reduced hardware wiring costs Reduced space requirements
Modular Architecture	Installation flexibility Easily installed Hardware purchases minimized Expandability
Variety of I/O Interfaces	Controls variety of devices Eliminates custom control
Remote I/O Stations	Eliminates long wiring conduit runs
Diagnostic Indicators	Reduced troubleshooting time Proper operation of signal
Modular I/O Interface	Neat appearance of control panel Easily maintained Easily wired
Quick I/O Disconnects	Service w/o disturbing wiring
All System Variables Stored in Memory	Useful management/ maintenance Data can be output

or programs. Figure 1, identifies the basic parts of the PLC. In addition to a power supply system and a housing that is

--[PARTS OF A PROGRAMMABLE CONTROLLER]--

Signals From Process

INPUT INTERFACE

PROGRAMMING TOOL

CPU

MEMORY

PROGRAMMING LANGUAGE
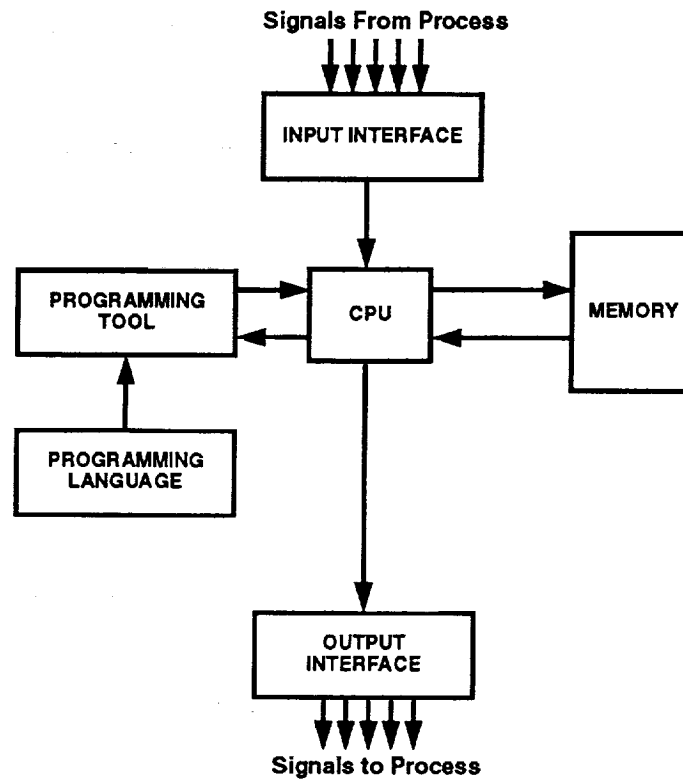
OUTPUT INTERFACE

Signals to Process

Figure 1. Parts of a Programmable Controller

appropriate for the physical and electrical environment, PLC's consist of the following parts: an input interface, central processor unit (CPU), memory section, programming language, programming tool, and an output interface.

The Input Interface provides connection to the machine or process being controlled. The principal function of the interface is to receive and convert field signals into a form that can be used by the central processing unit.

The Processor and Memory provide the main intelligence of the PLC. Fundamental operating information is stored in memory as a pattern of bits that is organized into working groups called words. Each word stored in memory is either an instruction or piece of data. The data may be reference data or a stored signal from the process that has been brought in through the input interface. The operation of the processor and memory of the PLC can be described as a fairly simple repetitive sequence:

1. Look at the process being controlled. This is accomplished by examining the information from the input interface.

2. Compare the information with control information supplied by and stored in the program.

3. Decide whether any control action is needed.

4. Execute the control action by transmitting signals to the output interface.

5. Look again at the inputs.

The processor continually refers to the program stored in memory for instructions concerning its next action and for reference data.

The Output Interface takes signals from the processor and translates them into forms that are appropriate to produce control actions by external devices.

The Program and Program Language. The program is written by the user and stored in the PLC. The program is a representation of the actions that are necessary to produce the desired output control signals for a given process condition. The program includes sections that deal with bringing the process data into the controller memory, sections that represent decision making, and sections that deal with converting the decision into physical output action. Programming languages have many forms. Early versions were restricted to match the conventions of relay logic which consisted of ladder diagrams that specified contact closure types and coils. This type of program consists of a representation of a relay logic control scheme. The relay ladder language types are

still popular. Alternative languages use Boolean representation control schemes as the base of the computer representation.

The Programming Tools provide connection between the programmer and the PLC. The programmer devises the necessary control concepts and then translates them into the particular program form required by the selected PLC. The tool produces the pattern of electrical signals that corresponds to the symbols, letters, or numbers in the version of the program that is used by humans.

Process Improvements
The use of control and monitor equipment with the benefit of a PLC could lead to:

• Increased system availability

• Decreased downtime requirements to recover from a failure

• Decreased cost in materials and man-hours for installation

• Increased system visibility

• Increased flexibility to meet new requirements.

Reference

National Technology Transfer Inc. (PLC Seminar, Aurora, Colorado, 1992)

Technique	During the design of new (or upgrades to) motor generator set type DC drives, consider the use of solid state assemblies for control functions.

DC DRIVE — SOLID STATE CONTROL

Use solid state regulators on motor generator sets to enhance fault detection and diagnostics

Benefits	Use of solid state controls instead of magnetic amplifiers can improve system restoration time in the event of a failure. Features such as fault detection, modular construction, and packaging can be easily employed. Diagnostics for system health status and problem resolution can also be readily provided. Incorporation of these features can result in improved system performance and availability.
Key Words	Solid State Assemblies, System Restoration, Maintainability, Performance, Availability
Application Experience	National Space Transportation System Shuttle Ground Support Systems.
Technical Rationale	At KSC the 175- and 250-Ton Bridge Cranes in the Vehicle Assembly Building (VAB) were using metadynes (electromechanical rotating amplifiers) for control function. The metadyne had a long history of maintenance problems because of brush wear, contamination and corrosion. It required extensive pre-operation maintenance attention to support Shuttle processing. In addition, the metadyne units often required maintenance during processing operations impacting processing schedules. KSC replaced the metadynes with solid state controller units resulting in decreased maintenance actions including pre-operation maintenance and improved system performance and availability. Fault isolation and removal and replacement of failed components is easier and less time consuming. Since failures occur at a less frequent rate, the need for numerous operating spares is reduced. Furthermore, the "off equipment" in-shop maintenance of failed units requires much less time and money to effect a repair. Reduced maintenance and downtime allow for the crane to be ready and operating to support Shuttle processing in a more timely manner.
Contact Center	**Kennedy Space Center (KSC)**

DC Drive - Solid State Control
Technique OPS-6

The use of solid state assemblies for control functions represents a great improvement over previous control methods. Historically, the first method of obtaining adjustable speed using DC motors was the constant potential DC supply using field adjustment. This provided a small range of adjustment. This method was followed by the rotating M-G system of Ward Leonard patented in the 1890's. This drive used an AC motor driving a DC generator to convert AC to DC power. The motor and generator may be combined in a single frame and use a common shaft, or separate coupled units (See Figure 1). The output DC voltage is controlled by adjusting the field excitation of the DC generator. Depending on the accuracy required, armature voltage or a tachometer may be used as a feedback signal in a closed loop system. An important aspect of this drive is that power flow is reversible. The motor acts as a generator, driving the generator as a motor, which drives the AC motor which then pumps power back into the AC lines. This ability, called regeneration, is a useful feature in decelerating large inertias or holding back overhauling loads. This is a very important consideration when replacing the M-G with a conventional packaged silicon-controlled rectifier (SCR) drive.

In the late 1940's, electronic tube drives began to replace M-G drives. These used vacuum, thyratron, excitron, or ignitron tubes for armature circuit control. They had limited acceptance because of tube life limits and water cooling requirements on larger ratings. By the early 1960's the tubes were replace with the solid state thyristor drives. Magnetic amplifier drives were developed in the mid-1950's when silicon diodes became popular. They were never as widely used because of difficulties of reactor design and

acceptable response rate. However, they were rugged and highly reliable once in satisfactory operation.

During the early 1960's the thyristor or SCR became readily available. This device is similar in operation to a thyratron tube. Today it dominates the direct current drive field. Special circuits enable the SCR to regenerate and reverse readily. Larger and less expensive SCR's have extended the range to well over 1000 HP. Figure 2 illustrates a controlled rectifier drive. Note that the gateing control and SCR bridge have replaced the M-G set of Figure 1, resulting in reduced rotating machinery.

Solid State Operation
Figure 3 shows the assemblies comprising a solid state control system for DC drives. A single phase thyristor power converter supplies up to 200 volts positive or negative at 20 amperes to the generator field. A closed-loop controller (speed regulator) provides for armature voltage with IR drop compensation or AC/DC tachometer feedback speed control and linear acceleration and deceleration. A firing circuit provides an isolated gate drive to the power converter. A bi-directional adapter used in conjunction with the firing circuit assembly provides bi-directional current to the field of a DC generator for contactorless reversing or to regulate to zero output voltage in the presence of residual magnetism of the DC generator. Protective circuitry includes a voltage sensing relay for safety interlocking and an isolator for isolated armature current feedback.

References

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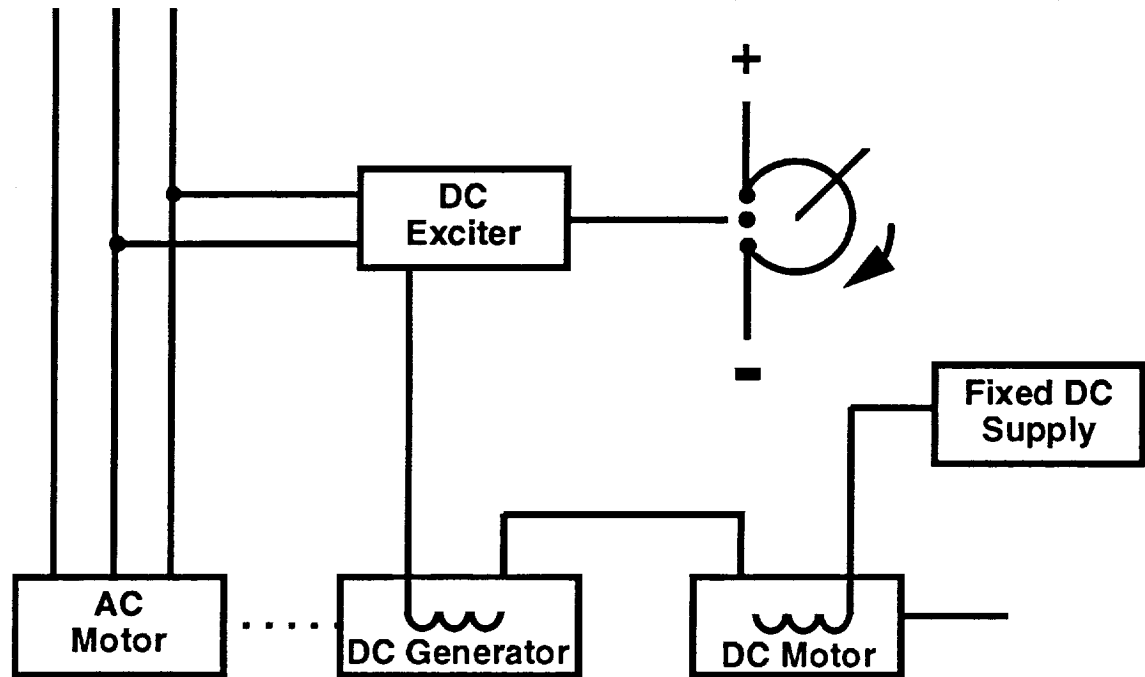
3-Phase AC Supply

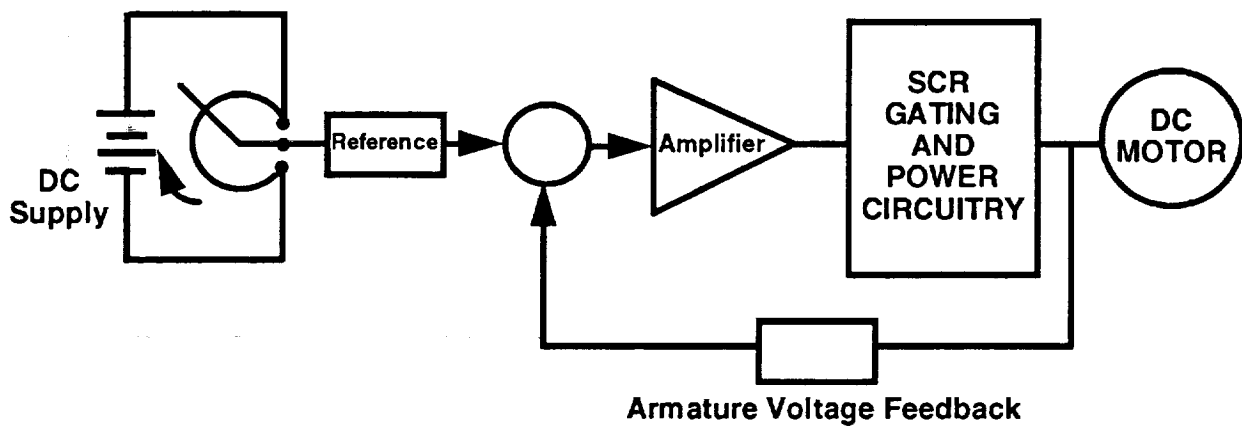*Figure 1. Rotating M-G System*

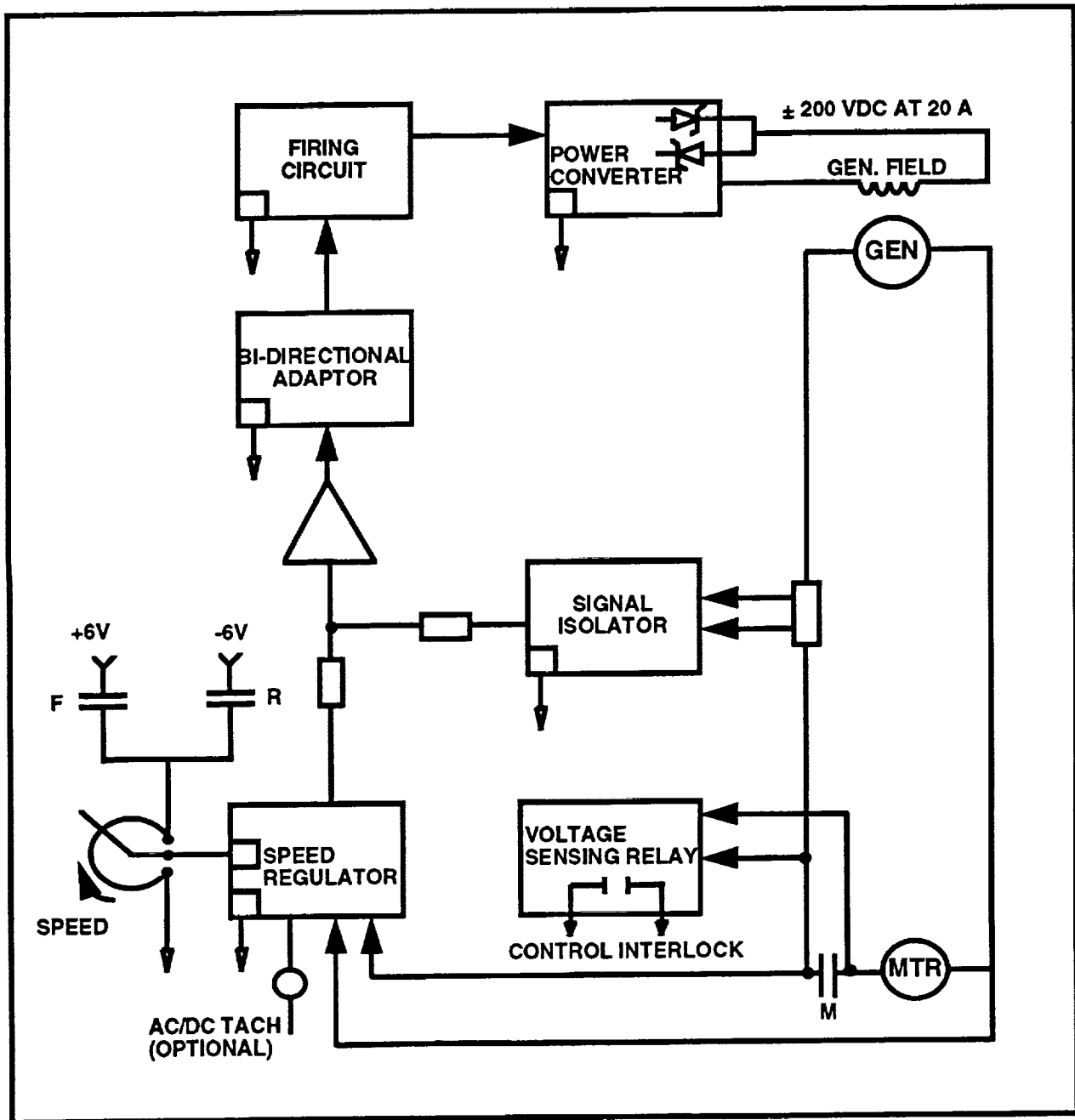*Figure 2. Controlled Rectifier Drive*

Figure 3. M-G Control-Reversing Simplified Schematic Motor Generator

Technique	During the design of new or modifications to existing systems requiring motor speed control, consider the use of alternating current (AC) variable frequency drive systems for motor control.

AC - VARIABLE FREQUENCY DRIVE SYSTEMS

AC variable frequency systems for motor speed control offer advantages over other mechanical methods

Benefits	AC variable frequency drive systems for motor speed control offer several advantages over systems that use DC or AC motors coupled with mechanical devices (clutches and pulleys) to achieve motor speed control. These advantages enhance system maintainability resulting in: • Improved system maintainability, reliability, and performance. • Reduction of preventive and corrective maintenance (manhours and materials) by elimination of mechanical devices. • Increased system availability. • Self-contained diagnostic test capability. • Reduced size and mechanical complexity. • Reduced life cycle costs.
Key Words	AC Variable Frequency Drive, System Performance, Availability
Application Experience	Launch Complex 39A & B, Main Propulsion System, Liquid Oxygen Subsystem
Technical Rationale	Variable frequency drive systems are installed at the Shuttle launch pads at KSC. The system allows for a direct coupling between the main propulsion system liquid oxygen pump and drive motor. This eliminates the motor clutch system, a high maintenance item, and gaseous nitrogen lines used to purge the clutch system.
Contact Center	**Kennedy Space Center (KSC)**

AC - Variable Frequency Drive Systems
Technique OPS-7

The use of A/C variable frequency drive systems provides greater efficiency for motor speed control than mechanical devices with DC or AC motors. AC variable frequency drive systems allow for direct coupling and eliminates the need for mechanical devices such as clutches and pulleys. Elimination of these mechanical devices results in decreased maintenance downtime and repair costs. Adjustable speed AC drives also offer many advantages over DC drives because of simplicity, high-speed capability, and low maintenance requirements of induction motors. These motors are suitable for adverse conditions such as dirty air, explosive atmospheres, and inaccessible locations.

Components

Typically, an adjustable frequency drive system for an AC induction motor will consist of a converter module, DC link module, and inverter module. The following is a description of an adjustable frequency drive system. The configuration shown and the type of control scheme used classify the drive as a current source inverter type. Figure 1 illustrates three fundamental steps used in converting the AC input into a variable AC output.

The converter module can be thought of as a programmable DC voltage source where the three AC input lines are rectified by silicon controlled rectifiers (SCR's) to provide a variable DC output. An SCR can be thought of as a controlled rectifier or switch that lets current flow in the forward direction when gated or opened. Then it cannot shut off again until the flow reverses or ceases. At this point the SCR regains its forward blocking capability until gated again.

The control circuitry in the drive turns the SCR's on 60 times per second to obtain the desired current flow. Each time a new SCR is gated, it then forces a previous one to shut off. If it is necessary to turn off all the SCR's, all gate signals are removed and the SCR's then turned off naturally when the AC input voltage is reversed.

The DC link module is so called because it is a device that connects the inverter and converter modules. Electronically it is an inductor or choke that filters the output of the converter module and provides a more uniform flow of current to the inverter module. Since the inductor tries to maintain a constant flow of current through it, this allows the voltage source converter to function as a current source to the inverter module.

The inverter module takes the filtered DC from the DC link module and converts it back to AC. Here the SCR's are gated, one after the other, steering this DC into and out of each of three input lines to the motor. The faster the SCR's are fired, the faster the motor turns. Since the AC line is not present here, external commutating capacitors are used to ensure that each time a new SCR is fired, an old or previously conducting one is shut off.

Drive Operation

The following paragraphs briefly discuss some of the characteristics of the drive:

a. Output voltage and current normally delivered to a motor from the AC input line are both sinusoidal. This is not true when operating the motor from a current source inverter (see Figure 1). The voltage waveform is closely sinusoidal with disturbances called commutation spikes. The output current is a high quality quasi-square
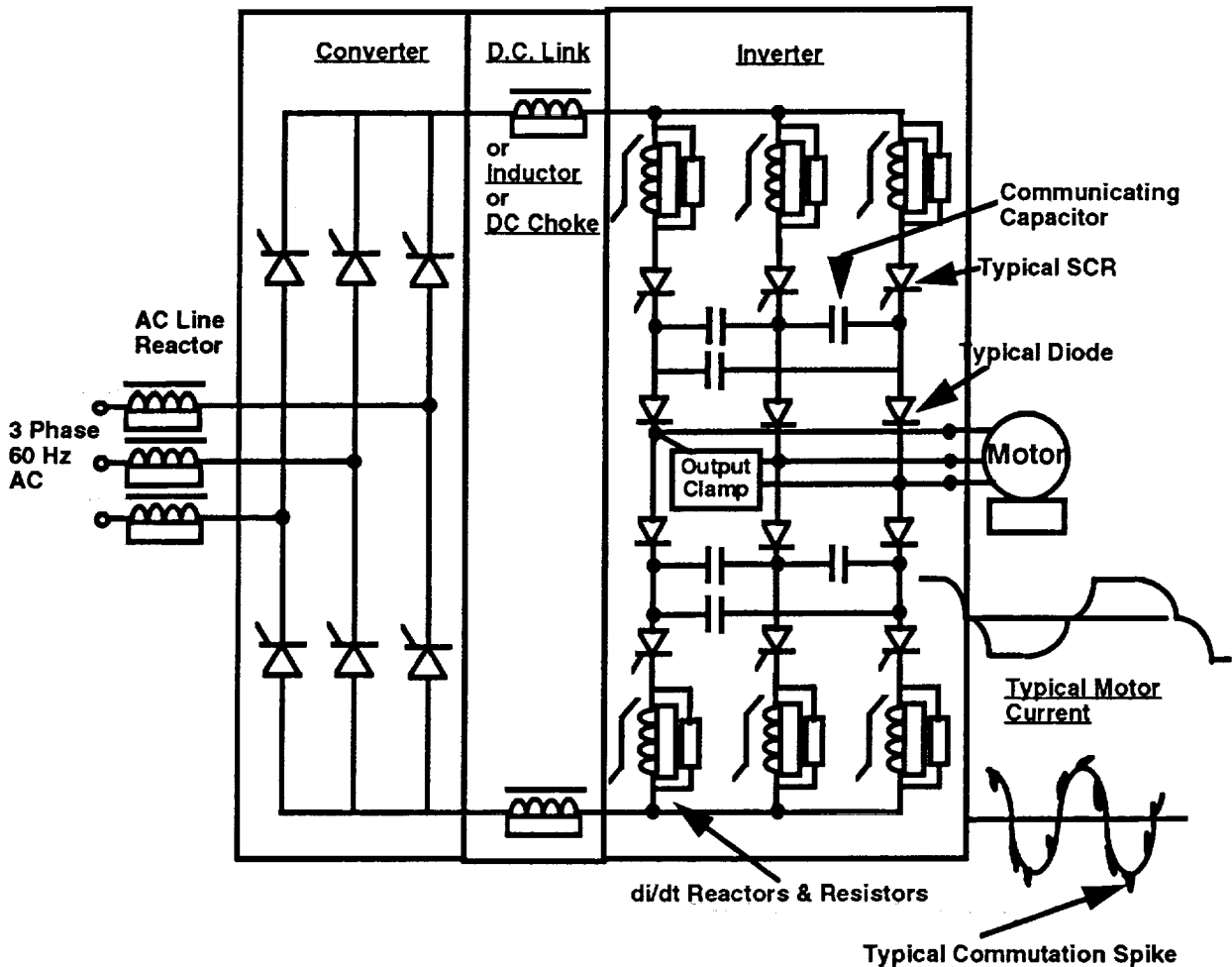
Figure 1. Simplified Adjustable Speed Drive

waveform. The current source inverter makes no attempt to define the shape of the output motor voltage. The output voltage is simply a result of the current and rotation of the motor. The shape of the current waveform is defined and its level is increased or decreased to obtain the required voltage. Stated more simply, the control circuitry contains an inner current regulator loop with an outer voltage regulator loop that ensures that the proper current and voltage are supplied to the motor.

b. Crowbar: Since during normal operating conditions the DC link or choke is carrying a large current, which implies a large amount of stored energy, it is worth discussing what happens should the input or output to the drive be suddenly disconnected. The inductor would normally develop whatever voltage is needed to maintain the constant flow of DC. To mitigate the danger of these damaging voltage levels, protective circuits are incorporated within the drive to provide a path for this DC. The protective schemes are based on the capability of both the

inverter and converter modules to provide a path for this current by firing two series SCR's in the converter and inverter modules, thus generating a direct short circuit path through which the current trapped in the inductor may flow. The process of firing these SCR's to provide a current path is called "crowbar."

c. Output clamp: With an abrupt loss of load, the protective mechanism operates as follows. The inverter output leads to the motor are equipped with a device called an "output clamp." If the motor is abruptly disconnected, the output current from the inverter will transfer to this clamp circuit until its level hits 950 volts DC. At this point, the control circuitry will force a "crowbar" and shut off the converter module. This prevents any further increase in output voltage; an orderly shutdown is performed.

d. Commutation: Commutation is a process by which an SCR is forced out of a conducting state by reverse biasing. Two types of commutation normally occur in the power circuit, natural and forced.

e. Regeneration: The SCR converter is a two-quadrant device capable of accepting power from the DC bus and returning it to the line when the DC bus potential is negative. This capability makes the current source inverter one of the few inverter types that are inherently regenerative without excessive circuit complication.

f. Low speed cogging: Each commutation in the inverter module causes the current flow to the motor to be abruptly stopped in one phase and started in another. This action forces the motor to turn one-sixth of a rotation on a 2-pole machine, one-half on a 4-pole machine, etc. This explains why, at

very low speeds, the motor appears to move in discrete steps rather than smoothly rotate. At a frequency of 1 Hertz, for example, a two-pole machine would perform one complete rotation in six distinct steps at a rate of six steps per second. This effect is reduced depending on the inertia of the connected load. The visual effect completely disappears at speeds above a few Hertz.

References

1. KSC Electrical Advanced Schematic Drawing 79K06382.

2. KSC Electrical Advanced Schematic Drawing 79K40029.

Technique	During new design or upgrades to existing transmission systems, consider the use of fiber optic systems in place of metallic cable systems.
	FIBER OPTIC SYSTEMS *Use of fiber optics provides superior maintainability characteristics and significant maintenance advantages over metallic cable*
Benefits	Properly designed fiber optic transmission systems will last for long periods of time without any preventive maintenance and can offer reduced maintenance downtime and repair costs. Well-built optical transmission lines and couplers are relatively immune to electromagnetic interference, adverse temperature, and moisture conditions and can be used for underwater cable. An optic fiber can be 20 times lighter and five times smaller than copper wire and still carry far more energy. Using fiber optic control circuits provides electrical isolation for safety in hazardous environments. Because optical cables carry no current they are safe to use in explosive environments and eliminate the hazards of short circuits in metal wires and cables.
Key Words	Fiber Optics, Maintainability
Application Experience	Kennedy Space Center Ground Support Systems (e.g., Launch Processing System, Ground Communications System).
Technical Rationale	Fiber optics can enhance the transmission quality, capacity, and safety environment of the system. The system designer should carefully weight the pros and cons of fiber optics vs. copper, microwave, or satellite for the transmission medium. Optical fiber, if cabled and installed properly, will last for years without any preventive maintenance. Reliability of optical cable is very good, and will enhance system availability, minimize downtime for maintenance, and reduce repair costs.
Contact Center	**Kennedy Space Center (KSC)**

Fiber Optic Systems
Technique OPS-8

Components and Operation

The basic elements found in fiber optic systems are a transmitter, fiber optic cable, receiver, and connectors. Figure 1 illustrates the main parts of a fiber optic system. The following is a brief description of these elements and their function:

- The Transmitter converts an electrical signal to a light signal. The transmitter consists of a driver and a source. The input to the driver is the signal from the equipment being served. The driver circuit changes the input signal into a form required to operate the source. The source, either a light-emitting diode (LED) or laser diode, does the actual conversion.

- The Fiber Optic Cable is the medium for carrying the light signal. The main parts of a fiber cable are the optical fiber, cladding, buffer jacket, buffer, strength members, and jacket. Figure 2 illustrates the main parts of a single fiber cable. The optical fiber contains two concentric layers called the core and the cladding. The inner core is the light-carrying part. The surrounding cladding provides the difference in refractive index that allows total internal reflection of light through the core. The buffer is the plastic coating applied to the cladding.

Cable buffers are one of two types, loose or tight. The loose buffer uses a hard plastic tube having an inside diameter several times that of the fiber. One or more fibers lie within the buffer tube. The tube isolates the fiber from the rest of the cable and the mechanical forces acting on it. The buffer becomes the load bearing member. As the cable expands and shrinks with changes in temperature, it does not affect the fiber as much. A fiber has a lower temperature coefficient than most cable elements, meaning that it expands and contracts less. The tight buffer has a plastic directly applied over the fiber coating.

This construction provides better crush and impact resistance; however, it does not protect the fiber as well from stresses of temperature variations. Because the plastic expands and contracts at a different rate than the fiber, contractions caused by variations in temperature can result in loss-producing microbends. Tight buffers are more flexible and allow tighter turn radii. Therefore; tight tube buffers are useful for indoor applications where temperature variations are minimal and the capability to make tight turns inside walls is desired.

Strength members add mechanical strength to the fiber cable. The most common strength members are Kevlar Aramid yarn, steel, and fiberglass epoxy rods. During and after installation, the strength members handle the tensile stresses applied to the cable so that the fiber is not damaged. Kevlar is most commonly used when individual fibers are placed within their own jackets. Steel and fiberglass members find use in multi-fiber cables. Steel offers better strength than fiberglass, but may not be the best choice for maintaining an all dielectric cable. Steel also attracts lighting, whereas fiber does not. The jacket-like wire insulation provides protection from the effects of abrasion, oil, ozone, acids, alkali, solvents, etc. The choice of jacket material depends on the degree of resistance required for different influences and costs.

- The Receiver accepts the light signal and converts it back to an electrical signal. The

receiver contains a detector, amplifier, and an output section. The amplifier enhances the attenuated signal from the detector. The output section performs many functions such as: separation of the clock and data, pulse reshaping and timing, level shifting to ensure compatibility (TTL, ECL, etc.) and gain control.

• <u>Connectors and splices</u>, which link the various components of a fiber optic system, are vital to system performance. A connector is defined as a disconnectable device used to connect a fiber to a source, detector, or another fiber. It is designed to be easily connected and disconnected many times. A splice is a device used to connect one fiber to another permanently. Connection by splices and connectors couples light from one component to another with as little loss of optical power as possible. The key to a fiber optic connection is precise alignment of the mated fiber cores (or spots in single-mode fibers) so that nearly all the light is coupled from one fiber across the junction to the other fiber. Contact between the fibers is not required. However, the demands of precise alignment on small fibers create a challenge to the designer of the connector or splice.

Maintainability design features that should be addressed in the design for fiber optic systems should provide for fault localization and isolation, modular replacement, and built-in test and check-out capability.

Improvements
Fiber optics systems offer many benefits. In sensing systems, sensitive electronics can be isolated from shock, vibration, and harsh environments, resulting in more economical packaging. The number of repeaters required for low attenuation cable is less than

with conventional systems and for short hauls of less than 10 km, no repeaters are necessary. In the absence of electrical current, the life of a fiber optic system's components equals the useful life of the control system, the light source, and the electronics. Maintenance and repair costs are reduced dramatically. Installation costs of fiber optic cables are lower than metal cables because the shipping and handling costs are about one-fourth and labor costs one-half that of current metal cables.

References

1.   RADC-TR-88-124, *Impact of Fiber Optics on System Reliability and Maintainability*, June 1988.

2.   RADC-TR-80-322, *Failure Rates for Fiber Optic Assemblies*, October 1980.

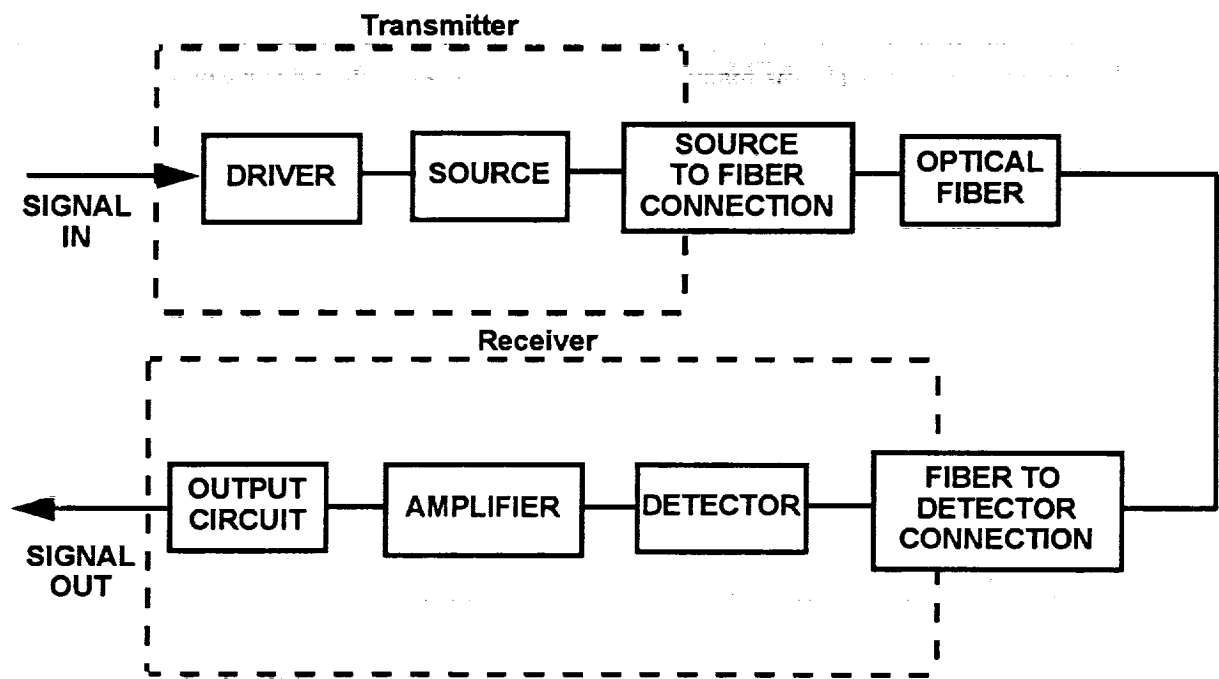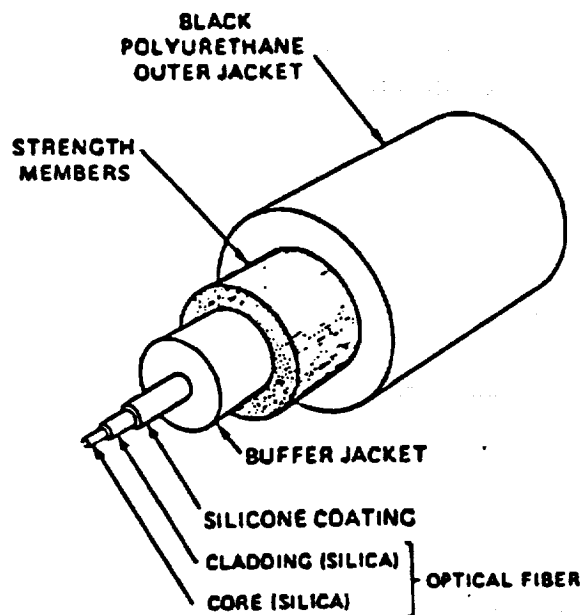3.   AWP, *Technician's Guide for Fiber Optics*, 1987.

Transmitter

```
SIGNAL     DRIVER  —  SOURCE  —  SOURCE      —  OPTICAL
IN                                TO FIBER       FIBER
                                  CONNECTION
```

Receiver

```
         OUTPUT   —  AMPLIFIER  —  DETECTOR  —  FIBER TO
         CIRCUIT                                 DETECTOR
SIGNAL                                           CONNECTION
OUT
```

Figure 1. Basic Fiber Optic Link

BLACK
POLYURETHANE
OUTER JACKET

STRENGTH
MEMBERS

BUFFER JACKET

SILICONE COATING

CLADDING (SILICA) } OPTICAL FIBER

CORE (SILICA)

Figure 2. Parts of a Fiber Optic Cable

C-2

Technique	Use a separate, hand-operated, spring-loaded, vented regulator in pneumatic system designs to provide reference pressures for pilot controlled pressure regulators. Specify application in system/equipment specifications, requirements documents, and design policies and practices.

PNEUMATIC SYSTEMS— PILOT-CONTROLLED PRESSURE REGULATOR LOADING

Use vented pressure regulators for reference pressures to ensure maintainability of pneumatic systems

Benefits	Design of a pneumatic systems using vented pressure regulators offers the following maintainability advantages: • Requirement for a separate relief valve in the pilot-loading circuit is eliminated. • Logistics support requirements (materials, parts, tools) are decreased by elimination of additional relief valves. • System availability is increased by elimination of additional components and their maintenance/downtime requirements. • Elimination of components enhances maintainability and increases reliability. • Overall life cycle costs are improved by decreased maintenance and downtime requirements, and increased system availability.
Key Words	Pneumatic, Regulator, Pressure
Application Experience	Apollo, National Space Transportation System (STS), Pneumatic Ground Support Systems
Technical Rationale	When pneumatic system requirements mandate the use of pilot operated pressure regulators, the use of vented pressure regulators to supply reference pressure is mandatory. This reduces the system component count and associated logistics requirements.
Contact Center	**Kennedy Space Center (KSC)**

Pneumatic Systems - Pilot-Controlled
Pressure Regulator Loading
Technique OPS-9

Pressure in pneumatic systems must be
controlled. Primary points of control are
downstream of the source (compressor) and
the system receiver (tank). Control of
pressure is required downstream of the
compressor for system safety and
downstream of the receiver to maintain a
steady pressure source for efficient operation
of other system components. Pneumatic
systems use pressure regulators to provide
this control. For those systems using
standard dome-loaded (pilot-operated)
regulators, this practice requires use of
separate vented regulator for loading the
pilot operated regulators. Figure 1 shows a
regulator system with separate relief valves.
A venting type regulator limits downstream
pressure to a level lower than that of the
upstream (receiver) pressure. It also acts as
a relief valve for its leg of the circuit in the
event of pressure build up. This method
eliminates the need for a separate relief valve
in the dome-loading circuit. Figure 1 also
shows an example of a vented system which
illustrates this method.

References

1. KSC-SD-Z-0005A, *Standard for Design*
of Pneumatic Ground Support Equipment.

2. Parker-Hannifin Corp., Bulletin 0225-
B1, *Fluid Power.*

NON–VENTING

REGULATOR (NON–VENTING)
SPRING LOADED

RELIEF VALVE
(VENT)

PNEU.
INPUT

REGULATED
OUTPUT

PILOT OPERATED
(DOME LOADED)
REGULATOR

VENTING

(VENT)

REGULATOR (VENTING)
SPRING LOADED

PNEU.
INPUT

REGULATED
OUTPUT

PILOT OPERATED
(DOME LOADED)
REGULATOR
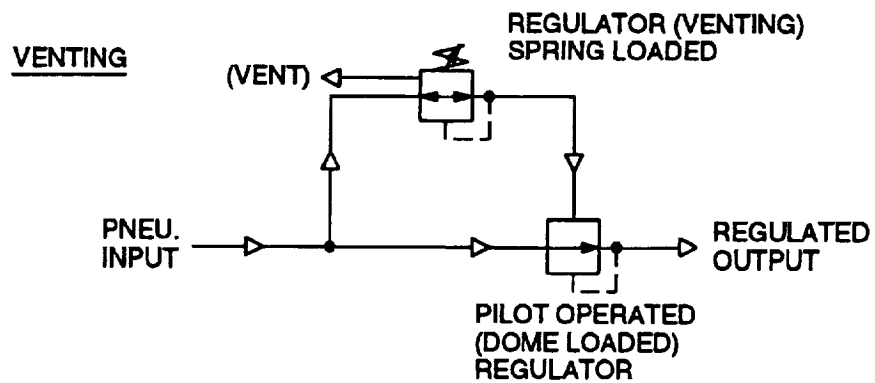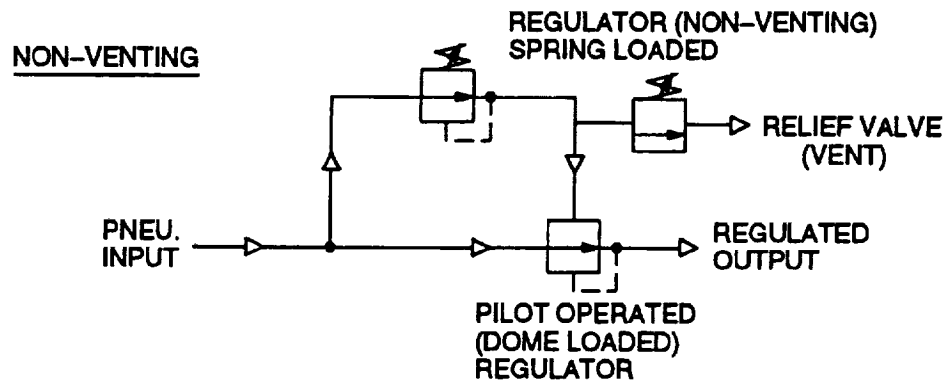
THIS APPLICATION ELIMINATES
THE RELIEF VALVE

Figure 1. Examples of Non-Vented and Vented Regulator Systems (Schematics)

Technique	Incorporate modular, fault tolerant power switching devices in new system designs and system upgrades. Specify application in system/ equipment specifications, requirements documents, and design policies and practices.

MODULAR AUTOMATED POWER SWITCHING DEVICE

Use modular, automated, fault tolerant power switching devices to enhance maintenance procedures

Benefits	Miniaturizing of conventional electronic components and assembling them in convenient groupings provides the following benefits: • More efficient base of maintenance can be achieved. • Logistics support requirements (materials, parts, etc.) are reduced by stocking modules as opposed to piece parts. • Keeping modules at lowest level of maintenance (throw-away) will minimize the requirements for sophisticated test equipment and highly skilled technicians. • Modular design will result in improved fault detection by isolating the problem at the module level instead of at the piece part level. • Module design can be sized to accommodate various loads. • Sealed modules provide increased environmental protection.
Key Words	Power, Switching, Modular
Application Experience	National Space Transportation System
Technical Rationale	Incorporation of the technique will achieve the goal of avoiding high maintenance costs from premature failure of hardware due to moisture or sand intrusion and other severe environmental conditions. Shuttle program operations around the world have shown that this switchover device has been extremely reliable even under conditions that are normally detrimental to electrical equipment.
Contact Center	**Kennedy Space Center (KSC)**

Modular Automated Power Switching
Device
Technique OPS-10

This technique recommends providing
modular, single-fault tolerant, power
switching devices that enhance ease of
maintenance and expedite system restoration.

Application
The design of lighted visual Landing Aids
presently installed at several Space Shuttle
landing sites around the world specified that
the Ball/Bar lights for the Inner Glideslope
must be powered by a primary and backup
power source with automatic switchover in
the event of primary source failure. The
Reliability/Maintainability Engineers had to
ensure the system would not prematurely fail
and that the switchover mechanism was
relatively inexpensive, self-contained, and
easy to install/maintain. As a result of this
effort, the modularized automated power
switching device was developed and
implemented (see Figure 1).

Failure to utilize this technique could result
in excessive cost if commercial Automatic
Transfer Switches are utilized instead. The
Ball/Bar light system is critical to Shuttle
landing operations. These systems must be
up and operational prior to a Launch
Commit decision. Failure prior to launch
could result in a very costly delay to the
Shuttle program.

References

1. NSTS 07700, Vol. X, *Space Shuttle
Flight & Ground System Specification*, Rev.
J, June 14, 1990.

2. KSC Drawing No. 80K52361, *Automatic
Transfer Switch Wiring Diagram for
Ball/Bar Lights.*

Figure 1. Modularized Automatic Power Source Switching Device
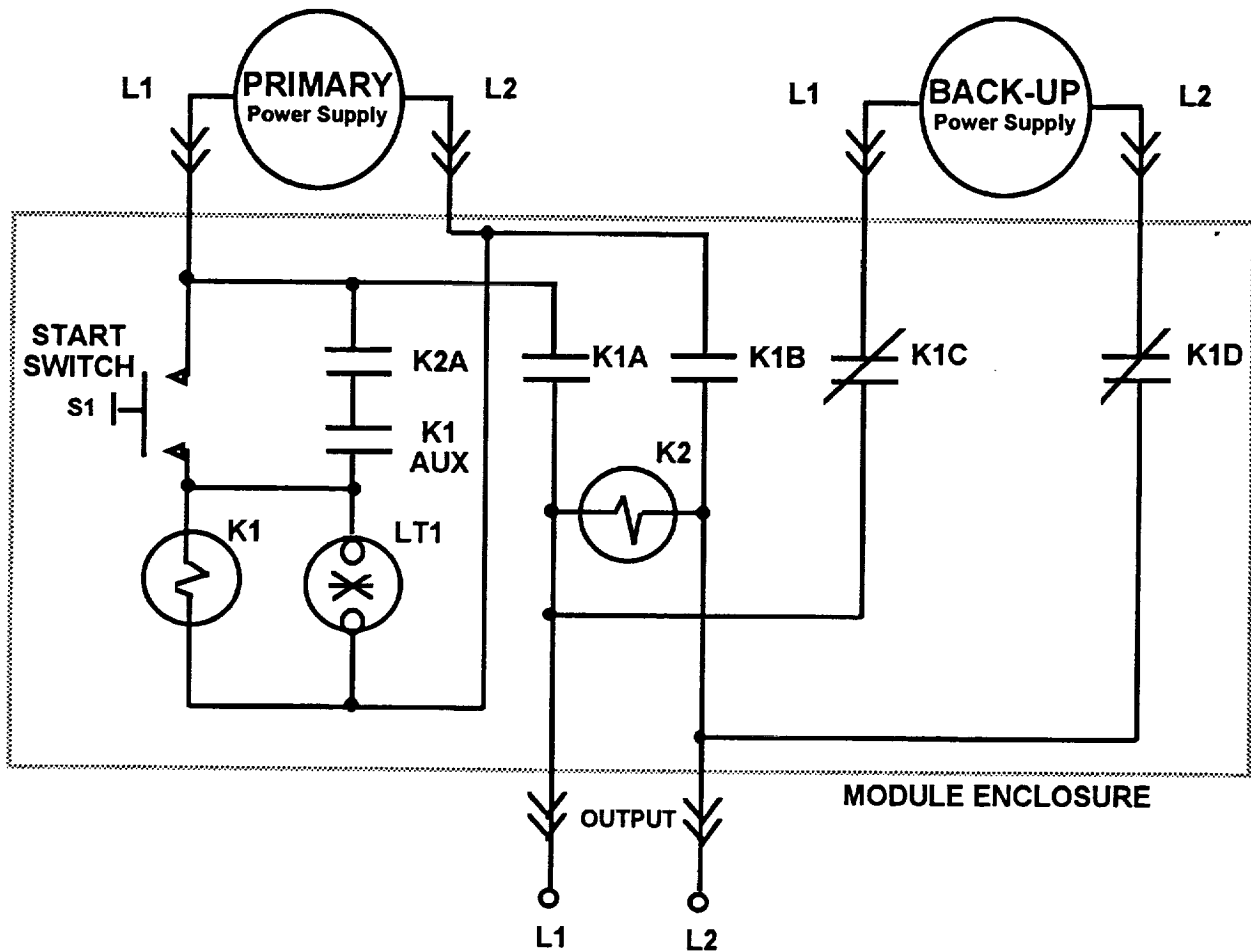
- IF K1A OR K1B FAILS OPEN - K2 DROPS OUT CAUSING THE BACK-UP POWER SUPPLY TO COME ON LINE.

- IF THE PRIMARY POWER SUPPLY FAILS - K2 DROPS OUT CAUSING THE BACK-UP POWER SUPPLY TO COME ON LINE.

- S1 IS USED TO SUPPLY THE PRIMARY LINES AND IS ALSO USED TO BY-PASS K2A & K1 AUX TO ACTIVATE AND LOCK ON K1.

Technique	Install filters immediately upstream of all interfaces in pneumatic systems to control dirt and water contamination.

<div align="center">

PNEUMATIC SYSTEM CONTAMINATION PROTECTION

Control contamination and reduce maintenance burden through strategic installation of filters

</div>

Benefits	Proper use of filters, prevents contaminated gas from interfacing with component and system operation, provides the following benefits: • Decreased component failure caused by contamination. • Efficient and effective means of servicing system/equipment by filter cleaning or replacement. • Increased system availability due to reduction in system maintenance.
Key Words	Pneumatic, Protection, Contamination
Application Experience	Apollo, National Space Transportation System, Pneumatic Ground Support Systems
Technical Rationale	System gas must be conditioned before it is allowed to enter a new system. Installing filters immediately upstream of interfaces achieves this objective and also reduces dirt and water contamination that can interfere with component and system operation.
Contact Center	**Kennedy Space Center (KSC)**

*Pneumatic System Contamination
Protection
Technique OPS-11*

No matter how well a system is designed or how expensive, particulate-contaminated gas interferes with component and system operation. System gas must be conditioned; it must be decontaminated before it is allowed to enter a pneumatic system. The KSC design standard for pneumatic systems defines the following requirements for filters:

- Filters shall be installed immediately upstream of all interfaces where control of particulate matter is critical and at other appropriate points as required to control particulate migration.

- Selection of filters shall be made only after analysis of overall system performance requirements. This ensures maximum protection of critical components and minimal performance penalty (pressure drop).

- Filter housings and elements shall be constructed of 300 series stainless steel to reduce particulate contamination due to corrosion. Seal materials shall conform to manufacturer's recommendations and the requirements specified herein. The element construction should be welded instead of soldered whenever possible to simplify cleaning. Where 300 series stainless steel is specified, type 303 and other austenitic stainless steels should be avoided whenever possible because of susceptibility to stress corrosion cracking. However, overall cost should be the deciding factor.

- Filter elements shall maintain filtering quality and not be damaged in any way when subjected to worst-case system conditions (i.e., maximum design flow rate and element clogged to its maximum design capability).

Providing unconditioned gas in a pneumatic system will have the following effects:

- Degraded system performance because of contamination.

- Increased maintenance cost and downtime to recover from problems induced by contamination.

- Decreased system availability.

References

1. KSC-SD-Z-0005A, *Standard for Design of Pneumatic Ground Support Equipment.*

2. Parker-Hannifin Corp., Bulletin 0225-B1, *Fluid Power.*

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This manual presents a series of recommended techniques that can increase overall operational effectivness of both flight and ground based NASA systems. It provides a set of tools that minimizes risk associated with:
- Restoring failed functions (both ground and flight based)
- Conducting complex and highly visible maintenance operations
- Sustaining a technical capability to support the NASA mission using aging equipment or facilities

It considers (1) program mangement – key elements of an effective maintainability effort; (2) design and development – techniques that have benefited previous programs; (3) analysis and test – quantitative and qualitative analysis processes and testing techniques; and (4) operations and operational design techniques that address NASA field experience. This document is a valuable resource for continuous improvement ideas in executing the systems development process in accordance with the NASA "better, faster, smaller, and cheaper" goal without compromising safety.

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