Space Station Engineering and Technology Development

Proceedings of the Panel on Maintainability

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Proceedings of the
Panel on Maintainability
March 20–21, 1985

ad hoc Committee on Space Station Engineering
and Technology Development

Aeronautics and Space Engineering Board

Commission on Engineering and Technical Systems

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May 15, 1985

Dr. Joseph F. Shea
Chairman, Space Station Engineering
and Technology Development Committee
Aeronautics and Space Engineering Board
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear Dr. Shea:

Enclosed is the report of the recent meeting in Huntsville on space station maintainability. Bernie Maggin and I met with Phil Culbertson, members of his space station staff, and representatives from the Office of Aeronautics and Space Technology and reviewed the results of the meeting.

The major purpose of the meeting was, of course, to provide a forum where representation from NASA and industry could exchange experiences and views on how the maintainability goals of NASA might be achieved with acceptable cost. Representatives from a number of non-aerospace organizations discussed their experience in dealing with the complex interaction of reliability, maintainability, logistics, transportation, and costs. The discussions emphasized the need for systems level guidance early in the design and development phase.

Everyone recognizes that NASA is still formulating many of the major system level strategies for the space station. The panel did feel, however, that given the particular NASA program management structure, it is important that system level concepts for maintainability be provided to the Level C centers and the Phase B contractors in time to affect the studies under way and to provide a common base for the preliminary design effort in the latter part of Phase B. Phil Culbertson and the other NASA representatives appreciated and understood this concern.

It was noted at the NASA review that the panel could meet again for a more definitive review of the evolving maintainability program, if NASA so desired.

Sincerely,

Lawrence R. Greenwood
Chairman, Panel on
Maintainability

Enclosure

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Aeronautics and Space Engineering Board

Preface

In 1984, at the request of the National Aeronautics and Space Administration (NASA), the Aeronautics and Space Engineering Board (ASEB) undertook a study of NASA's space station program. The results of this study by the ad hoc committee of the ASEB on Space Station Engineering and Technology Development were published this year. NASA found the study useful and asked the ASEB to continue examination of the evolving space station program through a series of more specific studies:

- maintainability
- research and technology in space
- solar thermodynamics research and technology
- program performance
- onboard command and control
- research and technology road maps

The purpose of this examination of maintainability, the first of the series, is to provide comments on approaches to long-term, reliable operation at low cost in terms of funds and crew time.

The panel consisted of selected members of the committee and representatives from industry with special knowledge and experience in the science, art, and engineering pertinent to maintainability. The panel was briefed by NASA staff members involved in the development of the space station maintainability program and on questions and issues to be resolved. The panel, in roundtable fashion, discussed these matters. The deliberations of the panel, following active dialogue with the NASA representatives, are presented without attribution in this report of the proceedings.

These proceedings contain a brief synopsis of NASA's presentations, including questions and issues; notes on the roundtable discussion; and a summary of the panel's observations for NASA's consideration in the development of its maintainability program for the space station. A set of the NASA presentations is appended for completeness.

Acknowledgements

The panel was aware of the fact that NASA was in the process of negotiating with industry for selection of Phase B space station concept definition and preliminary design contractors. It was aware that NASA has not had an opportunity to develop its position on maintainability much beyond that reflected in the Phase B requests for proposals. In addition, the panel was aware that the program team responsible for maintainability was being established and staffed at the time of this review.

The briefings and discussions were open and candid. The panel expresses its appreciation to the NASA presentors, industry participants, and NASA attendees for their spirited and constructive discussion.

The panel recognizes that it is too early to formulate a firm position on space station maintainability. However, the panel believes and NASA program management has confirmed that this interchange was timely and useful in providing a preliminary assessment of and comments on NASA's approach to maintainability.

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Introduction

BACKGROUND

In 1984 the ad hoc committee on Space Station Engineering and Technology Development of the Aeronautics and Space Engineering Board (ASEB) conducted a review of the National Aeronautics and Space Administration's (NASA's) space station program planning. The review addressed the initial operating configuration (IOC) of the station. The results of the committee's study, released in February 1985, were factored into the development of NASA's space station program and its request for Phase B (concept and preliminary design) proposals issued to industry in September 1984 and awarded this past April.

NASA found the work of the ad hoc committee very useful and asked the ASEB to reconstitute the ad hoc committee to address:

- onboard maintainability and repair
- in-space research and technology program and facility plans
- solar thermodynamic research and technology development program planning
- program performance (cost estimating, management, and cost avoidance)
- onboard versus ground-based mission control
- technology development road maps from IOC to the growth station

The objective of the committee's new assignment is to provide NASA with advice on ways and means for improving the content, performance, or effectiveness of these elements of the space station program.

In response, the ad hoc committee established individual panels to address each subject. The participants of the panels were to come from the committee, industry, and universities and thus provide each panel with individuals experienced in the area of special interest.

It was decided that the subjects of maintainability, program performance, and onboard mission control would be addressed in round-table forums focusing on concepts, system design, and organization.

This tack was taken in view of NASA's interest in program definition and development and not in program critique at this time.

It was decided that the subjects of research and technology in space, solar thermodynamic research and technology development, and technology development road maps would be addressed in workshops that focus on NASA program activity and plans.

It was also decided that the deliberations of the panels would be reported as proceedings to expedite the documentation and dissemination of the information.

THE MAINTAINABILITY PANEL

The task statement setting up the maintainability roundtable noted:

> NASA background material will cover such matters as design philosophy for the initial and growth station; specifications; and station operations and services, covering the range of essential to nonessential functions. Questions and issues of particular concern and subjects that NASA would like the panel to address will also be identified.
>
> Of particular interest to NASA are approaches to providing high reliability and long life at low initial and operational costs and preservation of crew time for mission work. Pertinent are views on design philosophy and specifications and the related technology developments that will make the achievement that enhances the probability of success possible. Pertinent technology includes redundancy and failure mode design and diagnostics, artificial intelligence, and automated repair/replacement.

The proceedings reported here cover the Maintainability Panel's meeting at NASA's Marshall Space Flight Center on March 20-21, 1985. The list of panel members, participants, and NASA representatives is presented on page iv. The meeting agenda is presented in Appendix A. The panel was briefed by NASA representatives; panel participants discussed their views on maintainability; the panel engaged in general discussion; and then the panel organized into two subgroups. One subgroup addressed maintenance concepts; the other, maintenance technology; and each considered related NASA questions and issues.

The subgroup comments were reviewed with the full panel. This proceedings report presents the results of this process. The panel's observations and comments are noted without attribution.

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NASA Briefings

The briefing graphics of the National Aeronautics and Space Administration (NASA) representatives are presented in Appendix B. The following paragraphs summarize this material and include the questions and issues identified by the presentors. Where pertinent, related panel comments are included.

Richard Carlisle, NASA Headquarters--Opening Comments. The panel was reminded that the roundtable was intended to be a forum for the exchange of ideas. NASA hopes to gain from participants' experience and use the information for structuring space station maintainability guidelines. Carlisle noted that the space station is different from earlier manned space systems in that it will have a long, indefinite life. The design must allow the crew to use most of its time for mission support. Because past NASA programs have had little need for attention to onboard maintainability, NASA has not had to give this matter much attention.

Bryant Cramer, NASA Headquarters--Elements of Maintainability and Key Questions. The objective of the discussion is to develop an understanding of an optimal approach to space station maintainability. The subsystems must have a capability for essentially indefinite life through maintenance, exchange, and/or upgrading. The associated work load must not affect crew productivity or safety. A possible goal might be no more than 3 hours per day per crew member for a 5-day week.

Maintenance has engineering, assurance, and operational aspects and attributes related to avoiding and facilitating maintenance.

Questions related to maintainability reviewed at the meeting and contained in an earlier statement by Dr. Cramer,* in summary, are:

- Maintainability requirements?
- Process for identifying requirements? Modeling?
- Driver issues in formulation of plan?
- Approach to conducting system engineering trade studies?
- Approach to implementation?
- Trades between reliability and maintainability? Use of automation?
- Are maintenance goals identified/assigned to each subsystem?
- Balance between mean time before failure versus ease of maintenance as related to mean time to replacement?
- Process to determine orbital replaceable unit (ORU) support level?
- Determination of automation level for high maintainability?
- Application of human factors engineering?
- Role of computer modeling?
- Preservation of maintainability objectives in view of limited resources?
- Maintainability buildup from the initial operating configuration (IOC), scarring?
- Checking for achievement of maintainability objectives before flight?

Richard Storm, NASA Headquarters--Planning Guidelines. The program is being approached through dedicated study using the NASA centers and study contractors. Development should start in 1987 with the IOC in place in the early 1990s. The U.S. cost through IOC is $8 billion.

The station will be built and sustained through the use of the Shuttle providing long-term, continuous service with men. The station will have both manned and unmanned elements, be evolutionary, and maintainable.

The reliability/maintainability issues are:

- maintenance demand versus crew time
- program priority versus crew time
- reliability boundary--the most reliable versus lowest acceptable
- life cycle cost alternatives
- internal access versus external access
- software (repair and maintenance)
- spares availability
- ORUs stored on board versus on ground
- safety/safe mode operations
- sustaining support
- analytical methodology controversial--lacks credibility

*Dr. Cramer had prepared a statement on maintainability philosophy and issues for the panel prior to the panel meeting. Extracts from this statement are appended to his presentation material.

The approach to resolving such issues encompass actions that result in: fail-safe, restorable design; building "best" state-of-art hardware; and designing for accessibility/modularity and replaceability. Trade studies should address ORU levels and space requirements. Studies should also address anticipated maintenance and service requirements.

It will be assumed that the resupply cycle is 90 days, that design will be fail-operational/safe/restorable with low probability of two failures in critical systems in a 90-day period, and that the prime mode of restoration is replacement.

There are a number of technology development areas that address long life that require attention. They relate but are not limited to software, electric power generation, propellant handling, thermal devices, life-support equipments, and external operations.

Some key program challenges include design for permanence, costs and schedules, the in-house conduct of systems engineering and integration, international integration, and funding constraints.

Harold E. Benson, Johnson Space Center--Systems Engineering and Integration. The maintainability issue for the space station is to develop a basic design to allow effective maintenance. In part, due to cost constraints, this may be difficult to implement fully as the program matures. The operating environment and the fact that the crew members are not maintenance and repair specialists put special, difficult demands on maintainability. To add to the design problem, the station is a long-life system (30 years) with international participation. Some issues relate to commonality of hardware/software and growth.

Program management (Level B) will be responsible for the integration of the full maintainability plan. This will include integrating and scheduling of related effort by Level C according to their assigned work packages. This will include related logistics activity.

The present program plan (Phase B) calls for baseline space station configuration selection by the end of the year and documentation of design and implementation plans (including maintainability) by the end of 1986.

Costs for providing maintainability are projected to be significant, warranting careful assessment and attention. Factors that must be considered include initial design, development, hardware, and scarring for future modifications; logistics support in space and on the ground; and supporting activity.

Because of environmental and operational factors, maintainability by the crew both inside and outside the station will present special challenges. Automation and robotics may be of special value and interest and require establishment of design criteria.

There will be special needs for information. Because of limited knowledge of the broad range of systems and the limited crew (and training limitations), there will be a need for basic and updated maintenance information to be available to the crew. These data will have to be on board or data uplinked in a timely manner.

NASA has had relatively limited experience with long-life systems. This raises special hardware vendor problems related to sustained support and/or availability of required data over an extended period of time that will have to be addressed.

From programmatic considerations, management will have to address: issues of commonality of equipments and treatment between major systems, approaches to growth and the size of the steps, implication of foreign involvement on maintainability, and the establishment of a consistent set of criteria that all elements of the design can use to assure compatibility.

Shelby L. Owens, Johnson Space Center--Project (Level C) Approach to Maintainability. The present major thrusts involve maintainability trade studies for hardware and software directed at interim requirements. These studies include commonality.

Some major factors of concern (not in order of priority) include:

- logistics and crew support requirements including human factors
- impacts on users and on-orbit requirements
- data management and decision making
- autonomous operations
- safety and reverification
- growth

The present plan is to conduct task and trade studies through the Phase B contracts as identified in the request for proposals. The statement of work notes that there should be commonality, trade studies (maintainability versus reliability), maximization of maintainability features, and approaches that satisfy the requirement for indefinite life.

In spite of NASA's experience and demonstrated capability to develop and operate reliable systems, NASA has not developed nor operated systems with the lifetime demands of the space station, i.e., indefinite life, growth in orbit, maintainable in orbit, and interfacing with other vehicles and multiple interest groups.

Joseph H. Levine, Johnson Space Center--Reliability Division Approach. Addressed were differences between space station and earlier programs and reliability-maintainability assurance roles and issues.

The significant maintainability factors for the station that differ from earlier work are:

- indefinite life and onboard maintenance
- less time-critical systems and commonality
- fail-operational/fail-safe/restorable
- use of robotics
- onboard fault isolation, restoration
- logistics support
- crew capability limitations
- increased extra-vehicular activity

To provide reliability and maintainability, the reliability division will have to pursue the following kinds of activity: definition of requirements and participation in trades, assessment of approaches including optimization of the use of the crew, evaluation of program plans and their implementation down to ORUs, and definition of special tools and standards. The division will need to participate in maintainability demonstrations, data system definition and development, and resolution of problems affecting maintainability matters.

The critical issues are viewed as related to:

- identification of unproven systems and elements difficult to access/restore
- selection of an approach that assures all groups participate uniformly
- selection of appropriate techniques to analytically assess maintenance and general crew time and to minimize use of the crew
- the crew time for prelaunch and direct in-flight maintenance--spare requirements
- use of robotics for routine and extra-vehicular work
- technology development to enhance program approaches
- studies to provide direction to all phases of logistics: spares (ground and in-flight), storage, and obsolescence.

Joe Lusk, Marshall Space Flight Center (MSFC)--Center Role in Maintainability. MSFC has a major responsibility for identifying and developing the logistics support program plan for the space station. This includes the space-born logistics module and its outfitting. MSFC also has the responsibility for developing the integrated space station maintainability plan. It is recognized that equipment design affects support needs, which in turn impact system effectiveness and efficiency. These matters should be addressed before the design is fixed.

Logistics is considered to include all elements of the operation (i.e., maintenance planning, logistics analyses and management, training, equipment handling, and support facilities). The task includes development of the maintainability plan and encompasses such matters as recording of equipment status, configuration control, tracking of operating times, and establishing maintenance procedures.

The maintainability plan is envisioned to include development of Level B requirements and taking actions that influence the design, development, and station life. The thrust of the effort is directed at improved operational readiness, reduced near- and long-term (life-cycle) costs, and efficient operation of the station. It is intended that the maintainability plan (system requirements, data requirements, guidelines for analyses and reviews, and schedule for reviews) be integrated into the overall program plan.

The proposed maintainability philosophy includes:

- critical systems fail-operational/fail-safe; noncritical systems fail-safe
- removal and replacement (ORU changeout and return to ground for rework)
- space station major modules returned to ground as last resort
- onboard diagnostics for detection down to ORU
- noncritical systems allowed to fail-/degrade- operational until spares are available (resupply, 90-day cycle)
- for health and safety, have planned maintenance
- for contingencies, provide test equipment and tools and provide functional capability repair on board.

It is recognized that maintainability affects all parts of the program (reliability, safety, human factors, logistics, crew systems). All requirements must be integrated and logistically supported. Requirements will help identify levels of redundancy that in turn affect system monitoring requirements, replacement/repair decisions, and spare requirements.

All of this background is required to define corrective and preventative maintenance policies. (Current activity builds on earlier work on the problem of maintainability--Philosophy on Space Station Maintenance/Maintainability, J. Lusk, MSFC/PM01, Nov. 28, 1983; Space Station Maintainability Study Input for CDG Study #2, J. H. Leet, KSC/PT-LMO, Jan. 17, 1984; and Space Station Reliability-Maintainability White Papers, JSC, Dec. 1984.)

Joseph P. Joyce, Lewis Research Center--Electric Power Systems. The electric power generating system options for IOC are solar photovoltaic and solar thermodynamic. Maintainability terms were defined:

- Maintainability--Capability to complete maintenance and repair and the verification of success (impacts design)
- Maintenance--Periodic (and unplanned) activity to prolong design operation (impacts design)
- Reliability--Insight as to when a loss may occur (impacts logistics)
- Repair--Action to return the degraded, malfunctioning, or damaged items to design operation (impacts crew and logistics)

The design target is to provide an electric power system that will operate without interruption and with minimum interference from other space station program elements. This is one of the critical systems. Since nearly all other systems and operations depend on electric power, an uninterrupted power supply is vital. Interference from other space station systems should be minimal.

Maintainability consideration includes many factors that impact interface standards, system design, and operational support. Some of these factors relate to accessibility, override, hazard avoidance, growth, interface definition, diagnostics, fault detection, contamination, resupply, spares, and storage.

Maintainability will be addressed in the Phase B studies. Definition work on supporting activity and requirements has begun.

F. J. Logan, Goddard Space Flight Center (GSFC)--Platforms and Attached Payloads. The work includes not just the attached payloads and free-flying platforms, but also their assembly and servicing facilities and laboratory module outfitting.

The key to successful design will be the iterative process of trades between maintainability, system design, and costs. All of the NASA center work package managers and the Phase B contractors are required to work this problem.

Issues to be resolved include:

- crew time for maintenance
- reliability versus maintenance
- cost versus availability versus redundancy
- logistics space on board
- resupply frequency
- criticality of element, subsystem
- safety
- commonality
- built-in test/diagnostics versus manual operation

GSFC has some experience with multimission, modular spacecraft (MMS) maintenance. These systems were designed so that functions were distributed and isolated. Failures can be readily identified and modules easily replaced through the use of remotely controlled systems. This is a proven technique that could be used for the space station's ORUs. Other ideas have potential for the station: the MMS flight-support system that replaces MMS equipment and a thermal protective system (built-in layers) that can be easily restored to operational capability.

George B. Finelli, Langley Research Center (LaRC)--Fault-Tolerant Systems Research. The basic approach of fault tolerance is to design a system that continues performing its intended function(s) in the presence of faults through multiple redundancy, detection/isolation of failures, and architectural reconfiguration. These capabilities could allow automatic maintenance, increase autonomy, reduce crew load, assist in growth, reduce operating costs, and possibly reduce initial cost.

Research issues include understanding the effects of system architecture and fault-tolerant software on reliability and performance. Currently, most reliability analyses tend to be optimistic because they fail to consider the effects of software errors, transient faults, double faults, and single-event upsets.

The goal of the LaRC fault-tolerant systems research is to define design and assessment methodologies for such systems. The intended products of this research are methods for validating the performance and reliability of complex electronic systems, comparative analyses of integrated system concepts, and guidelines for the design of verifiable, highly reliable systems. To date, most of the work done has addressed aircraft matters. But, the facilities and capabilities can be used to address space station design issues.

Present research includes development of tools and techniques, using varied analytic and test techniques, for both software and hardware. One subject under study is the use of redundancy and periodic maintenance as the means for limiting the probability of failure.

Fault-tolerant systems can provide graceful degradation through fault detection, isolation, and reconfiguration and, consequently, provide increased autonomy and reduced testing, enhance identification of elusive symptoms, and reduce removals associated with unconfirmed faults. LaRC is verifying the benefits of fault-tolerant systems through trade-off studies. Such systems can favorably affect costs and maintenance requirements through the reduction of time, spares, and operational activity devoted to maintenance/repair/replacement.

<u>Joel H. Leet, Kennedy Space Center (KSC)--Maintainability Philosophy</u>. Prime maintainability considerations during the early program phase relate to influencing the design: during the detailed design and production phase (designing-the-support) and during the operations phase (supporting-the-design). Because of the close relationship, integrated logistics considerations and the effect of maintainability on the logistics system must be considered through all program phases. The end result will be the system in use at KSC during operations to support the space station (provisioning, resupply, maintenance, repair, training, and documentation).

The maintainability philosophy encompasses thoughts expressed by other NASA presentors:

- maintenance on orbit
- minimal training
- evolution--growth capability

- primary crew function--time for user work with minimum demand on users
- common hardware and software
- maintainability factored into support and life-cycle cost decisions

The data base (lessons learned) from past space and related earth-based systems, including the U.S. Department of Defense and industry, is being examined and will be factored into the program development effort.

This earlier work shows that: maintainability must be responsive to mission and operational requirements and needs to be factored into the design early and iterated; critical systems should be isolated; spares should be certified; common interfaces between primary and secondary systems should be avoided; software language for both flight and testing procedures should be compatible; flight and ground crews should be involved in design and review board activity; and costs should be considered throughout the effort.

Important design and development considerations include: establishment of program-level management and support policy early, as well as criteria for maintainability; a strong top management advocacy; assessment of new technology; and establishment of ways to measure the performance and effectiveness of system implementation.

3

Discussion

This section of the report reflects the substance of the roundtable discussion, without attribution, in the form of short statements. The statements, which address a range of matters from status to suggested actions, are organized by philosophy/guidelines, technology, and organization/management.

PHILOSOPHY/GUIDELINES

- Maintenance/repair (and other space station operational activities) should not detract the crew from the prime function of mission support.

- The target of 3 hours per crew member per day for maintenance/repair is too high. A more practical target might be 3 hours per month.

- Representative maintenance concepts have not been generated by the National Aeronautics and Space Administration (NASA). The matter has thus far been treated in a very general way. NASA needs to identify a preliminary maintenance concept as the first step in developing a maintainability plan. This is needed to guide the early, as well as later, Phase B activity, when in-depth study of this important matter is initiated.

- All program participants (government and industry) need to be provided with a consistent set of maintainability guidelines if related system activities are to interface effectively.

- The maintenance concept should be quantified, to a reasonable degree, and provided to all involved groups for review and comment. The feedback should be iterated. This work should be the responsibility of a single group, Level B.

- There is an array (depending on criticality) of system requirements, and each requires separate treatment.

- Cost is an important program driver. Maintainability and repair considerations impact design and early- and long-term costs. Thus, it is important to take cost implications into account early in the design effort.

- A system design guideline should be established that states that the probability of a catastrophic failure will be extremely low, and a value should be set for this very low probability of failure.

- It is anticipated that NASA will have developed a reasonable position on maintainability and reliability in the January-February 1986 time frame, when some of the Phase B work is completed.

- NASA has been examining the matters of reliability, maintainability, and repairability over a period of several years through intercenter working groups and special studies. This work has produced reports and a series of white papers on these subjects. Related earthbound work has been examined but found to be of limited value in terms of space station applicability.

- The in-house work has covered operations as well as design and users' needs related to onboard payloads and freeflyers.

- The Marshall Space Flight Center has developed top-level maintainability guidelines. However, this has not been worked with the other centers or Level B.

- A separate contract (outside of the Phase B group of contracts) will be let by MSFC to develop a maintainability plan and help structure the logistics support plan. This activity will be iterated with the Phase B work.

- The subject of safety appears to require more attention.

- It is not possible to generalize requirements down through all systems due to unique services and/or requirements and criticality. So, goals and guidelines should allow the exercise of reasonable judgment by the system designer.

- As a matter of principle, the maintainability specification or criteria should not be too confining. Confinement will not allow contractors the opportunity to exercise their ingenuity and creativity.

- To help assure communication between parties, maintainability and related terms need to be defined.

- Airlines and commercial air transport airplane manufacturers have developed maintainability guidelines.* Current design is based on

*A report setting forth guidelines developed by Boeing, based on design/operational experiences with their aircraft down through the 747 aircraft, was given to NASA Level B representatives.

identifying incipient failures, mechanical or electrical, through inspections, checks, and testing. This approach should be considered judiciously for the space station. The question of blatant failure needs to be addressed. This treatment has to be given to standby systems too. A point to note is that aircraft operators, fundamentally, do not replace components at fixed times.

It would appear to be inappropriate to set specific system/subsystem values for designers; it would be better to set overall concepts for basic systems.

- In aircraft, for a new design, it has been the practice to dedicate time (approximately 2 weeks) to a relatively complete set of maintainability demonstrations. This type of action may be appropriate for the space station using the buoyancy tank and mock-ups to simulate extra-vehicular activity operations. However, in-station (shirt sleeve) operation presents a special problem.

- In commercial aircraft operations there is a minimum operationally ready equipment list. The flight (operation) does not go without an operational check-off of these equipments. A similar check-off may be appropriate for the station before special activity, i.e., orbital maneuvering, vehicle docking, and turning on power to an onboard payload.

- The levels of repair planned for need to be responsive to appropriate criteria and standards for different classes of system criticality. The general rule may well be replacement of elements and components.

- Due to upgrading and replacement, it does not appear that a 30-year life through direct maintenance is a realistic design driver for components and elements of the station and could be an unnecessary cost factor. It would appear to be more realistic to design for shorter lifetimes with a view to replacement with advanced components and systems for all but major structural elements.

TECHNOLOGY

- A sustaining engineering activity, in view of growth and long life, will be required as will an ongoing technology development effort related to maintainability.

- Measures of maintainability need to be defined to assist in and provide a consistent base for analyses and evaluation.

- The subject of mission success needs to be addressed as part of the maintainability assessment. There has to be a way to measure and identify failures to be tolerated through design and performance assessments.

- Modular design can pay for itself in ease of assembly, test, and replacement. But, the design must consider accessibility and simplicity.

- The Langley Research Center work on fault tolerance is currently directed at aircraft. The facility and staff can be applied to space station issues. This application should be examined.

- The Air Force has a large program on redundancy management. Contacts should be made to review this work and its applicability to station development.

- The military services are very involved with the subject of integrated diagnostics for a self-sustaining weapon system capability.* However, they have not established an approach to evaluating designs for maintainability and repairability. This matter is being worked by the services and should be followed.

- One significant problem is the inability to detect and isolate equipment failures with high confidence.

- The failure problem manifests itself in: large ambiguities that are costly in spares, logistics, and induced failures; high false removal rates (airlines have experienced values as high as 50 percent); the need for large, specialized support groups; shortages of storage space and work skills; long mean times for repair and operational readiness; and extensive test equipment, training, and documentation.

- The Navy has a program to support the development of integrated diagnostics. The program's objectives include technology improvement, reduction of false removals, maintainability improvement, and reduction in cost of diagnostics.

- The Navy's integrated diagnostics effort is directed at providing a cost-effective capability for detecting and isolating known or expected problems without ambiguity. It has three phases: Phase I (present)--concept definition and system specification, Phase II (FY 1985)--detail specification for software and hardware, and Phase III (FY 1986-1990)--full-scale development of guides and standards.

*Mr. Michael Battaglia of the Naval Electronic Systems Command made a presentation on this work. His presentation material was distributed. He also presented copies of the following reports for NASA: Report for the Department of Defense on the Implementation of Integrated Diagnostics, The National Security Industrial Association, Sept. 1984 (full report and executive summary); and Proceedings of the 1984 National Conference on "Supporting Weapon System Technology Through the 1990s," The National Security Industrial Association, Aug. 14-16, 1984 (Vol. I and conference summary).

The expected payoffs: diagnostic capability should go from 50-75 percent to 99-100 percent; support personnel reduction, 25 percent; training reduction, 50 percent; false alarms from 85 to 1-2 percent; unnecessary removal from 30-70 percent to less than 1 percent; and time for maintenance should be reduced by 50 percent.

- There is a need to assist the crew in decision making because, as noted in the request for proposal (RFP), crew time is very important.

- Design to cost and crew time are important evaluation criteria for trade studies. But, some way to quantify crew time is needed.

- The Air Force Studies Board of the National Research Council has initiated a study on fault isolation. (See Appendix C--Statement of Task.) The National Security Industrial Association (NSIA) has just completed a study on this subject. A report is in process. NSIA is also conducting a technology survey. NASA needs to examine and keep in touch with these activities.

  The NSIA report addresses state-of-technology and future needs. It shows that management attention from the start is critical and that diagnostic design, a systems engineering function, has to be iterative.

- Past experience indicates that overworking the crew is a real and serious problem.

- Large electronic telephone switching systems are designed to provide very high levels of reliability (down times of about 2 minutes per year). These systems use up to 12 levels of redundancy. They depend on sensing and remote diagnostics for trouble shooting down to a low systems level. A central control station manager directs field repair people (such an approach may be appropriate for the space station). This capability has to be designed into the system from the start.

- Representative, important technology development areas are: knowledge-based systems, laser video disk, expert systems, artificial intelligence, logic modeling, smart bits, signature analysis, fault-tolerant designs, probes/robotics, self-improving diagnostics, and computer-aided design and analyses capability (i.e., AJE/UPE, CAD/CAM/CAT/CAE, and LSI/VLSI/VHSIC).

- Safe designs should have redundancy in both main and standby critical systems.

- To keep work loads and time lines for crews contained, automation, including built-in testing, has an important role to play in initial and design growth.

- Trade studies should include reliability, safety, and low cost considering replacement, repair, inspection, and test.

- A starting place for NASA trade studies would be the reference configuration in the RFP, divided into subsystems and classes of functional criticality. The trade studies would identify design guidelines for desired performance and minimum costs and help develop guidance for iteration with the Phase B contractors.

- Satellite communication earth stations were subjected initially to periodic human checking. Now, with the system mature, only checks by instruments are made. The outage time averages about 25 minutes per year over a 10-year period. Design features are high redundancy and short chain-of-command.

- It is anticipated that, for the space station, there will be a long shakedown period followed by more settled and routine operation. In the past, this transition period has tended to be a problem for NASA.

- Current satellite systems (communications) have displayed lifetimes longer than expected. Early satellites had lifetimes of 3 to 4 years; new systems, 9 years and still going. New designs are predicted to have useful lives of 10 years. Several factors contribute to long life: make equipment good, specify existing/proven equipment, and use fixed-price/incentive contracts. Tie contractor incentives to system life. Where new equipment must be used, the key is test, test, and test. If changes are made, make them in small increments. Make heavy use of redundancy.

- Human factors did not appear to get specific attention. This could be part of a long-term problem--crew causing problems while fixing problems. In this regard, it may be a better practice to have required onboard spares integrated into the system (redundancy) rather than replaceable.

- There may be a tendancy to overstress wearout. Wearout has not been a problem with unmanned spacecraft. Unproven design has caused problems indicating a need for careful validation of new designs. On the station, wearout will have to be dealt with in the sense of easy access for assessment/replacement and possibly repair.

- To reduce maintainability requirements, design should incorporate redundancy and have greater capacity/capability than the minimum acceptable requirements specified. Systems should be designed to degrade gracefully so that there is time to decide on and take action.

ORGANIZATION/MANAGEMENT

- The centers have a responsibility for addressing all maintenance issues including payloads and spacecraft operating with the station. The RFP covers the subject, but very broadly.

- The presentations reflect that space station maintainability, per se, has received some attention but that relatively little attention has been given to maintainability related to use of the station as a service center for attached payloads, platforms, and the orbital maneuvering/transfer vehicles. The Goddard Space Flight Center has the responsibility for this activity, but it is not clear that servicing maintainability has been considered. This includes maintainability of the serviced items themselves.

- The technical aspects of maintainability are not the whole problem. Organization and management (assignment of responsibilities and authorities) are also important and affect program success.

- A top-level set of maintainability objectives and strategy is required to coalesce activity between centers and contractors. This will allow correlatable definition of criteria for the next lower level of maintenance and repair design and operational concepts.

- In weapon systems (possibly for the space station too) operational readiness problems persist because: system requirements fail to reflect diagnostic needs; integration of diagnostics not accomplished (too many separate functions); organizational structure not in place; analytical tools not available; and funding support short.

- Space station hardware and software maintainability needs to be addressed by design engineers. This includes component/system design that provides the capability to accept updated technology without impacting users. The subject is important enough to warrant special design reviews.

- NASA has identified many of the major maintainability issues but not how to resolve them. It is reasonably clear that what is needed is a logic net and feedback mechanism to integrate and set the process in motion.

- A problem with long-life systems is replacement of hardware including instrumentation, i.e., companies discontinue manufacturing or go out of business. In cases where original design data are needed and manufacturers could go out of the business, it may be necessary to make arrangements to preserve drawing and other information.

- In the commercial communications area there has been heavy dependency on corporate memory and on careful specification for final design and development. These factors are expected to be important to the long-life space station system too.

- There did not appear to be a commonality of approach to maintainability between center groups and the presentations were general. However, work is just getting under way. If maintainability is to be effectively addressed and factored into the design, as it should be, the effort that is under way must be a serious, in-depth effort.

4

Summary Observations

The panel discussed and drafted a definition of and an approach to maintainability. This definition and approach is presented here.

The panel organized in two groups to consider the National Aeronautics and Space Administration's (NASA's) present posture on maintainability and the questions and issues raised. One group summarized views on maintenance concepts and the other on systems/technology. The observations of the two groups were reviewed by the panel and are also summarized in this section of the proceedings. Finally, a general summary statement is presented.

Subsequent comments submitted by panel members--J. W. Schaefer (remote testing) and P. E. Partridge (replacement/maintainability philosophy)--are presented in Appendix D.

MAINTAINABILITY DEFINITION

In view of the need for a common understanding of maintainability, a definition of maintainability and a process for implementing the capability was developed and briefly reviewed by the panel. This definition and process follows:

> Maintainability is the capability to carry out a set of procedures which will enable the space station system to perform its mission with minimum disruption and maximum safety. Low overall cost is a system criteria.
> The term mission includes all elements of the space station system. It entails the servicing of other spacecraft and user equipments/instruments associated with the space station itself and the polar platforms that will interface with maneuvering and transfer spacecraft, serviced by the Shuttle.
> Maintainability is not reliability or commonality. Procedures should not be confused with design, i.e., a system design must provide the capability to maintain

the system performance and enable economical repair and replacement of components with no disruption of service. Thus, the design must accommodate maintenance procedures. Operational procedures should encompass switching to fault-tolerant or other built-in redundancy.

The design of the system should be such that it will facilitate maintainability to achieve lowest overall cost.

But which procedures should be selected and implemented? Here, reliability and commonality enter. They are products of specific design.

To determine the maintainability procedures to use, trade-off studies are made considering maintainability, reliability, commonality, supportability (logistics) under the constraint of minimum disruption of critical systems, maximum personnel safety, and lowest overall cost.

These studies and the design approach can be addressed through:

- Use of the request for proposal reference configuration to identify criticality of major systems hardware and software, in a hierarchical manner, using failure mode and effects analyses plus time to restoration to operating conditions.
- Performing trade studies that minimize cost and consider replacement (including logistics), repair, redundancy and fault tolerance, reliability, commonality, and other factors.
- Using the result of these studies to define a set of major system design guidelines considering such matters as crew maintenance time, need for storage on orbit, modularity, extra-vehicular activity, and internal vehicular activity.
- Developing preliminary designs that incorporate the results of the trade-off analyses.
- Repeating above for subsystems.

THE GROUPS

The concept group was chaired by K. Holtby. Its members were J. Barker, A. Mager, C. Mathews, G. Neumann, J. Schaefer, and C. Syvertson.

The systems/technical group was chaired by J. Harrington. Its members were M. Battaglia, M. Grogan, R. Hammond, C. Marvin, S. Metzger, and P. Partridge.

Concept Group Observations

- A reference concept for maintainability is needed for all center and contractor groups. This concept should address such things as fail-operational/fail-safe, on-condition maintenance, inspection philosophy (e.g., off line for major maintenance), and onboard spares versus redundancy.
- Maintainability integration should occur at the systems engineering and integration (SE&I) level. A cadre of contractor personnel may have to be located at the SE&I office for this function or may have to attend periodic meetings to integrate maintainability plans.
- Servicing of satellites, orbital transfer vehicles, and other user vehicles should be considered along with the space station maintainability plans at the SE&I level.
- A remote maintenance center on the ground should be studied and evaluated.
- Trade studies are needed to evaluate external crew activity versus automated systems for external maintenance. This also applies to manual versus automatic inspection.
- Each orbital replaceable unit (ORU) has to be testable at its interface for performance. Don't go to too low a level too soon--an ORU should probably be the biggest component that can go through the hatch.
- As failure rates for components decrease (e.g., microprocessor integration), the number of components in an ORU can increase.
- Software changes should be made by data link from the ground. Configuration control of software should be handled in the same manner hardware is handled.
- Distributed computing systems are recommended in order to provide isolation of critical and noncritical functions and embedded software. All computers on any given data bus should be tested together in a systems analysis and integration laboratory.
- Avoid reinventing systems (e.g., control moment gyros and redundancy management). NASA should coordinate with the Department of Defense.
- Advanced technologies should be developed in parallel with mainstream space station systems and components but should not be controlled in the same detail or charged with the costs associated with a mainstream development.
- Appropriate for advanced automation application are
  - robotic arm
  - fault-tolerant systems
  - diagnostic systems
  - repetitive operations and recording.
- NASA should review the National Research Council's Air Force Studies Board summer study on diagnostic technology.
- Budgets for maintainability matters should be assigned to contractors and performance against these plans/budgets tracked. A system for surfacing critical items at Level B should be established.
- Human factors engineering should focus on safe handling of equipment and maintenance tasks including such matters as restraints and foot holds. Anthropomorphic models should be used during design.

Mock-ups should be used to demonstrate both external and internal vehicular activity functions.

- Advanced technology should be introduced in an evolutionary manner. To the extent, possible new technology should be introduced in noncritical applications and then graduate into critical systems.

Systems/Technology Group Observations

Requirements necessitating a high degree of maintainability relate to flight and crew safety, preservation of mission, and continuity of service.

The most appropriate approach to basic trade-offs between reliability and maintainability for given subsystems include: use of best technology available, addition of redundancy as required to achieve mean time to failure objectives for the function, and addition of maintainability as required for the criticality of the function.

Key questions raised ask: does computer modeling have a role in answering questions relating to maintainability, and can maintainability be added downstream? The respective responses are:

- Yes--various programs exist to predict failure paths and modes and mean time to failure. Existing programs should be used where possible to avoid high costs of special software development.
- Not economically--should be part of the design concept at the beginning (i.e., diagnostics and switch over to hot spares); capability is expensive to add later.

Different systems will require different maintainability approaches, depending on the mission requirements. For example:

- The communication and data processing system would probably have built-in spare units that could be switched to in an emergency.
- The power system could degrade to a fraction of its total power before crew safety or flight safety were affected. Replacement of panels, for example, could wait until the next supply ship. There may be no need for onboard spares.
- Life-support system redundancy is obviously essential.

These examples illustrate how different the ORU problem is for major subsystems.

NASA raised many technical questions relating to the implementation of maintainability. A common theme was found.

There is an understandable desire to categorize the maintainability elements of the space station, preferably in quantitative terms. This leads to questions such as:

- What are the drivers and their relative importance?

- For each element, how are initial cost versus maintenance cost and mean time to failure versus mean time before replacement compared?
- Can mathematical models be set up for the above?

The range of elements on board the station vary widely in their criticality and technical composition. No single, meaningful, broadly applicable answer is possible. The maintainability of each element must be evaluated case-by-case in accordance with specific appropriate criteria, in order of importance, such as:

- crew safety
- achievement of mission objectives, continuity of service from customers' viewpoint
- maintaining long-life integrity of the space station
- crew time

Insufficient data now exists on the various space station elements to permit definitive, in-depth analytical study. It is clear that this level of study needs to be deferred until the new contractors reach a substantive point of subsystem definition including approximate weight, size, and, most important, technical heritage.

To minimize the extent of maintenance, it would be highly desirable to use, to the extent possible, space proven hardware. This not only eliminates development cost, but also provides a high degree of confidence in the equipment--based on current experience, in some instances, 7- to 10-year lifetimes.

It is not considered realistic to attempt designs for 30-year lifetime because of extensive and costly development and technical obsolescence. Even if achievable, it is doubtful that 30-year subsystem equipment would be desired because of technological improvement.

Close coupling is required between the NASA system designers/ integrators, who set the overall system specifications, and the Phase B subsystem contractors, to provide an interactive system definition/ design process. The various contractors should consider the problem of maintainability, i.e., amount of redundancy, nature of redundancy, monitoring, accessibility, tools needed for replacement, from the start of the project and not as an add on.

Based on two decades of successful commercial communications satellite experience, it is now possible to procure equipments/ subsystems that have demonstrated 7 to 10 years of operating life in orbit without requiring maintenance. The design and construction of these equipments should follow these principles:

- Design--Base the design on previously flight-proven designs to the greatest extent possible.
- Components--Use military-specified parts plus additional burn-in as per current commercial satellite practice.
- Redundancy--This feature is essential.

Equipment life is a statistically defined variable; once design problems have been solved, a back-up unit must be available no matter how low the probability of failure of the original unit. The number of redundant units depends on the importance of that unit to the mission and its expected probability of failure. This number may likely be less for the space station than for a 10-year commercial satellite since the latter cannot be maintained during its lifetime while the space station will be supplied every 90 days.

In support of this concept, it is noted that large electronic communication switching systems, which operate with only about 2 minutes of outage per year, achieve this result by extensive use of redundancy.

Based on this experience, NASA should, where possible, procure subsystems that have proven to be reliable. When such units do not exist, it is recommended that they be designed and built in accordance with the above principles.

It is also recommended that periodic testing of units be performed through the monitoring of significant parameters rather than by complete engineering tests of all subsystem performance parameters.

Contractor personnel involved in the design and construction of the space station and its many subsystems may not be available to NASA during the lifetime of their operation. NASA engineers should work very closely with the contractors during the design and construction period so that they become thoroughly familiar with the theory, operation, and test of these equipments. Such experience is indispensable in later operation and maintenance in orbit. It will likely require a full-time NASA presence in contractors' plants.

5

Closing Comments

The panel recognizes that the National Aeronautics and Space Administration (NASA) is in the formative period of development of its organization and staffing for the space station maintainability program. The panel is pleased to have had an opportunity to provide its views to NASA at this formative stage in the development of the program. The panel also recognizes that although maintainability has been under active study for an extended period by NASA, the approach to be followed by the space station program has not been developed and awaits input from the Phase B (concept and preliminary design) contractors.

The panel takes the position that maintainability is a critical element of the program. It permeates design from the very start of concept development through design of hardware and software through operations. Maintainability affects costs from design through test and through operations. It is a critical element in maximizing utility through operational availability and long life.

The panel's brief dialogue on the subject with NASA space station program representatives leads the panel to make these broad observations:

- It is clear that maintainability considerations must be addressed early in the design. An early set of maintainability design guidelines based on a stated maintainability philosophy should be identified. This should build on an evaluation of program needs that include the station itself, its services, and associated free-flying spacecraft and payloads.

- NASA needs to be sure it moves effectively to develop an overall maintainability strategy/approach and plan and to communicate this fact to program Level C and associated contractors.

- NASA needs to be sure that the Phase B contractors, at the time of commitment to preliminary design, have the guidance required for trade-off analyses that account for such matters as initial operating configuration cost, system support costs, crew time, scarring, and robotics.

- It is important that the system engineering and integration organization have the responsibility and authority reflected in the organizational structure to develop and implement the required maintainability plan in time to affect Phase B preliminary design activity.

The panel believes that NASA's space station program management has time, between the letting of the Phase B contracts and the development of guidance for the start of preliminary design (some 10 to 11 months), to take the kinds of actions addressed above. However, success requires early, quick, definitive action on the part of program management at all levels.

Appendixes

A. Meeting Agenda
B. NASA Briefings
C. Fault Isolation Study Statement of Task
D. Further Deliberations

APPENDIX A

SPACE STATION ENGINEERING AND TECHNOLOGY DEVELOPMENT
Maintainability/Repairability Panel Meeting

AGENDA

March 20-21, 1985
NASA Marshall Space Flight Center
Huntsville, Alabama

Wednesday, March 20

Introductions Objectives Approach	R. Greenwood, Chairman
Charge to Panel--Terms of Reference	R. Carlisle, NASA
Briefs: Onboard Maintenance and Repair-- Current Views and Key Issues/Questions	NASA (See Appendix B)
Individual Experiences and Views: Philosophy, Requirements, Specifications	Panel
Open Discussion	Panel
Organization of Subgroups to Draft Position Statements	Chairman

Thursday, March 21

Subgroup Meetings Concept group--K. Holtby (Chairman), J. Barker, A. Mager, C. Mathews, G. Neumann, J. Schaefer, C. Syvertson Subsystem/technical group--J. Harrington (Chairman), M. Battaglia, M. Grogan, R. Hammond, C. Marvin, S. Metzger, P. Partridge	
Subgroup Position Drafting	Subgroups
Review of Subgroup Material	Panel

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APPENDIX B

NASA BRIEFINGS

National Aeronautics and Space Administration

SPACE STATION MAINTAINABILITY
ASEB SPONSORED PANEL DISCUSSION

MSFC
MARCH 20-21, 1985

D.B. CRAMER

MAINTAINABILITY PANEL DISCUSSION

- **BASIC OBJECTIVE:**
  - To achieve a better understanding of the optimal degree of maintainability appropriate for Space Station.
- **APPROACH:**
  - Exchange of perspectives between NASA and the aerospace industry.

MAINTAINABILITY PANEL DISCUSSION

- SPACE STATION SUBSYSTEMS MUST BE CAPABLE OF ALMOST INDEFINITE LIFE THROUGH:
  - -Scheduled maintenance
  - -Effective and efficient completion of unscheduled maintenance
  - -Periodic exchange of elements
  - -Systematic, incremental upgrades
- AGGREGATE MAINTENANCE LOAD MUST BE BALANCED AGAINST CREW PRODUCTIVITY AND SAFETY
- AS A GOAL, ALL MAINTENANCE SHOULD NOT REQUIRE MORE THAN 3 HOURS PER DAY PER CREW MEMBER FOR 5 DAYS/WEEK

MAINTAINABILITY PANEL DISCUSSION

- "MAINTENANCE" MAY BE FUNCTIONALLY SUBDIVIDED:
  - Maintainability - an engineering activity
  - Maintainability assurance - an SR & QA activity
  - Maintenance - an operational activity

- MAINTAINABILITY HAS MANY ATTRIBUTES:
  - Designs that avoid maintenance
    - --Long life designs
    - --More reliable components
    - --Redundancy
  - Designs that facilitate maintenance
    - --Automated diagnosis and fault isolation
    - --Level of orbital replacement unit (ORU)
    - --Commonality of ORUs
    - --Human factors engineering
    - --Crew skill mix and training
    - --Ample availability of required procedures and related information
    - --Appropriate supporting facilities
    - --Environments that are supportive of the maintenance process

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MAINTAINABILITY PANEL DISCUSSION

- UNDERLYING QUESTION IS THE CHARACTERIZATION OF THE PROCESS WHICH WILL CONFIDENTLY IDENTIFY THE MOST COST-EFFECTIVE COMBINATION OF MAINTAINABILITY ATTRIBUTES
- THIS SEEMS LIKE A CLASSIC PROBLEM IN SYSTEM ENGINEERING
- THE REQUIRED DATA ARE NOT EASILY ASSEMBLED-IS THERE ENOUGH DATA TO MODEL THE PROBLEM?
- SHOULD WE APPROACH THE PROBLEM ANALYTICALLY OR INTUITIVELY?

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MAINTAINABILITY PANEL DISCUSSION

KEY QUESTIONS (FROM MY PERSPECTIVE)

- WHAT ARE THE PRIMARY INDEPENDENT VARIABLES OF A MAINTENANCE STRATEGY?
- WHAT ARE THE "DRIVER" REQUIREMENTS NECESSITATING HIGH MAINTAINABILITY?
- AS A FIRST ORDER TRADE STUDY, HOW DO WE BEST APPROACH THE RIGHT BALANCE BETWEEN THE AVOIDANCE OF MAINTENANCE (RELIABILITY) AND THE EASE OF MAINTENANCE (MAINTAINABILITY)?
- THE MANIFOLD USE OF ADVANCED AUTOMATION TO ACHIEVE COST-EFFECTIVE MAINTAINABILITY SEEMS APPROPRIATE - HOW DO WE BEST APPROACH THIS MULTIFACETED PROBLEM?

MAINTAINABILITY PANEL DISCUSSION

- SHOULD WE EXTENSIVELY USE COMPUTER MODELING TO APPROACH THE MAINTAINABILITY QUESTION?
- HOW DO WE BEST APPROACH IMPLEMENTATION?
- THE LEVEL OF ORU AND COMMONALITY OF ORUs AFFECT MANY THINGS - HOW DO WE BEST APPROACH THIS QUESTION?
- DO WE ASSIGN MAINTENANCE GOALS TO EACH SUBSYSTEM?
- DO WE PUBLISH MAINTAINABILITY GUIDELINES ONCE THE TRADE STUDIES ARE COMPLETED?
- HOW DO WE PRESERVE MAINTAINABILITY OBJECTIVES IN AN ENVIRONMENT OF SCARCE RESOURCES?

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NASA
3/12/85
B. Cramer

MAINTAINABILITY

"The purpose of this round table discussion is to develop a better understanding of the optimal degree of maintainability appropriate for the Space Station.

It is clear that Space Station subsystems must be capable of an almost indefinite life through a well planned process of scheduled maintenance, a comprehensive capability to deal quickly and efficiently with unscheduled maintenance, and a periodic exchange of major equipment elements. In addition, these subsystems must be capable of being upgraded and expanded in order to meet the increasing operational requirements of the Space Station. Maintainability is viewed primarily as an aspect of design which facilitates the process of maintenance, namely, the restoration of equipment to operational status following a failure. The process of maintenance involves many aspects of Space Station design and operations. Initially, it involves those features of the equipment itself that either facilitate maintenance or reduce the need for maintenance, such as more reliable parts, long-life designs, built-in diagnosis and fault isolation, orbital replacement unit (ORU) commonality, good access, clear labeling, and other related aspects of human factors engineering. These design features are fully utilized through the exercise of the appropriate procedures, skills, and training on the part of the crew. Lastly, there should be the required ORUs, ample associated information, the secondary facilities to effect the repair, and an environment that is supportive of the maintenance process.

Crew productivity is also heavily involved with maintainability. The commercial and scientific objectives of the Space Station are critically dependent on the availability of the crew to work with payloads. These payload activities should not be compromised by the crew performing maintenance. Making Space Station subsystems appropriately maintainable is a logical approach which can meet both the commercial and scientific objectives of the Space Station and still permits the necessary maintenance to be accomplished.

As stated above, the purpose of this round table discussion is to gain a better understanding of the appropriate degree of maintainability within Space Station subsystems." ---

The kinds of issues that are most likely to be raised would include the following:

> What are the requirements that most necessitate a high degree of maintainability?

What is the appropriate process to identify the right amount of maintainability?

What are the "driver" issues in formulating a maintainability plan?

Given the manner in which the Space Station is organized, what is the preferred approach to conducting the system engineering trade studies necessary to identify a near-optimal degree of maintainability?

Once a near-optimal degree of maintainability has been identified, what is the preferred approach for implementation, given the present Space Station Program organization?

What is the most appropriate approach to the basic trade-off between reliability and maintainability to achieve a given subsystem availability?

How should one balance the need for maintenance (as reflected by the MTBF) against the ease of maintenance (as reflected by the MTTR)?

What is the appropriate process to determine the level of ORU that is most consistent with crew time, crew skills, crew training, stowage volume for spares, secondary equipment, etc.?

What are the most cost-effective applications of advanced automation to assist in attaining high maintainability?

Of the various aspects of human factors engineering that are applicable to maintainability, which appear to be the most cost-effective?

Does computer modeling have a role in the maintainability questions?

What is the preferred approach to allocating maintenance goals to various subsystems?

How does one best preserve maintainability objectives in an environment of scarce resources?

Assuming constraints on IOC costs may limit maintainability, can one subsequently add maintainability? Is there such a thing as "maintainability scar"?

How does one know if maintainability objectives are being met, short of flight operations?

SPACE STATION MAINTAINABILITY PRESENTATION

TO

NATIONAL RESEARCH COUNCIL
AERONAUTICS AND SPACE ENGINEERING BOARD

Richard Storm
March 20, 1985
Mgr., Space Station Product Assurance
Space Station Program Office
NASA Headquarters
Washington, D.C.

SPACE STATION PLANNING GUIDELINES

MANAGEMENT RELATED

- Three year extensive definition (5-10% of program cost)
- NASA-wide participation
- Development funding in FY 1987
- IOC: early 1990's
- Cost of initial capability: $8.0B
- Extensive user involvement
  - Science and applications
  - Technology
  - Commercial
- International participation

ENGINEERING RELATED

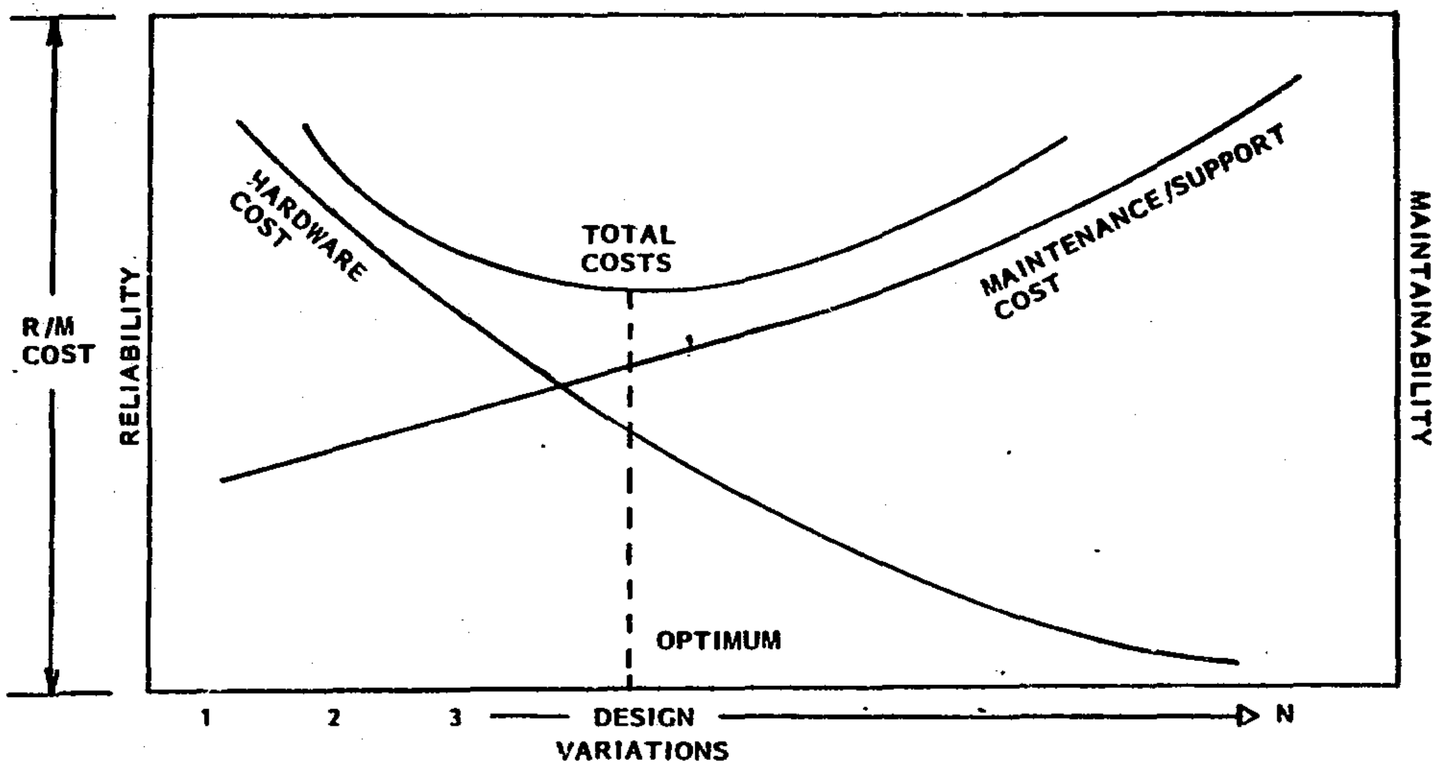
- Continuously habitable/DECADES
- Shuttle dependent
- Manned and unmanned elements
- Evolutionary
- Maintainable/restorable
- Operationally semi-autonomous
- Customer friendly
- Technology transparent

RELIABILITY/MAINTAINABILITY ISSUES

- MAINTENANCE DEMAND versus CREW TIME
- PROGRAM PRIORITY versus CREW TIME
- RELIABILITY BOUNDARY – THE MOST RELIABLE versus LOWEST ACCEPTABLE
- LIFE CYCLE COST ALTERNATIVES
- INTERNAL ACCESS versus EXTERNAL ACCESS
- SOFTWARE R-M
- SPARES AVAILABILITY
- ORU's STORED ON-BOARD versus ON-GROUND
- SAFETY/SAFE MODE OPERATIONS
- SUSTAINING SUPPORT
- ANALYTICAL METHODOLOGY IS CONTROVERSIAL — LACKS CREDIBILITY

LIFE CYCLE COST TRADE

ACQUISTION AND SUPPORT COSTS AS A FUNCTION OF RELIABILITY/MAINTAINABILITY LEVELS



NOTE: SYSTEM DESIGN OPTIONS GOING FROM HI-RELIABILITY, LO-MAINTENANCE TO LO-RELIABILITY, HI-MAINTENANCE CONFIGURATIONS

SPACE STATION MAINTAINABILITY APPROACH

FAIL OPERATIONAL/FAIL SAFE/RESTOREABLE DESIGN

BUILD "BEST" STATE OF ART HARDWARE THAT WE KNOW HOW TO BUILD - DON'T SKIMP

EMPHASIZE: ACCESSIBILITY-
MODULARITY - FEET TO THE COALS
REPLACABILITY-

R-M TRADE STUDIES TO HELP DETERMINE OPTIMIUM ORU LEVELS AND SPARES REQUIREMENTS

EARLY IDENTIFICATION OF ANTICIPATED MAINTENANCE AND SERVICING TASKS AND ESTIMATED FREQUENCIES - ADDRESS PROBLEM AREAS

SOME UNDERLYING ASSUMPTIONS

90 DAYS BETWEEN RE-SUPPLY MISSIONS

FAIL-OP/FAIL SAFE DESIGN SHOULD RESULT IN (HIGH) PROBABILITY OF NO TWO FAILURES IN A CRITICAL SYSTEM DURING A 90 DAY PERIOD

ANY FAILURES THAT DO OCCUR SHOULD BE RESTORED DURING THE OVERLAP PERIOD WHILE THE RESUPPLY ORBITER IS ATTACHED

PRIME MODE OF RESTORATION IS REPLACEMENT

TECHNOLOGY CHALLENGES

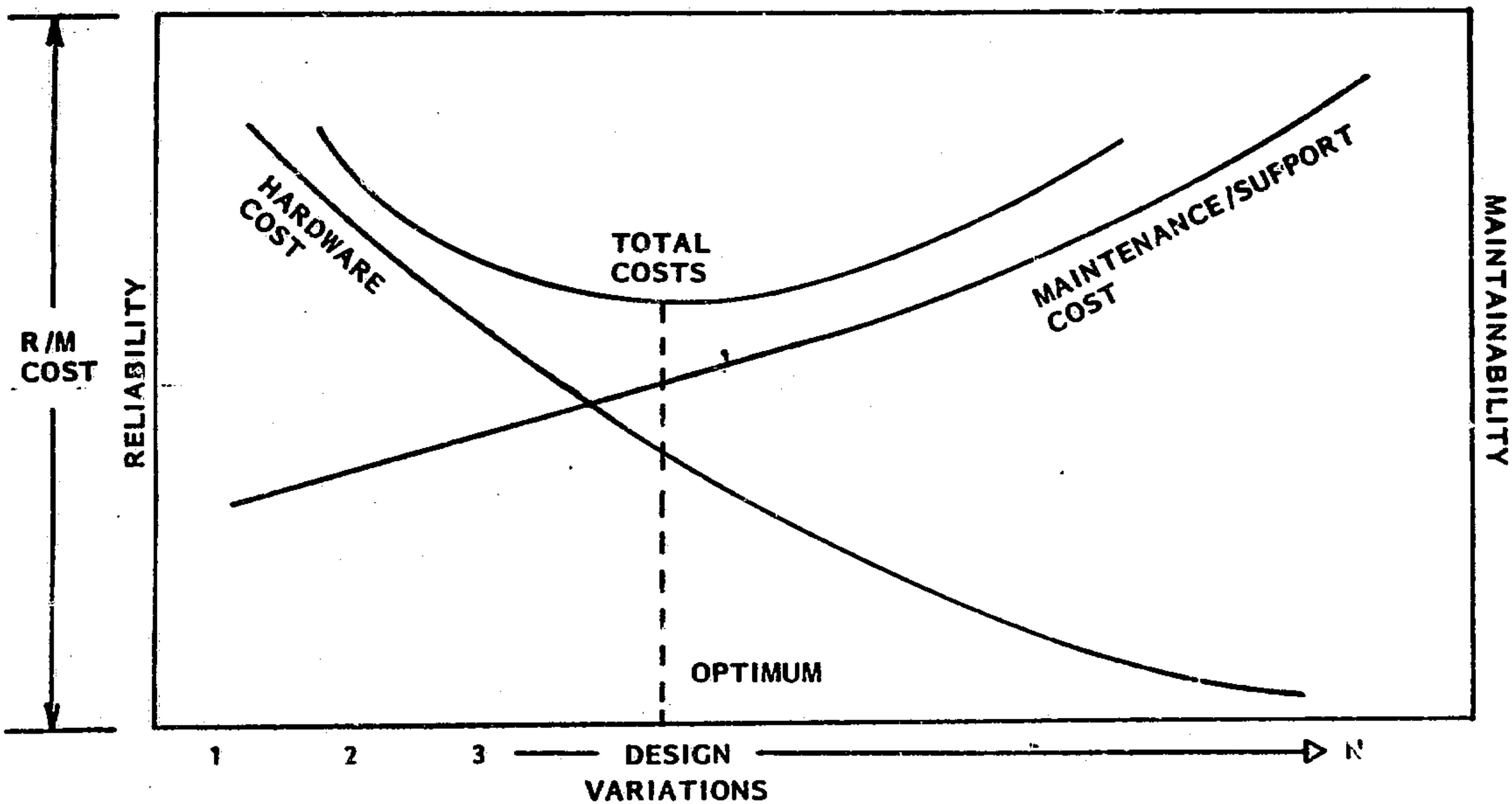
Advanced end to end information systems	fault tolerant software user friendly systems distributed architecture
High capacity electrical power generation	concentrated GaAs arrays regenerative fuel cells nuclear systems
Cryogenic fluid management	propellant transfer long term propellant storage integrated H/O economy
Thermal management	high capacity heat pipe radiators integrated thermal bus thermal coatings
Crew systems and life support	water loop closure CO_2 loop closure extended EVA
Human capabilities	end effectors quick response EVA telepresence

* (bracket around all items)

*LONG LIFE TECHNOLOGY SERVICING/MAINTENANCE TECHNOLOGY

LIFE CYCLE COST TRADE

ACQUISTION AND SUPPORT COSTS AS A FUNCTION OF RELIABILITY/MAINTAINABILITY LEVELS



NOTE: SYSTEM DESIGN OPTIONS GOING FROM HI-RELIABILITY, LO-MAINTENANCE TO LO-RELIABILITY, HI-MAINTENANCE CONFIGURATIONS

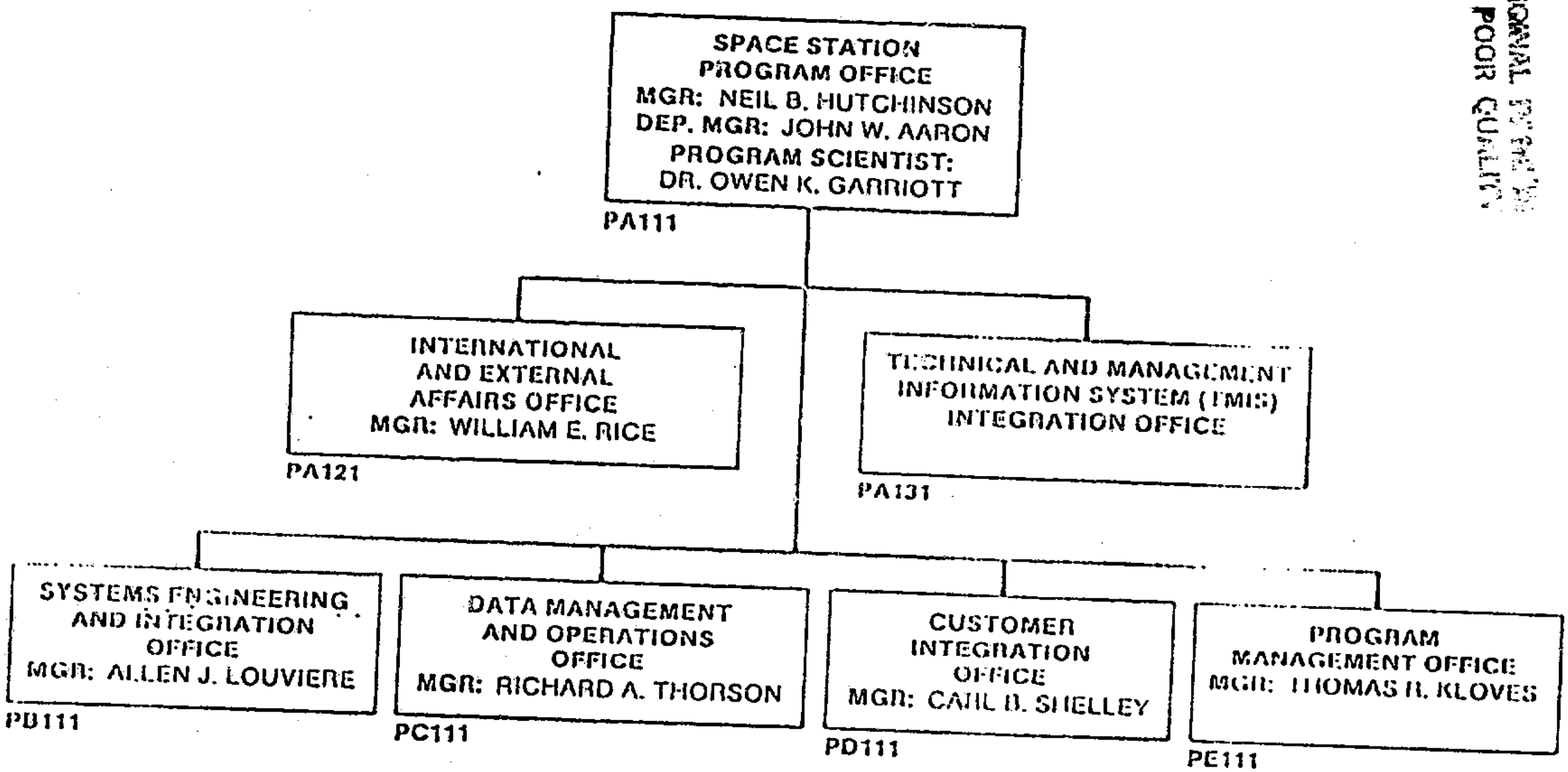
SOME CHALLENGES FOR NASA

- Design for "permanence," maintainability, and growth
- Build to cost and schedule
- Conduct systems engineering/integration in-house
- Orchestrate the international dimension:
  - politics
  - technology
  - development and operations
  - management
- Maintain customer focus when time, money and engineering begin to pinch

NASA HQ MF84-1473 (1)
4-30-84

PRESENTATION TO
NATIONAL RESEARCH COUNCIL
AERONAUTICS & SPACE ENGINEERING BOARD

HAROLD E. BENSON
MARCH 20, 1985
SPACE STATION PROGRAM OFFICE (LEVEL B)
SYSTEMS ENGINEERING & INTEGRATION


SPACE STATION PROGRAM OFFICE
MGR: NEIL B. HUTCHINSON
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MAINTAINABILITY ISSUES ON SPACE STATION

O NEED DEFINITION	- A DESIGN TO ACCOMPLISH MAINTENANCE
O COST	- WILL BE DIFFICULT TO IMPLEMENT AS PROGRAM MATURES
O ENVIRONMENT	- 0 "G" AND ATM PRESSURE/VACUUM
O INFORMATION	- A READY UPDATE SYSTEM WILL BE REQUIRED SINCE MAINTENANCE CREW WILL NOT BE IN PLACE
O SPACE STATION IS LONG TERM	- 30 YEAR SYSTEM NOT 1 FLIGHT, MULTIFLIGHT OR 7 YEAR SYSTEM - NEW CHALLENGE FOR SPACE INDUSTRY
O PROGRAMMATIC	- COMMONALITY, GROWTH, INTERNATIONAL, MANAGEMENT OF WP 1-4 COMMONALITY, GROWTH/INTERNATIONAL C-1-1

LEVEL B

O PRODUCT MAINTAINABILITY PLAN　　　　SCHEDULE

NASA
S-84-04399A

Work Package Summary Definition

- WP-01-MSFC
  - SE&I Support
    - ECLSS Analysis
    - Logistics Analysis
    - OMV/OTV Interface Analysis
    - Common Module Commonality Analysis
    - Propulsion Analysis
    - Reboost Analysis
    - Laboratory Analysis
- WP-02-JSC
  - SE&I Support
    - Growth Analysis
    - DMS Analysis
    - Comm/Tracking Analysis
    - Loads Analysis
    - Thermal Analysis
    - Control Analysis
    - Assembly Sequence Definition
    - STS Proximity Operational Berthing Analysis
    - Crew Interface Analysis
    - Resource Integration Analysis
- WP-03-GSFC
  - SE&I Support
    - Platform Configuration and Commonality Analysis
    - Platforms/Satellites Servicing Analysis
    - Attached Payloads Analysis
    - Laboratory Analysis
    - Station/Platform Interface Analysis
- WP-04-LeRC
  - SE&I Support
    - Power System Analysis

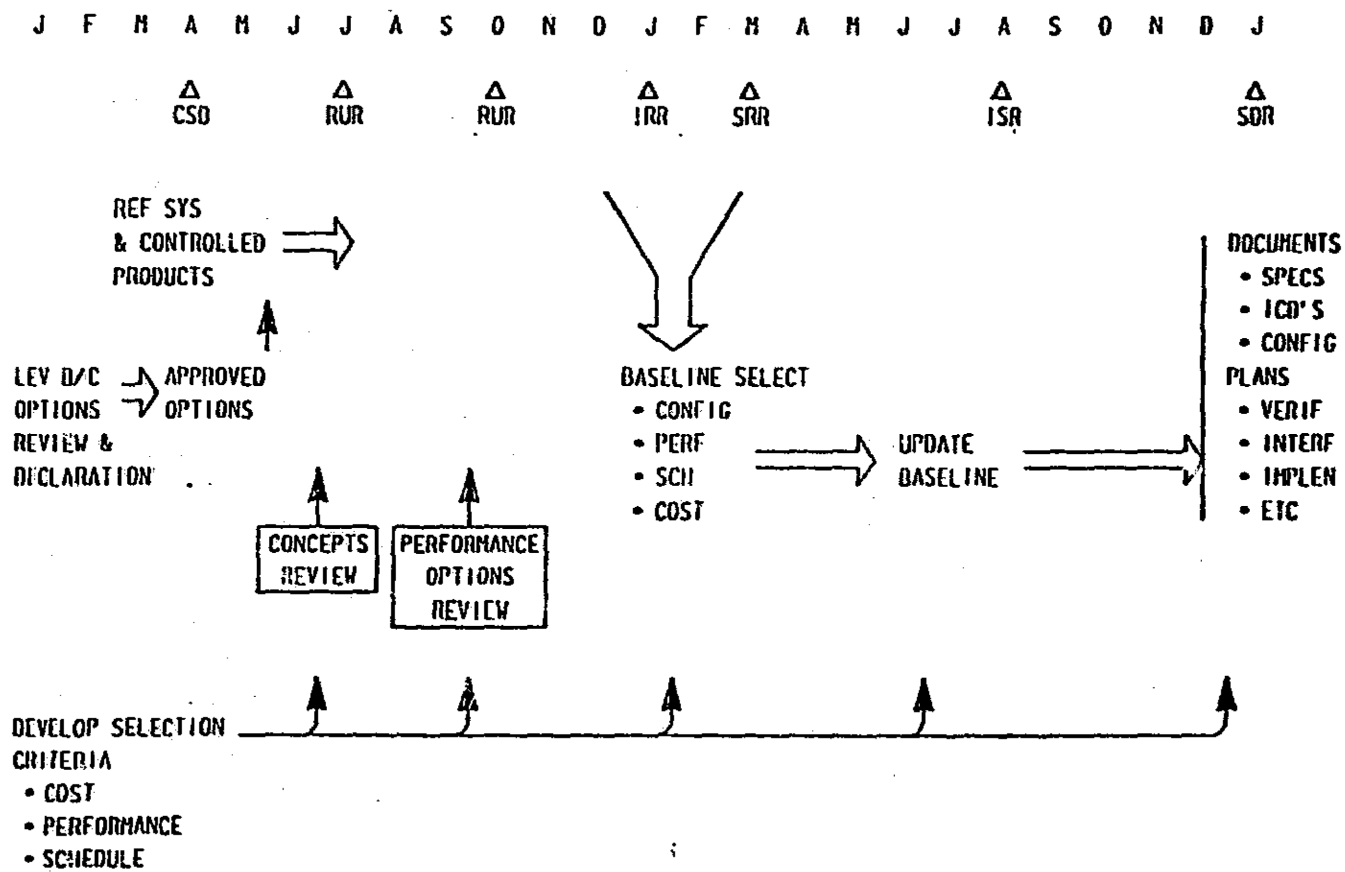
- Hardware/Software
  - Common Module
    - Structure
    - Distribution for:
      - DMS
      - Power
      - ECLSS
      - Thermal
      - Communications
  - ECLS System
  - Propulsion System
  - Laboratory Module Outfitting (1)
  - Logistics Module Outfitting (2 or 3)
  - OMV/OTV Accommodations
  - Applications Software
- Hardware/Software
  - Assembly Structure
    - Truss
    - Module Interconnect
    - Airlock
    - STS Berthing
    - Pwr, Therm., Gimbals
  - Manipulators
  - Resources Integration
  - Thermal Control System
  - EVA System and Airlock Outfitting
  - Guidance, Navigation and Control System
  - Comm/Tracking System
  - DMS
  - Habitat Module Outfitting
  - STS Interface
  - Applications Software
- Hardware/Software
  - Platforms
  - Attached Payload Accommodations
  - Platform and Free-Flier Servicing Accommodations
  - Laboratory Module Outfitting (1)
  - Applications Software
- Hardware/Software
  - Power System
    - Generation
    - Conditioning
    - Storage
  - Applications Software

Note: The upper portion depicts the supporting analysis work and the lower portion identifies actual end-item deliverables in Phase C/D. Both portions constitute a set of WP responsibilities for the Definition and Preliminary Design Phase

Figure C-1-1

NASA
S-85-00459

φB Convergence Concept



COST

- O IF YOU AGREE ON THE DEFINITION (A DESIGN TO ACCOMPLISH MAINTENANCE) - THEN... A DESIGN COSTS!
- O A MEASURE OF THE VALUE OF THE DOWNTIME MUST BE ESTABLISHED IN ORDER TO DETERMINE THE WORTHINESS VALUE OF THE MAINTAINABILITY COSTS.
- O LOGISTICS IS AN ADDITIONAL (COST) ON A MAINTAINABLE DESIGN
- O MAINTAINABILITY IMPLEMENTATION WILL BE (COSTLY) -
  - O INITIAL COSTS
  - O SCARRING WEIGHT AND OVERHEAD
  - O SPARING/COMMONALITY
  - O TRAINING
- O NEED! A CRITERIA MUST BE ESTABLISHED AND FOLLOWED ON THE SPACE STATION MAINTAINABILITY ISSUES

M COSTS = LOGISTICS (INVENTORY + WAREHOUSING + TRANSPORTATION). + LABOR (GROUND + IVA + EVA) + INITIAL (DDT&E + SCAR)

ENVIRONMENT

- 0 0 "G" CAUSES ADDITIONAL DESIGN IMPLICATIONS, NUTPLATES, ETC.
- 0 MAINTAINABILITY WILL BE DIFFERENT FOR INSIDE VS. OUTSIDE
- 0 AUTOMATION AND ROBOTS MAY BE EFFECTIVE DUE TO THIS ENVIRONMENT
- 0 NEED! A SET OF DESIGN CRITERIA ESTABLISHED FOR INSIDE VS. OUTSIDE AND USE OF AUTOMATION

INFORMATION

- O NO TRAINED MAINTENANCE CREW WILL BE AVAILABLE, THEREFORE, GOOD INFORMATION TO PERFORM MAINTENANCE MUST BE AVAILABLE (LITTLE TIME OR SKILL)
- O A PROGRAM OVERHEAD WILL EXIST TO UPDATE MAINTENANCE FUNCTIONS IN ORDER FOR THEM TO BE AVAILABLE THROUGHOUT THE LIFE OF THE PROGRAM
- O THE MAINTENANCE INFORMATION (SCHEMATICS, ETC) WILL HAVE TO BE UPLINKED OR ONBOARD FOR CRITICAL ITEMS
- O INFORMATION SYSTEM WILL HAVE TO BE DESIGNED INTO THE STATION FROM INCEPTION

SPACE STATION IS LONG TERM

- NASA TO DATE HAS HAD LIMITED EXPERIENCE WITH SUCCESSFULLY ADDRESSED THIS PROBLEM.
- TECHNOLOGY, VENDORS OF EQUIPMENT CAN CHANGE. DESIGNS MUST ACCOMMODATE THIS OCCURRENCE
- GENERIC FAILURE MAY DEVELOP WITH LONG TERM OPERATIONS WHICH MUST BE CONSIDERED IN DESIGN
- ENVIRONMENTS OF ATOMIC OXYGEN, UV, ETC. WILL CAUSE DEGRADATION OF OUTSIDE MATERIALS WITH TIME WHICH WILL HAVE TO BE ADDRESSED

PROGRAMMATIC

COMMONALITY	-	ORU WILL ESTABLISH COMMONALITY OF TOOLS AND WILL LEAD TO DEVELOPMENT OF SOME COMMON HARDWARE.
GROWTH	-	WILL ESTABLISH SIZE OF GROWTH INCREMENTS.
INTERNATIONAL	-	ADDED IMPLICATIONS OF MAINTAINABILITY WHICH WILL HAVE TO BE ADDRESSED. WILL NOT BE WELL UNDERSTOOD UNTIL MID-WAY INTO PHASE B.
MANAGEMENT OF WP 1-4	-	USE OF 4 CENTERS AND 2 CONTRACTORS AT EACH CENTER REQUIRES EARLY ESTABLISHMENT OF CRITERIA SO THAT WORK WILL BE CONSISTENT.

PRESENTATION TO
NATIONAL RESEARCH COUNCIL
AERONAUTICS AND SPACE ENGINEERING BOARD

MARCH 20, 1985

JSC SPACE STATION PROJECTS OFFICE
SYSTEMS INTEGRATION OFFICE
SHELBY L. OWENS

ORGANIZATION

JSC SPACE STATION PROJECTS OFFICE - C. COVINGTON
ENGINEERING AND OPERATIONS OFFICE - T. REDDING
SYSTEMS INTEGRATION OFFICE - S. OWENS

SYSTEMS INTEGRATION RESPONSIBILITIES RELATED TO ON ORBIT MAINTAINABILITY

- O MAINTAINABILITY TRADE STUDIES AND PHASE B IMPLEMENTATION OF INTERIM REQUIREMENTS
  - HARDWARE AND SOFTWARE ISSUES
- O COMMONALITY TRADE STUDIES AND PHASE B IMPLEMENTATION OF INTERIM REQUIREMENTS

MAJOR FACTORS TO BE CONSIDERED IN THE IMPLEMENTATION OF MAINTAINABILITY AND COMMONALITY REQUIREMENTS

- O LOGISTIC IMPLICATIONS RESULTING FROM MAINTAINABILITY AND COMMONALITY REQUIREMENTS
- O SPECIALIZED CREW REQUIREMENTS (IVA, EVA, TRAINING, TIME, ETC.)
- O POTENTIAL IMPACTS TO CUSTOMER RELATED OPERATIONS
- O DESIGN IMPACTS RESULTING FROM ON ORBIT MAINTENANCE REQUIREMENTS
- O DATA MANAGEMENT SYSTEM REQUIREMENTS
- O AUTONOMOUS OPERATIONS IMPACTS
- O HUMAN FACTORS CONSIDERATIONS
- O RE-VERIFICATION STRATEGY
- O SAFETY ISSUES
- O MAINTENANCE/REPAIR/REPLACE DECISION MAKING
- O GROWTH AND TECHNOLOGY TRANSPARENCY CONSIDERATIONS

NASA's APPROACH TO IMPLEMENTING MAINTAINABILITY FOR THE SPACE STATION PROGRAM

- O BY TASK AND TRADE STUDY ASSIGNMENTS FOR EACH WORK PACKAGE DURING THE PHASE B CONTRACT

- O EXAMPLES:

SECTION C-1 STATEMENT OF WORK
3.2.2.4.A - COMMONALITY APPROACHES AMONG SSPE'S, MODULES, SUBSYSTEMS, PLATFORMS, AND EXISTING SYSTEMS SUCH AS THE NSTS.

.D - SSPE MAINTAINABILITY/MAINTENANCE AND SERVICING ANALYSIS INCLUDING RELIABILITY VERSUS MAINTENANCE TRADES, ETC.
NOTE: TO BE SUPPLIED IN DATA REQUIREMENT (DR)-02

3.3.2 --- THE CONTRACTOR SHALL CONDUCT ANALYSES OF HIS DESIGNS TO MAXIMIZE THE MAINTAINABILITY FEATURES
NOTE: TO BE SUPPLIED IN DATA REQUIREMENT (DR)-02

3.6.4 --- THE CONTRACTOR SHALL DEVELOP AN APPROACH TO ON ORBIT MAINTENANCE THAT SATISFIES THE REQUIREMENT FOR AN INDEFINITE STATION LIFE
NOTE: TO BE SUPPLIED IN DATA REQUIREMENT (DR)-07

MAJOR ISSUES OR CONCERNS

NASA HAS DEMONSTRATED THE CAPABILITY TO PROVIDE SYSTEMS THAT ARE

- O RELIABLE
- O REDUNDANT
- O AND SOMEWHAT MAINTAINABLE
  - O SKILLED PERSONNEL UTILIZED FOR GROUND REPAIR/MAINTENANCE
  - O ADAPTIVE WORK AROUND TECHNIQUES FOR ON-ORBIT REPAIRS

NASA HAS <u>NOT</u> DEVELOPED A SYSTEM WITH MAJOR GOALS OF

- O INDEFINITE LIFE
- O ON-ORBIT GROWTH POTENTIAL
- O TRANSPARENCY TO NEW TECHNOLOGY UPDATES ON ORBIT
- O SCHEDULED AND UNSCHEDULED MAINTENANCE ON ORBIT
  - O BOTH IVA AND EVA

- O COMMONALITY OF INTERFACES WITH MULTIPLE CUSTOMERS
  - O INTERNATIONAL
  - O COMMERCIAL
  - O MULTIPLE VEHICLES
  - O OTHER'S

TO SATISFY THESE SPACE STATION GOALS, NASA NEEDS ASSISTANCE AND TECHNICAL EXPERTISE FROM

- O AEROSPACE COMPANIES
- O COMMERCIAL INDUSTRY
- O INTERNATIONAL AND COMMERCIAL USERS AND SUPPLIERS
- O COMPREHENSIVE TRADE STUDIES BY NASA AND THE PHASE B CONTRACTORS

Lyndon B. Johnson Space Center

RELIABILITY DIVISION

NAME: J. H. LEVINE

DATE: MARCH 20, 1985

RELIABILITY-MAINTAINABILITY ASSURANCE FOR SPACE STATION

Briefing to: National Research Council
Commission on Engineering and Technical Systems
Aeronautics and Space Engineering Board
Space Station Panel on Maintenance and Repair
March 20 and 21, 1985
NASA-MSFC

NASA Lyndon B. Johnson Space Center	RELIABILITY DIVISION	NAME: J. H. LEVINE DATE: MARCH 20, 1985

SCOPE OF BRIEFING

- SIGNIFICANT DIFFERENCES BETWEEN SPACE STATION AND PREVIOUS SPACECRAFT PROGRAMS
- SPACE STATION RELIABILITY-MAINTAINABILITY ASSURANCE ROLE
- CRITICAL SPACE STATION RELIABILITY-MAINTAINABILITY ASSURANCE ISSUES

NASA
Lyndon B. Johnson Space Center

RELIABILITY DIVISION

NAME: J. H. LEVINE

DATE: MARCH 20, 1985

SIGNIFICANT DIFFERENCES BETWEEN SPACE STATION AND PREVIOUS SPACECRAFT PROGRAMS

- * SPACE STATION TO BE DESIGNED FOR INDEFINITE STATION LIFE SUPPORTED BY ON-ORBIT MAINTENANCE
- LESS EMPHASIS ON WEIGHT AND VOLUME FOR MOST SYSTEMS
- * MOST SYSTEMS DESIGNED TO BE LESS TIME CRITICAL IN THEIR FUNCTIONS
- * ADDED EMPHASIS FOR COMMONALITY ACROSS THE SPACE STATION
- * DESIGN CRITICAL SUBSYSTEMS TO BE FAIL-OPERATIONAL/FAIL-SAFE/RESTORABLE
- * DURING ASSEMBLY AND MAINTENANCE, CRITICAL SYSTEMS TO BE FAIL-SAFE
- * USE OF ROBOTICS TO SUPPORT MAINTENANCE AND PAYLOADS
- * ONBOARD CHECKOUT FOR FAULT ISOLATION AND RESTORABILITY PURPOSES
- INCREASED USE OF SOFTWARE FOR ONBOARD SYSTEMS AND INTERFACE WITH PAYLOADS
- INCREASED USE OF ONBOARD DATA MANAGEMENT SYSTEMS AND USE OF TMIS (TECHNICAL AND MANAGEMENT INFORMATION SYSTEM).
- PRACTICES TO EMPHASIZE COST-REDUCTION TECHNIQUES SUCH AS PROTOFLIGHTING
- ADDED EMPHASIS ON DESIGN-TO-COST AND SIGNIFICANTLY HIGHER LEVELS OF PRODUCTIVITY
- FINAL ASSEMBLY, INTEGRATION, AND DEMONSTRATION OF CAPABILITY WILL OCCUR ON ORBIT WITHOUT PRIOR GROUND DEMONSTRATION

* SIGNIFICANT TO MAINTAINABILITY

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RELIABILITY DIVISION

NAME: J. H. LEVINE

DATE: MARCH 20, 1985

SIGNIFICANT DIFFERENCES BETWEEN SPACE STATION AND PREVIOUS SPACECRAFT PROGRAMS
(CONCLUDED)

- *INCREASED SENSITIVITY TO LOGISTICS FROM SPARES, GROUND REPAIRS, STORAGE, AND OBSOLESCENCE STANDPONTS
- *FINITE MANPOWER RESOURCE TO ACCOMPLISH MAINTENANCE ON ORBIT
- *INCREASED USE OF EXTRAVEHICULAR ACTIVITY
- *LONG PERIOD OF NO COME-HOME AND SUPPORT CAPABILITY
- TIGHT CONFIGURATION CONTROL EXTENDING OVER A LONG TIME PERIOD
- TECHNOLOGY TRANSPARENCY CONSIDERATIONS FOR SYSTEMS UPGRADING TO PERMIT GROWTH THROUGH EVOLUTION

* SIGNIFICANT TO MAINTAINABILITY

NASA Lyndon B. Johnson Space Center	RELIABILITY DIVISION	NAME: J. H. LEVINE DATE: MARCH 20, 1985

SPACE STATION RELIABILITY-MAINTAINABILITY ASSURANCE ROLE

- PARTICIPATE IN THE DEFINITION OF THE SPACE STATION MAINTAINABILITY REQUIREMENTS
- PARTICIPATE IN RELIABILITY-MAINTAINABILITY TRADES TO OPTIMIZE CREW TIME REQUIREMENTS
- PARTICIPATE IN DEFINING MAINTAINABILITY TASKS AND "HOW-TO" COMPLIANCE TECHNIQUES
- PARTICIPATE IN THE EVALUATION OF THE ADVANCED DEVELOPMENT PROGRAMS TO ASSURE ADEQUATE UNDERSTANDING OF MAINTAINABILITY
- PARTICIPATE IN DEFINING ORU'S FOR EACH SUBSYSTEM CONSISTENT WITH COMMONALITY AND APPLICATION NEEDS
- PARTICIPATE IN DEFINING SPECIAL COMMON NEEDS SUCH AS STANDARD TOOLS, CONNECTORS, FASTENERS, BOX SHAPES, ETC.
- PARTICIPATE IN THE DEVELOPMENT OF MAINTAINABILITY DEMONSTRATIONS
- PARTICIPATE IN THE DEVELOPMENT OF A MAINTAINABILITY DATA SYSTEM
- PARTICIPATE IN THE RESOLUTION OF PROBLEMS HAVING A MAINTAINABILITY IMPACT

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NAME: J. H. LEVINE

DATE: MARCH 20, 1985

CRITICAL SPACE STATION RELIABILITY-MAINTAINABILITY ASSURANCE ISSUES

- SINCE THE USE OF PROVEN AND MATURE DESIGNS ARE VITAL TO LOW MAINTENANCE, WHICH SPACE STATION DESIGNS ARE EXPECTED NOT TO BE INITIALLY PROVEN DESIGNS?
- WHERE IS ACCESSIBILITY AND RESTORATION OF FAILED ITEMS EXPECTED TO BE DIFFICULT?
- WHAT IS THE OPTIMUM APPROACH TO ASSURING THAT WORK PACKAGE USING CENTERS PARTICIPATE IN COMMONALITY DESIGN BASELINES, CHANGES, TEST PROGRAMS, AND PROBLEM DISPOSITION TO ENHANCE RELIABILITY-MAINTAINABILITY SUCCESS?
- WHAT ARE PRACTICAL AND CREDIBLE ANALYTICAL TECHNIQUES TO EVALUATE CREW TIME ESTIMATES FOR IN-FLIGHT MAINTENANCE VERSUS CREW TIME AVAILABILITY?
- HOW MUCH CONFIDENCE SHOULD BE OBTAINED PRIOR TO LAUNCH RELATIVE TO ESTIMATES OF CREW TIME FOR IN-FLIGHT MAINTENANCE AND IN-FLIGHT SPARES REQUIREMENTS?
- WHAT ARE THE OPTIMUM TRADES TO MINIMIZE CREW TIME CONSIDERING FAULT ISOLATION COMPLEXITY, IN-FLIGHT SPARES, RELIABILITY, AND RESTORABILITY?
- WHERE CAN ROBOTICS BE USED FOR ROUTINE MAINTENANCE FROM A PRACTICAL STANDPOINT TO MINIMIZE EXTRAVEHICULAR ACTIVITY?

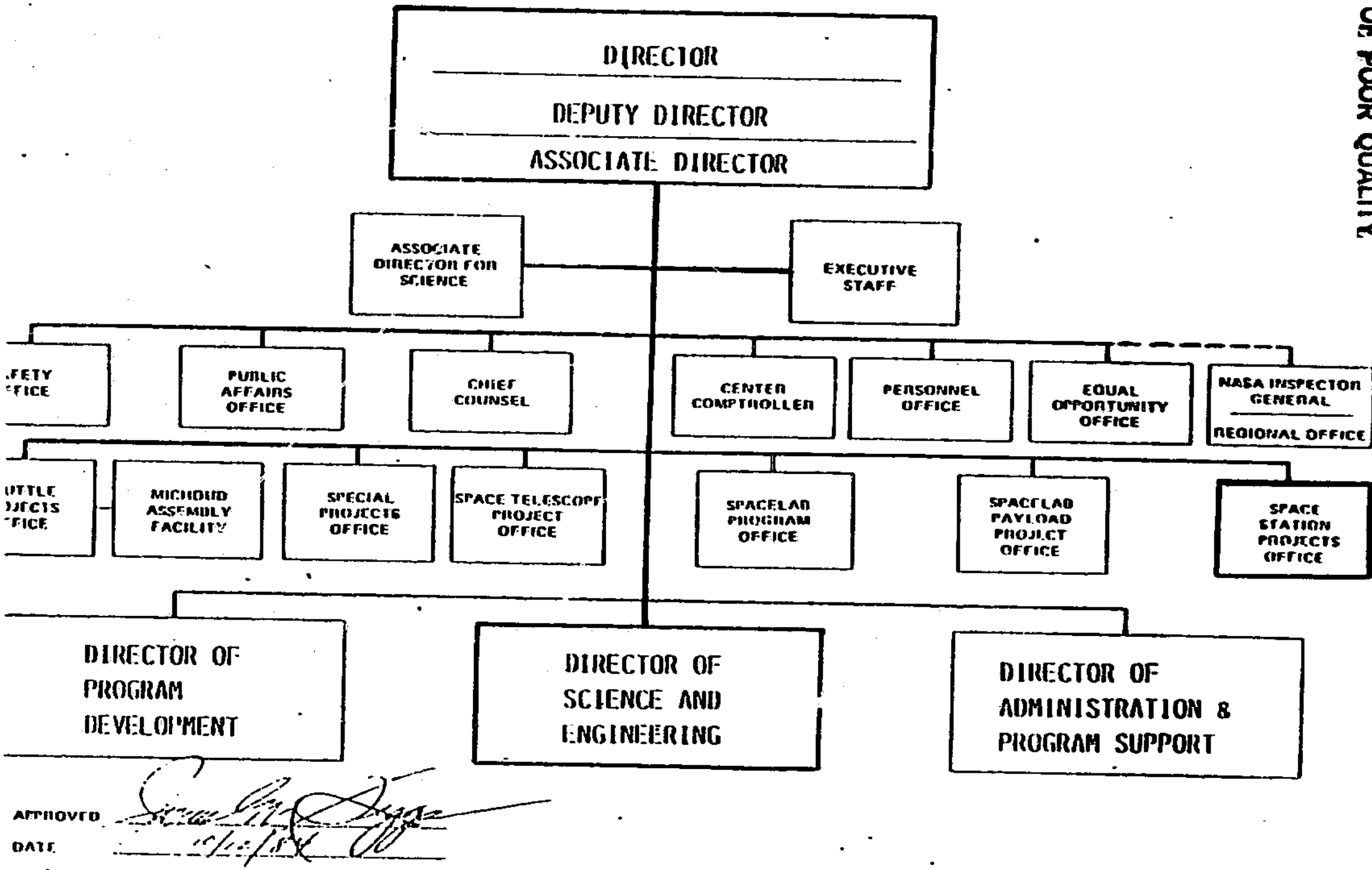
CRITICAL SPACE STATION RELIABILITY-MAINTAINABILITY ASSURANCE ISSUES (CONCLUDED)

- HOW CAN ADVANCED DEVELOPMENT PROGRAMS BE USED TO ANSWER MAINTAINABILITY ISSUES AND OBTAIN MAINTAINABILITY DATA?
- WHAT STUDIES NEED TO BE CONDUCTED TO PROVIDE DIRECTION TO LOGISTICS RELATIVE TO SPARES, GROUND REPAIRS, IN-FLIGHT STORAGE, AND OBSOLESCENCE?

J. Lusk
NASA MSFC

National Aeronautics and Space Administration

GEORGE C. MARSHALL SPACE FLIGHT CENTER



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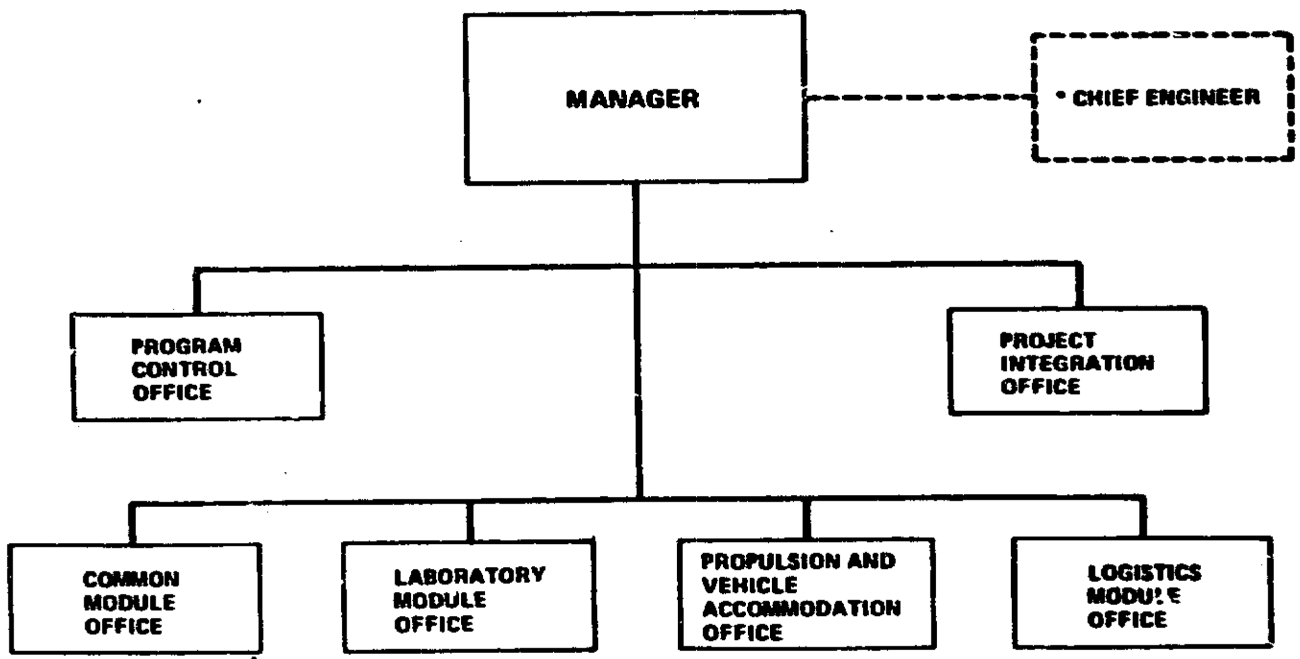
PROGRAM DEVELOPMENT
SPACE STATION PROJECT OFFICE



* STAFFED BY SCIENCE AND ENGINEERING PERSONNEL

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Work Package Summary Definition

- WP-01-MSFC
  - SE&I Support
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- WP-04-LeRC
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- Hardware/Software (WP-01-MSFC)
  - Common Module
    - Structure
    - Distribution for:
      - DMS
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      - ECLSS
      - Thermal
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  - ECLS System
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  - Laboratory Module Outfitting (1)
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    - Truss
    - Module Interconnect
    - Airlock
    - STS Berthing
    - Pwr, Therm., Gimbals
  - Manipulators
  - Resources Integration
  - Thermal Control System
  - EVA System and Airlock Outfitting
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    - Generation
    - Conditioning
    - Storage
  - Applications Software

Note: The upper portion depicts the supporting analysis work and the lower portion identifies actual end-item deliverables in Phase C/D. Both portions constitute a set of WP responsibilities for the Definition and Preliminary Design Phase

Figure C-1-1

ORIGINAL PAGE IS OF POOR QUALITY

MAINTAINABILITY

REASONS FOR EARLY CONSIDERATION

- o EQUIPMENT DESIGN INFLUENCES SUPPORT NEEDS
  - SUPPORT NEEDS IMPACT OVERALL SYSTEM EFFECTIVENESS AND EFFICIENCY
- o OFTEN, PRIME EQUIPMENT IS DESIGNED AND SUPPORT NEEDS EVOLVE AFTER DESIGN IS FIXED

MSFC ROLE IN SPACE STATION

MAINTAINABILITY

- LOGISTICS ANALYSIS
  - MSFC TO LEAD LOGISTICS ANALYSIS EFFORT FOR SPACE STATION PROGRAM AND DEVELOP INTEGRATED LOGISTICS SYSTEM
  - INTEGRATED LOGISTICS SYSTEM CONSISTS OF:
    - MAINTENANCE PLANNING
    - MAINTAINABILITY
    - LOGISTICS SUPPORT ANALYSIS
    - TRAINING
    - SUPPLY SUPPORT
    - PACKAGING, HANDLING, STORAGE, AND TRANSPORTATION
    - LOGISTICS MANAGEMENT
    - FACILITIES AND SUPPORT EQUIPMENT
- MAINTAINABILITY PLAN DEVELOPMENT

SPACE STATION LOGISTICS ANALYSIS

SPACE STATION LOGISTICS ANALYSIS DEVELOPS REQUIREMENTS FOR MAINTENANCE MANAGEMENT SYSTEM TO:

- PROVIDE EQUIPMENT STATUS, CONFIGURATION, AND LOCATION
- TRACK EQUIPMENT OPERATING TIMES
- TRACK HISTORICAL DATA
- MAINTAIN MAINTENANCE PROCEDURES

SPACE STATION MAINTAINABILITY PLAN

THE SPACE STATION MAINTAINABILITY PLAN WILL:

- DEVELOP LEVEL B MAINTAINABILITY REQUIREMENTS
- INFLUENCE DESIGN, DEVELOPMENT, AND LIFE OF SPACE STATION
- OBJECTIVES
  - o IMPROVE AND MAINTAIN OPERATIONAL READINESS
  - o REDUCE LIFE CYCLE COST
  - o PROVIDE DATA ESSENTIAL FOR MANAGEMENT AND EFFICIENT OPERATION OF SPACE STATION

SPACE STATION MAINTAINABILITY PLAN

MAINTAINABILITY PLAN TO BE INTEGRATED INTO OVERALL SPACE STATION PROGRAM

- DESIGN
- RELIABILITY
- MAINTENANCE
- TEST
- SAFETY
- LOGISTICS
- PRODUCTION
- FLIGHT OPERATIONS
- GROUND OPERATIONS

SPACE STATION MAINTAINABILITY

OTHER NASA PROGRAM EXPERIENCE

+

MANAGEMENT DICTATES

- NHB 1700.7A
- JSC 11123
- JSC 10615
- MSFC-STD-512A
- MIL-STD-1472B
- KHB 1700.7
- NHB 5300.4(1D-2)
- MSFC-SPEC-549
- MIL-STD-1629A
- MIL-STD-470
- MIL-STD-471
- MIL-STD-778
- MIL-HDBK-472

MAINTAINABILITY PLAN

- o SPECIFIES REQUIREMENTS FOR IMPLEMENTATION INTO PROGRAM CONTRACT.
- o SPECIFIES PREPARATION OF DATA REQUIREMENTS LISTS & DATA REQUIREMENTS DESCRIPTION
- o FURNISHES GUIDELINES TO ACCOMPLISH REQUIRED ANALYSIS AND REVIEWS
- o CALLS FOR PROGRAM MILESTONE REVIEWS AND SCHEDULES

85-27.JL

SPACE STATION MAINTAINABILITY PHILOSOPHY

- SPACE STATION SHOULD BE DESIGNED TO BE MAINTAINABLE ON-ORBIT BY REMOVE AND REPLACE (ORU CHANGEOUT)
- ORU's WILL BE RETURNED TO GROUND FOR REPAIR/REFURBISHMENT
- A SPACE STATION MODULE WILL BE RETURNED TO GROUND ONLY FOR CONTINGENCIES
- ON-BOARD DIAGNOSTIC TOOLS WILL DETECT FAILURES DOWN TO THE ORU LEVEL
- NON-CRITICAL SYSTEMS WILL BE ALLOWED TO FAIL AND OPERATE IN DEGRADED MODE UNTIL SPARES AVAILABLE
- SPARES RESUPPLIED EVERY 90 DAYS
- FLIGHT CRITICAL SYSTEMS SHOULD BE FAIL OPERATIONAL/FAIL SAFE. NON-CRITICAL SYSTEMS SHOULD BE FAIL SAFE.

85-27.JL

SPACE STATION MAINTAINABILITY PHILOSOPHY

- PERFORM PLANNED MAINTENANCE ON SYSTEMS FOR HEALTH AND SAFETY, SUCH AS FILTER REPLACEMENT
- FOR CONTINGENCIES, A SET OF TEST EQUIPMENT AND TOOLS WILL BE PROVIDED TO SUPPORT ON-BOARD REPAIR
- THE SPACE STATION WILL PROVIDE FUNCTIONAL CAPABILITY TO SUPPORT ON-BOARD REPAIR

SS MAINTAINABILITY/MAINTENANCE PHILOSOPHY

- o ALL SUBSYSTEMS (INCLUDING STRUCTURE) OF INITIAL SS WILL BE ON-ORBIT MAINTAINABLE:
  - PLANNED MAINTENANCE WILL BE VIA ORU REPLACEMENT, WITH SELECTED LOWER LEVELS OF OFF-LINE REPAIR (KEY ITEMS' BLACK BOX OR CARD REPLACEMENT, ETC.)
  - ALL OTHER SS EQUIPMENT WILL BE DESIGNED TO ALLOW UNPLANNED MAINTENANCE (EMPHASIS ON LOW-COST APPROACH):
    - o MINIMUM SPECIAL DESIGN AND TEST REQUIREMENTS FOR MAINTENANCE.
    - o MAINLY PROVIDE ACCESSIBILITY.
  - DESIGN COMMONALITY AND HIGH REDUNDANCY/SAFE HAVEN CONCEPT ALLOWS FAIRLY LOW LEVEL OF SS SPARES ($\leq$10% ?) TO BE REQUIRED ON-BOARD.
  - MAINTENANCE APPROACH FOR EQUIPMENT IN PRESSURIZED MODULES WILL BE SHIRT-SLEEVE, AND FOR EQUIPMENT IN UNPRESSURIZED AREAS WILL BE ONE OR MORE OF THE FOLLOWING (DEPENDING ON RESULTS OF DESIGN STUDIES):
    - o EVA
    - o RMS OR OTHER MANIPULATOR/EXCHANGER DEVICE
    - o COMBINATIONS OF ABOVE 2 APPROACHES
    - o SMART OMV

- o INITIAL SS WILL HAVE CAPABILITY OF MAINTENANCE OF FF SATS./PLATS
  - MAINTENANCE POLICY FOR PLANNED VS. UNPLANNED MAINTENANCE SHALL BE SIMILAR TO THAT STATED FOR BASIC SS ABOVE
  - SPARES FOR FF SATS/PLATS. WILL NOT BE STORED ROUTINELY ON SS – WILL BE DELIVERED AS NEEDED ON LOGISTICS FLIGHTS.
  - REMOTE MAINT. CAPABILITY OF FF SATS/PLATS. WILL BE VIA SMART OMV, BUT SS MUST ALSO HAVE CAPABILITY TO RETURN THESE TO VICINITY OF SS AND PERFORM MAINTENANCE, BECAUSE:
    - o SOME FF SATS./PLATS. WILL NOT HAVE EARLY REMOTE MAINT. CAPABILITY.
    - o SOME FIXES WILL REQUIRE UNPLANNED MAINTENANCE
  - MAINTENANCE OF FF SATS./PLATS. IN VICINITY OF SS SHALL BE EITHER:
    - o WHILE ATTACHED TO THE SS, WITH MAINTENANCE APPROACH AS IDENTIFIED FOR BASIC SS ABOVE
    - o WHILE FREE FLYING IN CLOSE PROXIMITY TO SS, WITH EVA VIA MMU BEING UTILIZED

- o INITIAL SS WILL HAVE CAPABILITY OF MAINTENANCE OF OMV
  - MAINTENANCE POLICY FOR PLANNED VS. UNPLANNED MAINTENANCE SHALL BE SIMILAR TO THAT STATED FOR BASIC SS ABOVE
  - SPARES POLICY FOR OMV SHALL BE SIMILAR TO THAT STATED FOR BASIC SS ABOVE
  - MAINTENANCE APPROACH WILL BE AS STATED FOR BASIC SS ABOVE (EXCEPT SMART OMV)

SPACE STATION MAINTAINABILITY

- MAINTAINABILITY SHOULD BE IMPLEMENTED THROUGHOUT ALL PHASES OF THE SPACE STATION PROGRAM

- MAINTAINABILITY HAS A VERY CLOSE ASSOCIATION WITH OTHER DISCIPLINES SUCH AS RELIABILITY, SAFETY, HUMAN FACTORS, LOGISTICS, CREW SYSTEMS, DESIGN, AND SYSTEMS ENGINEERING, ETC., MAINTAINABILITY MUST DRAW UPON REQUIREMENTS LEVIED BY THESE OTHER DISCIPLINES.

  - MAINTAINABILITY REQUIRED TO SUGGEST CANDIDATE COMPONENTS FOR EASY AND QUICK ACCESS TO REPLACE OR REPAIR

    - RELIABILITY IDENTIFIES "HIGH FAILURE RATE ITEMS"

    - SAFETY/HAZARDS ANALYSIS IDENTIFIES "SAFETY CRITICAL ITEMS"

    - DESIGN IDENTIFIES ITEMS NEEDING LUBRICATION, SERVICE, ADJUSTMENT, ETC.

  - MAINTAINABILITY REQUIRED TO SUGGEST LEVEL OF REDUNDANCY IN THE SYSTEM SINCE THIS WOULD AFFECT FREQUENCY AND POLICY FOR REPLACEMENT AND/OR REPAIR

    - RELIABILITY PERFORMS (WHEN REQUIRED) RELIABILITY TRADE STUDIES, RELIABILITY ALLOCATIONS, PREDICTIONS, COMPARISONS, FMEA'S (NHB 5300.4(1D-2)

    - SAFETY SPECIFIES FAULT TOLERANCE REQUIREMENTS AGAINST POTENTIAL HAZARDS (NHB 1700.7A).

    - CREW SYSTEMS IDENTIFIES REQUIRED OR PREFERRED HANDLING FIXTURES, EXTERNAL FEATURES, ETC.

SPACE STATION MAINTAINABILITY

- MAINTAINABILITY REQUIRED TO SUGGEST HARDWARE LEVEL OF REPLACEMENT AND/OR REPAIR
  - DESIGN/RELIABILITY/SYSTEMS ENGINEERING WOULD IDENTIFY A WORKABLE SYSTEM IN GENERAL AGREEMENT WITH AN END ITEM SPEC
  - LOGISTICS AND COST ENGINEERING WOULD PROVIDE COST INDICES FOR HARDWARE AND OPERATIONS
  - MAINTAINABILITY PROVIDES TRADE STUDIES TO OPTIMIZE SYSTEM UP TIME, MINIMIZE MAINTENANCE ACTIONS WHILE MAINTAINING ACCEPTABLE SAFETY, RELIABILITY, AND COST
- MAINTAINABILITY REQUIRED TO SUGGEST NUMBER OF SPARES REQUIRED
  - RELIABILITY PROVIDES DATA ON FAILURE HISTORY AND EXPECTED FAILURES
  - LOGISTICS IDENTIFIES STORAGE AND PACKAGING REQUIREMENTS, EARLY PROCUREMENTS, ETC.
  - MAINTAINABILITY MUST KNOW SYSTEM UP TIME REQUIREMENTS, CONSTRAINTS ON REPLACEMENT OR REPAIR TIMES DUE TO SAFETY, RELIABILITY, HANDLING, ETC.
- MAINTAINABILITY REQUIRED TO SUGGEST ITEMS TO BE MONITORED
  - SAFETY REQUIREMENTS SPECIFIES MONITORING OF INHIBITS AGAINST HAZARDS
  - FMEA IDENTIFIES CRITICAL ITEMS AS CANDIDATES
  - DESIGN/RELIABILITY IDENTIFY ITEMS SUBJECT TO WEAROUT OR DEGRADATION NEEDING STATUS MONITORING

85-27.JL

SPACE STATION MAINTAINABILITY

- MAINTAINABILITY REQUIRED TO SUGGEST CORRECTIVE AND PREVENTIVE MAINTENANCE POLICIES
  - WITH KNOWLEDGE OF COMPONENT AND SYSTEM RELIABILITY, SYSTEM CONFIGURATION, REPLACEMENT AND/OR REPAIR TIMES REQUIRED, LIMITED LIFE ITEMS, MEAN TIMES TO EXPECTED SYSTEM DOWNSTATES, SYSTEM UP TIME REQUIRED, ETC., A MAINTENANCE POLICY CAN BE ESTABLISHED TO PERFORM SCHEDULED PREVENTIVE AND CORRECTIVE MAINTENANCE ACTIONS TO SATISFY OVERALL REQUIREMENTS
  - LOGISTICS ARM OF GROUND OPERATIONS COULD KEEP FAILURE LOG SO AS TO ALWAYS KNOW "WORKING STATUS" OF ALL SYSTEMS. PERIODIC HEALTH CHECKS WOULD BE MADE OF REDUNDANT/STANDBY ITEMS TO MAINTAIN STATUS. A "NEW" LOG WOULD START AFTER THE SYSTEM RECEIVED A MAINTENANCE ACTIONS RESTORING THE SYSTEMS TO "INITIAL" CONDITION

SPACE STATION ENGINEERING AND TECHNOLOGY DEVELOPMENT

MAINTAINABILITY/REPAIRABILITY PANEL MEETING

WORK PACKAGE NO. 4 - ELECTRIC POWER SYSTEM

NASA LEWIS RESEARCH CENTER

CLEVELAND, OHIO

MARCH 20, 1985

JOYCE P. JOYCE
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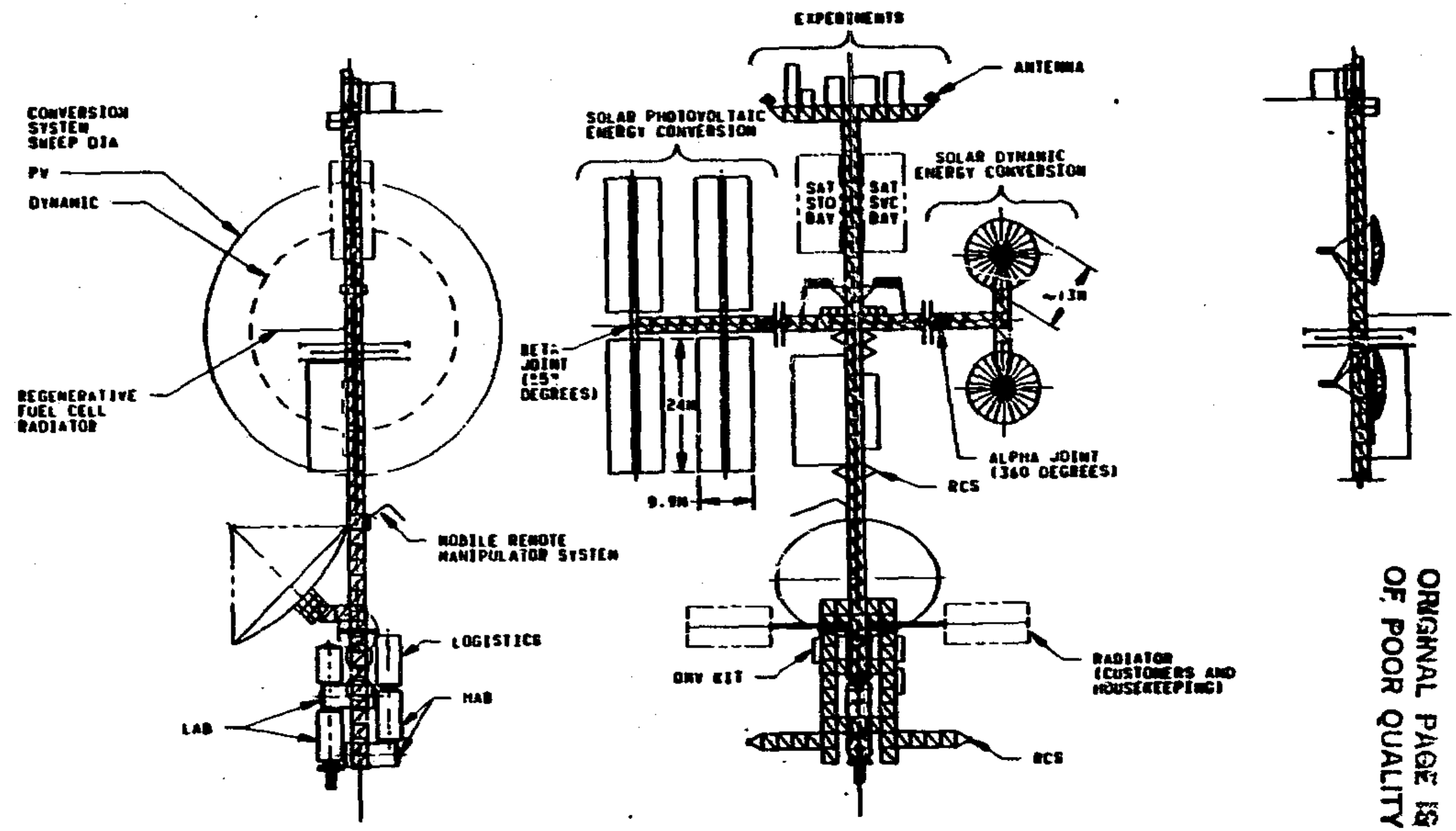
X 286

Lewis Research Center

NASA

SPACE STATION IOC REFERENCE CONFIGURATION -ELECTRIC POWER SYSTEM OPTIONS-



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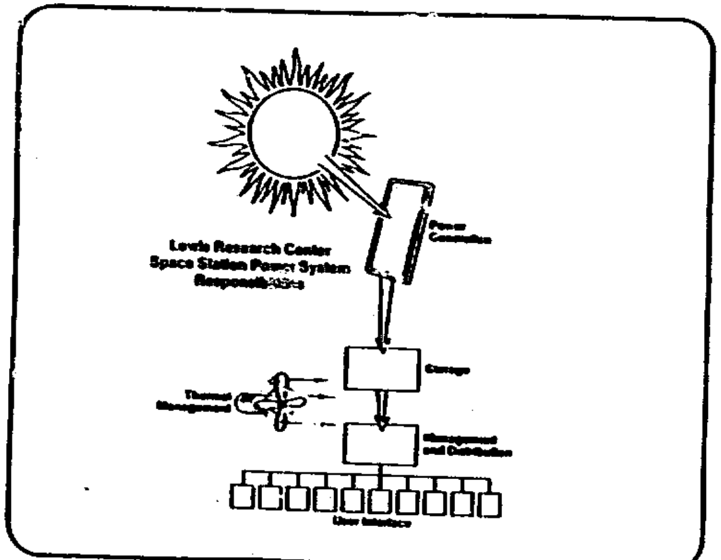
ELECTRIC POWER SYSTEM

CONSISTS OF THREE SUBSYSTEMS OF MODULAR DESIGN TO FACILITATE REPAIR/REPLACEMENT AND GROWTH

1. POWER GENERATION (PGS)*
2. ENERGY STORAGE (ESS)*
3. POWER MANAGEMENT AND DISTRIBUTION (PMAD)

*INCLUDES THERMAL MANAGEMENT AND REJECTION HARDWARE



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SPACE STATION

INITIAL OPERATING CAPABILITY

THE EPS MAY BE EITHER SOLAR DYNAMIC OR PHOTOVOLTAIC BASED

PRINCIPAL TECHNOLOGY OPTIONS

ENERGY CONVERSION	ENERGY STORAGE	POWER MANAGEMENT AND DISTRIBUTION
DYNAMIC	THERMAL	HIGH - VOLTAGE AC
BRAYTON	REGENERATIVE FUEL CELL	HIGH - VOLTAGE DC
RANKINE	Ni Cd BATTERIES	HIGH - VOLTAGE HYBRID
PHOTOVOLTAIC		
SILICON PLANAR		

C-2

ELECTRIC POWER SYSTEM

- OPERATIONAL FUNCTIONS -

- DELIVER UTILITY POWER TO CUSTOMER INTERFACE
- CONTROL THE SUPPLY OF POWER BASED ON PRE-SET PRIORITIES INCLUDES AUTOMATIC
  - MONITORING OF POWER GENERATION AND LOADS
  - ISOLATION OF PAYLOADS
  - REROUTING OF THE POWER TRANSMISSION PATH
- PROVIDE FLEXIBILITY FOR CREW TO RESET PRIORITIES TO COMPLETE SHORT TERM PLANNING OF CUSTOMER OPERATIONS ON-ORBIT

MAINTAINABILITY TERMS

TERMS	COMMENTS	IMPACTS
MAINTAINABILITY	THE CAPABILITY TO COMPLETE MAINTENANCE AND REPAIR, AND VERIFICATION OF SUCCESS	DESIGN
MAINTENANCE	THE PERIODIC ACTIVITY TO PROLONG DESIGN OPERATION	LOGISTICS DESIGN
RELIABILITY	THE INSIGHT AS TO WHEN A LOSS MAY OCCUR	LOGISTICS
REPAIR	THE ACTION TO RETURN THE DEGRADED, MALFUNCTIONING, OR DAMAGED ITEM TO DESIGN OPERATION	CREW LOGISTICS

MAINTAINABILITY

- ROLE -

DRIVE THE DESIGN OF THE ELECTRIC POWER SYSTEM TO BE AVAILABLE TO OPERATE WITHOUT INTERRUPTION AND WITH MINIMUM INTERFERENCE FROM OTHER SPACE STATION PROGRAM ELEMENTS

MAINTAINABILITY

- ISSUES -

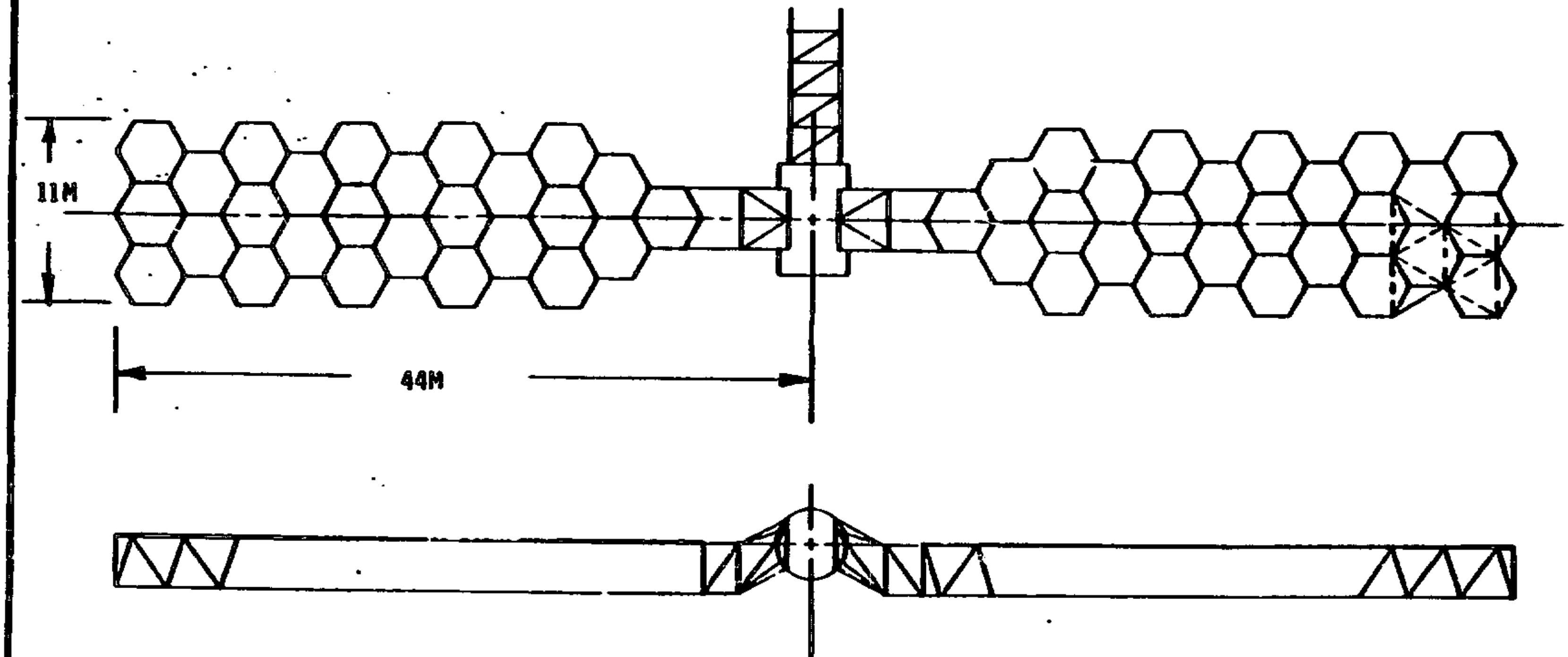
- IMPACT ON DESIGN -
  - VISIBILITY
  - ACCESSIBILITY
  - CLEARANCE
  - OVERRIDE CAPABILITY
  - HAZARDS AVOIDANCE
  - GROWTH CAPABILITY
- APPLICATION OF LESSONS LEARNED -
  - SOLAR MAXIMUM MISSION SPACECRAFT REPAIR
  - MSFC NEUTRAL BUOYANCY FACILITY TESTS. E.G. ORU HANDLING: ERECTABLE TRUSS EVALUATION
  - TRIDENT SUBMARINE DESIGN
- DEFINITION OF STANDARDS -
  - INTERFACE DEFINITION
  - DIAGNOSTIC TOOLS
  - FAULT DETECTION
  - VENTING FLUIDS
  - COOLING
  - CONTAMINATION

MAINTAINABILITY

- ISSUES CONT'D -

- FACILITATE - MONITOR/ISOLATE/DETECT FAULT
  INSPECT
  REMOVE
  RESUPPLY
  RECHARGE
- AVAILABLE RESOURCES - CREW (IVA/EVA/MMU)
  MRMS (ANOTHER REMOTE MANIPULATOR OR ROBOTICS)
  OMV (SMART END)
  DOCKING/BERTHING/POSITIONING (PLATFORMS)
- IMPACT ON LOGISTICS - SPARE PARTS
  STORAGE

EXAMPLE OF ERECTABLE ARRAY CONCEPT



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9-19-83
PGA

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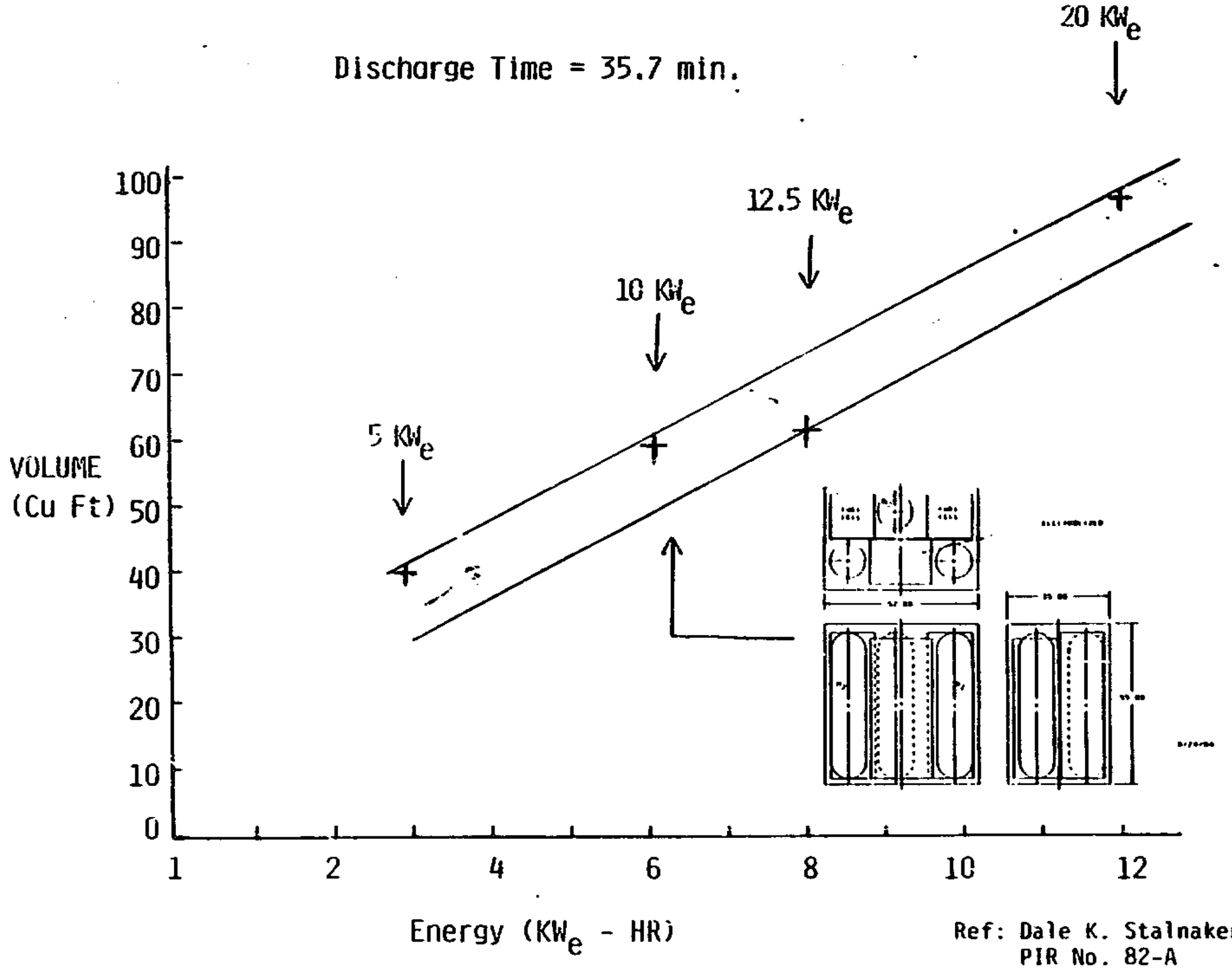
REGENERATIVE FUEL CELL ORU VOLUMES

Discharge Time = 35.7 min.



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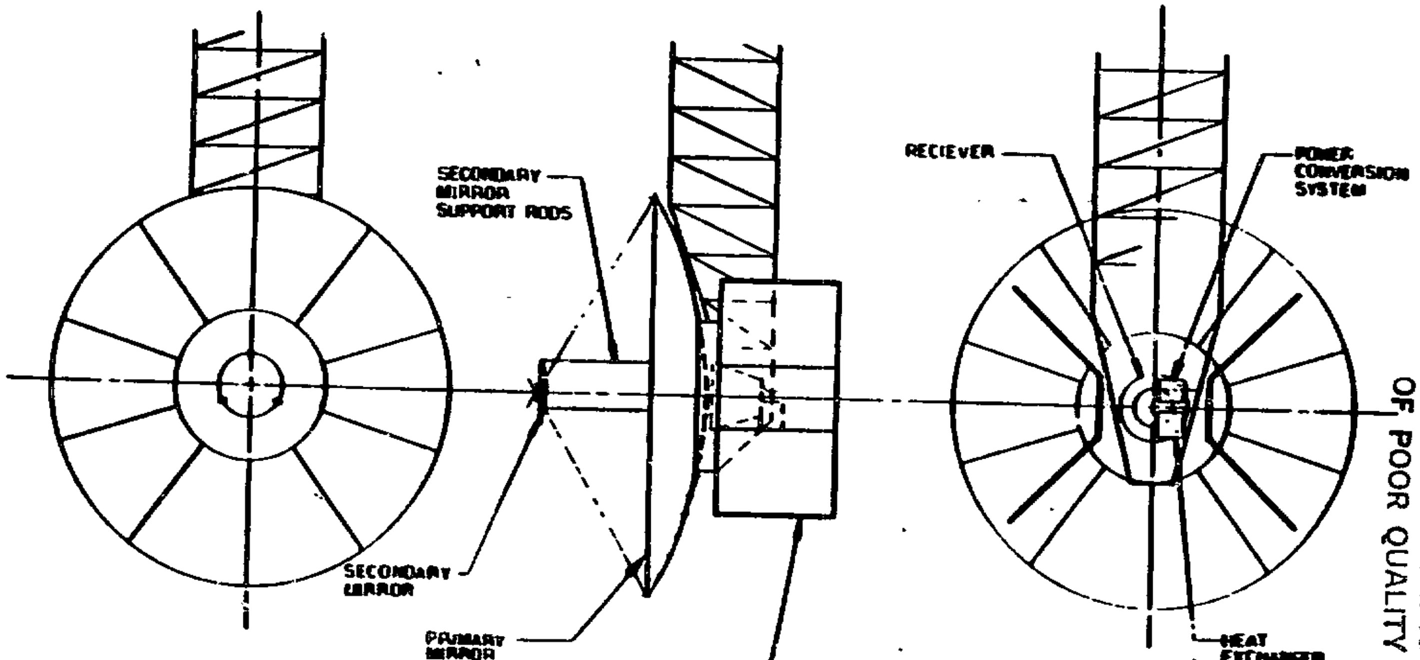


20KW SOLAR BRAYTON POWER
CONVERSION UNIT WITH DEPLOYABLE RADIATOR

12-1-83 PGA

CLOSING REMARK

- MAINTAINABILITY WILL BE AN IMPORTANT CONSIDERATION DURING THE ANALYSIS AND PRELIMINARY DESIGN ACTIVITY ABOUT TO BEGIN
- ACTIVITY HAS BEEN INITIATED TO ASSESS THE REQUIREMENTS TO PROVIDE A MAINTAINABLE ELECTRIC POWER SYSTEM

F. J. Logan
NASA GSFC

MAINTAINABILITY

WP-3

The GSFC role, with respect to maintainability is highlighted by the diverse SSPE's that the GSFC is responsible for. Despite the differences between the platforms, the attached payloads, assembly and servicing facilities, and the outfitting of a lab module, the key to a successful maintainability program for all four WP-3 elements is the ability to conduct three-way iterative trades between maintainability studies, preliminary system designers, and design to cost. The NASA managers have the responsibility to insure that this iterative process converges on the desired system at SDR.

To arrive at the optimum maintenance program for each WP-3 element will require a concerted effort involving WP-3, the other WP's, and the Phase B contractors. The contractors have a hard requirement to develop an on-orbit maintenance plan; to develop the plan will require hard decisions by WP-3 in defining parameters that must be studied, and insuring that the feedback to the designers is continuous. Inputs from the other WP's are required for ORU commonality studies that impact the maintenance plan. Some of the issues that must be resolved to satisfy the requirement for indefinite station life are:

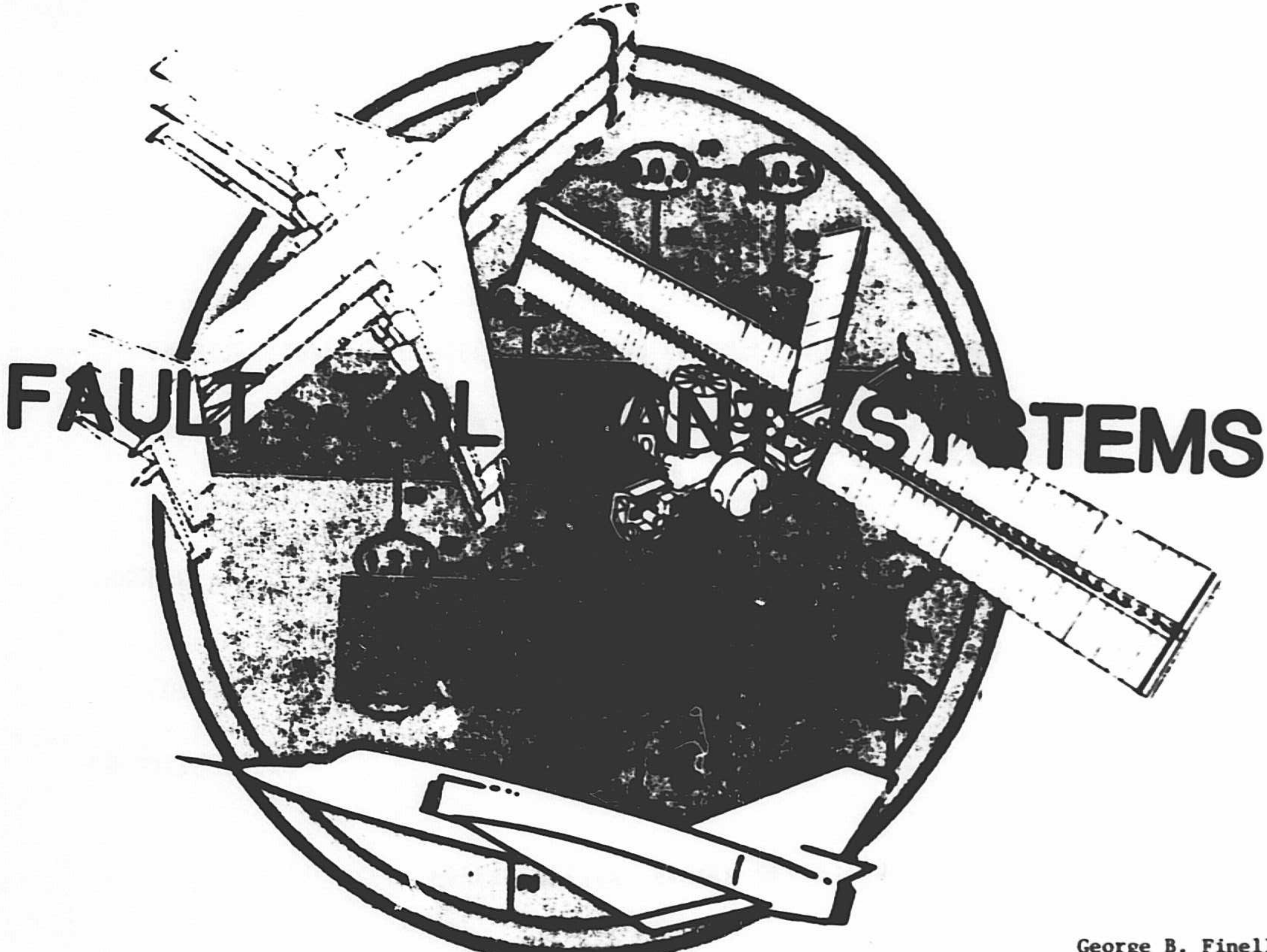
- % of crew time available for maintenance
- Trade reliability vs. maintenance
- Trade cost optimization vs. availability
- Logistic space on board the Space Station
- Resupply frequency
- Criticality of element or subsystem
- Safety
- Commonality
- Cost of built-in test equipment and diagnostic equipment vs. manual operation

Experience at GSFC

The GSFC is not without experience in the development of flight hardware that requires maintenance. In the mid-seventies, the first in-orbit maintainable spacecraft, the Multimission Modular Spacecraft (MMS), was developed at GSFC.

The basic premise of the MMS design was to isolate functional distribution so that when a failure occured, only one module would have to be replaced, and it was readily identified. This philosophy could be used in the design of Space Station ORU's to facilitate fault isolation and ORU design. The MMS module attachment fittings, with the associated blind mate scoop-proof electrical connectors were originally designed to be remotely serviced using the RMS with the service tool attached. This proven design is one possible solution for Space Station ORU's.

Although the MMS Flight Support System (FSS) is not planned to be serviced in orbit, the system was designed for maintainability with an expected life of fifty missions. The design philosophy used in the design of the 12 mechanisms could apply to the required mechanisms on the Space Station servicing facility and other Space Station mechanisms. Each mechanism consisted of a command drive unit with two motors, gearing, brake and overload switch, providing full redundancy up to the output shaft. All mechanisms have a manual override in the unlikely event that a failure would occur in the mechanism. Another FSS design feature that could apply to the Space Station is the thermal blankets with removeable outer layer painted with a white thermal finish. When the thermal paint deterioriates, the outer blanket is removed and replaced with the remaining layers left intact. This could be carried further for Space Station with several layers painted and removed as they lose their effectivity.



George B. Finelli
Fault Tolerant Systems Br.
Flight Control Systems Div.
Langley Research Center
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FAULT-TOLERANT SYSTEM DEFINITION

CHARACTERISTIC

- CONTINUE INTENDED FUNCTIONS IN THE PRESENCE OF FAULTS

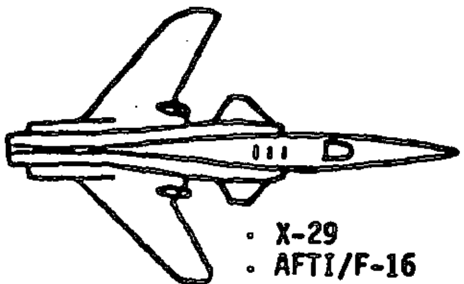
THROUGH

- MULTIPLE REDUNDANCY
- DETECTION AND ISOLATION OF FAILURES
- ARCHITECTURAL RECONFIGURATION UPON FAILURE IDENTIFICATION

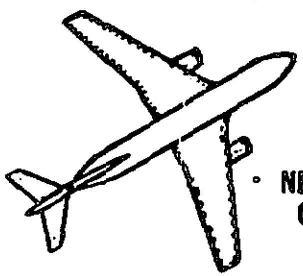
FAULT-TOLERANT SYSTEMS BENEFITS TO SPACE STATION

- ENHANCE AUTOMATIC MAINTENANCE
- INCREASE AUTONOMY
- REDUCE CREW WORKLOAD
- IMPROVE FLIGHT DATA SYSTEMS
- PROVIDE FLEXIBILITY AND GROWTH POTENTIAL
- REDUCE OPERATING COST
- POTENTIAL FOR REDUCED INITIAL COST

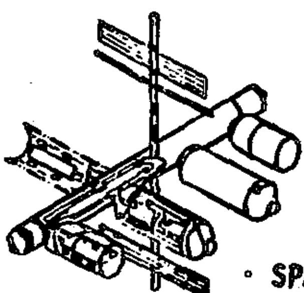
FAULT-TOLERANT SYSTEM ISSUES



- X-29
- AFTI/F-16
- LAVI
- ⋮



- NEXT GENERATION TRANSPORT
- ⋮



- SPACE STATION
- SHUTTLE
- ⋮

UNDERSTANDING THE IMPACT OF A SPECIFIC ARCHITECTURE DESIGN ON SYSTEM RELIABILITY AND PERFORMANCE

THE IMPACT OF FAULT-TOLERANT SOFTWARE ON SYSTEM DESIGN AND RELIABILITY

CURRENT ANALYTICAL RELIABILITY ESTIMATORS DO NOT CONSIDER SOME SIGNIFICANT ERRORS THAT MAY REDUCE SYSTEM RELIABILITY

- SOFTWARE
- TRANSIENTS
- DOUBLE FAULTS
- SINGLE-EVENT UPSETS
- ⋮

NEED CAPABILITY TO DETERMINE REALISTIC INPUTS TO ANALYTICAL ESTIMATORS

- ERROR COVERAGE PARAMETERS
- LEVEL AT WHICH FAULTS SHOULD BE MODELED
- FAULT MODELS AND ERROR DISTRIBUTIONS

EFFECTIVE, EFFICIENT VALIDATION PROCEDURES REQUIRED

FAULT-TOLERANT SYSTEMS RESEARCH

GOAL

DESIGN AND ASSESSMENT METHODOLOGIES FOR INTEGRATED, FAULT-TOLERANT FLIGHT CONTROL SYSTEMS

PRODUCTS

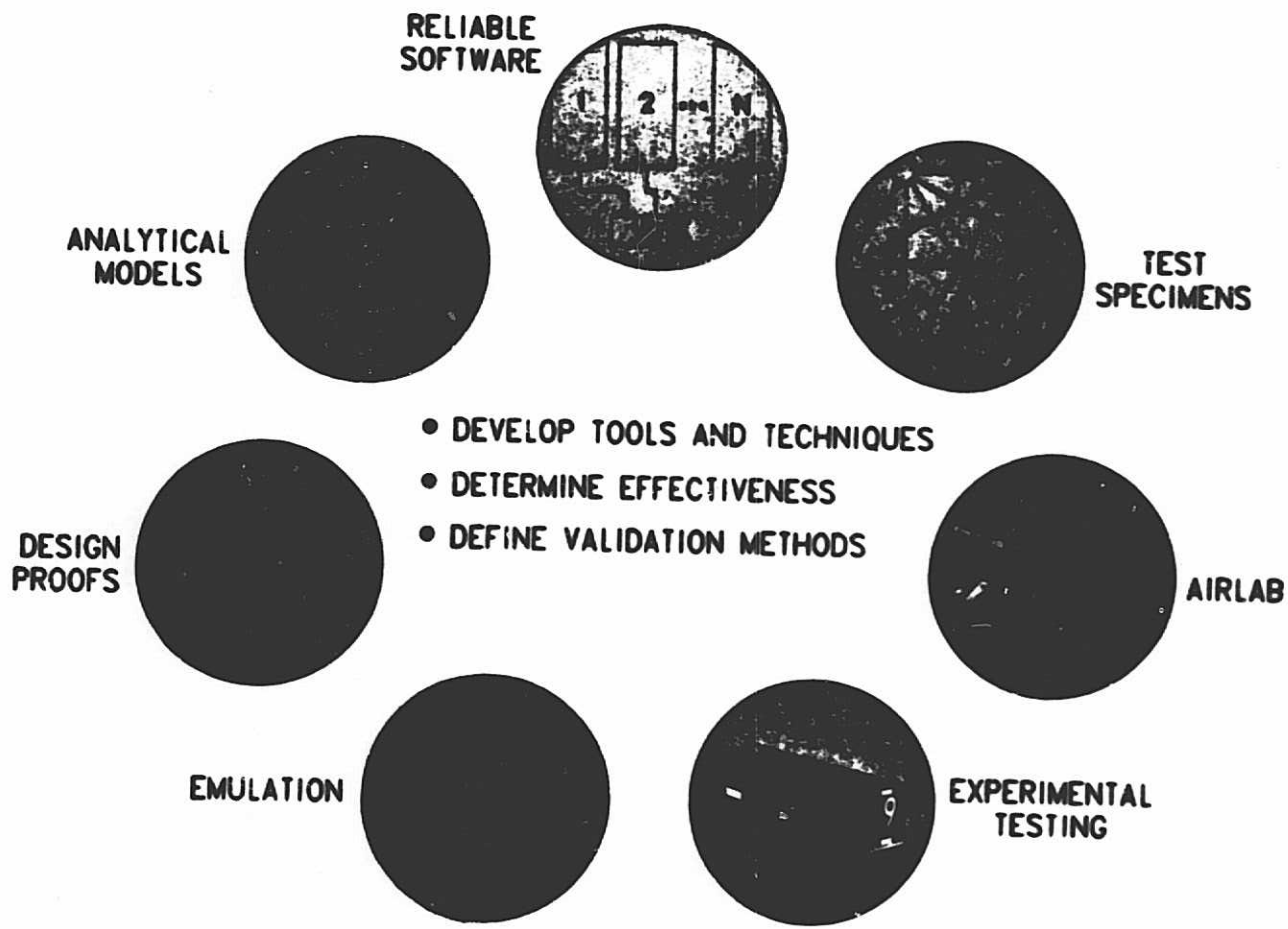
METHODS FOR VALIDATING THE PERFORMANCE AND RELIABILITY OF COMPLEX ELECTRONIC SYSTEMS

COMPARATIVE ANALYSES OF INTEGRATED CONTROL SYSTEM CONCEPTS

GUIDELINES FOR THE DESIGN OF VALIDATABLE HIGHLY RELIABLE ELECTRONIC CONTROL SYSTEMS

NASA
L-84-5670

FAULT-TOLERANT VALIDATION METHODOLOGY RESEARCH



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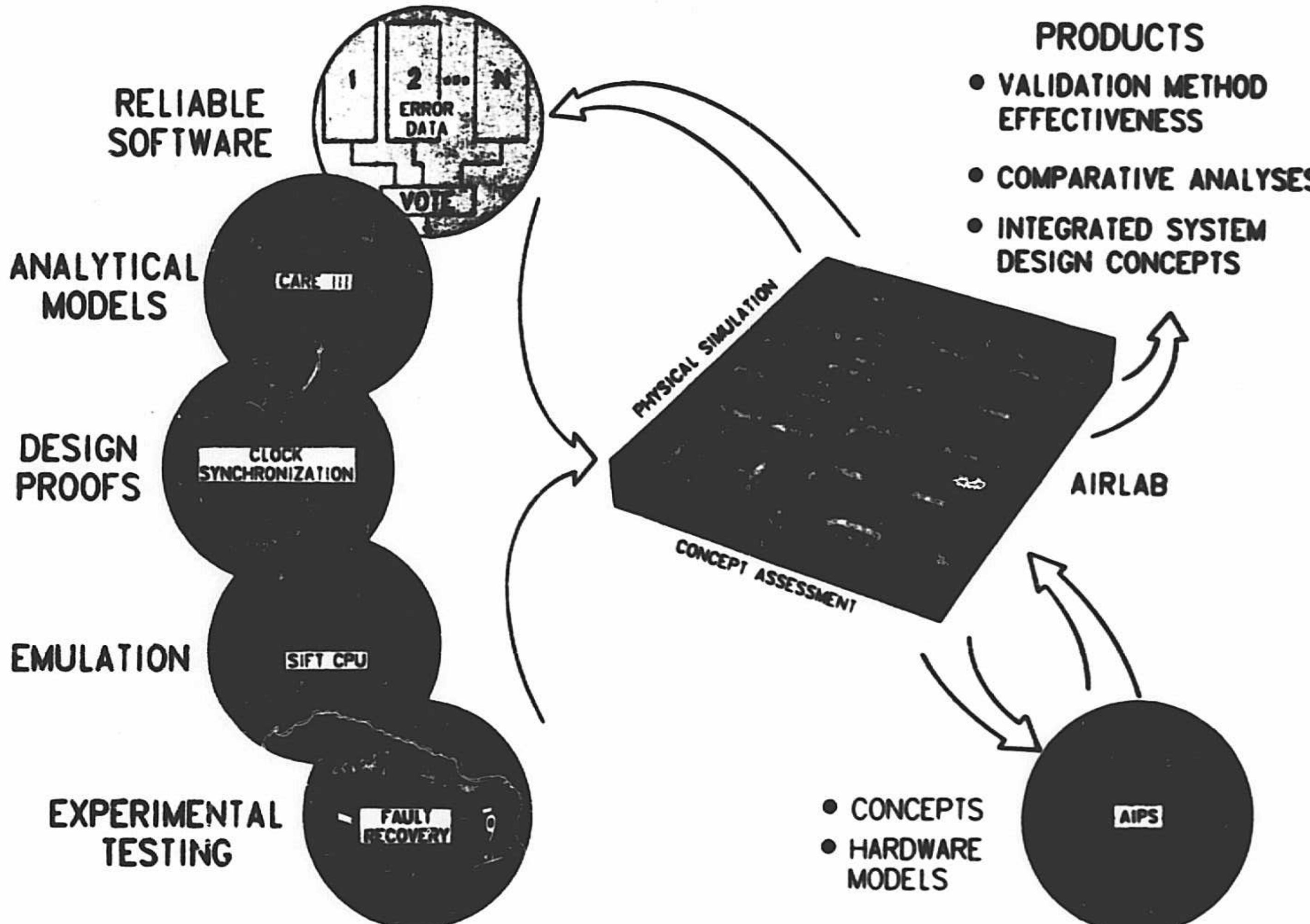
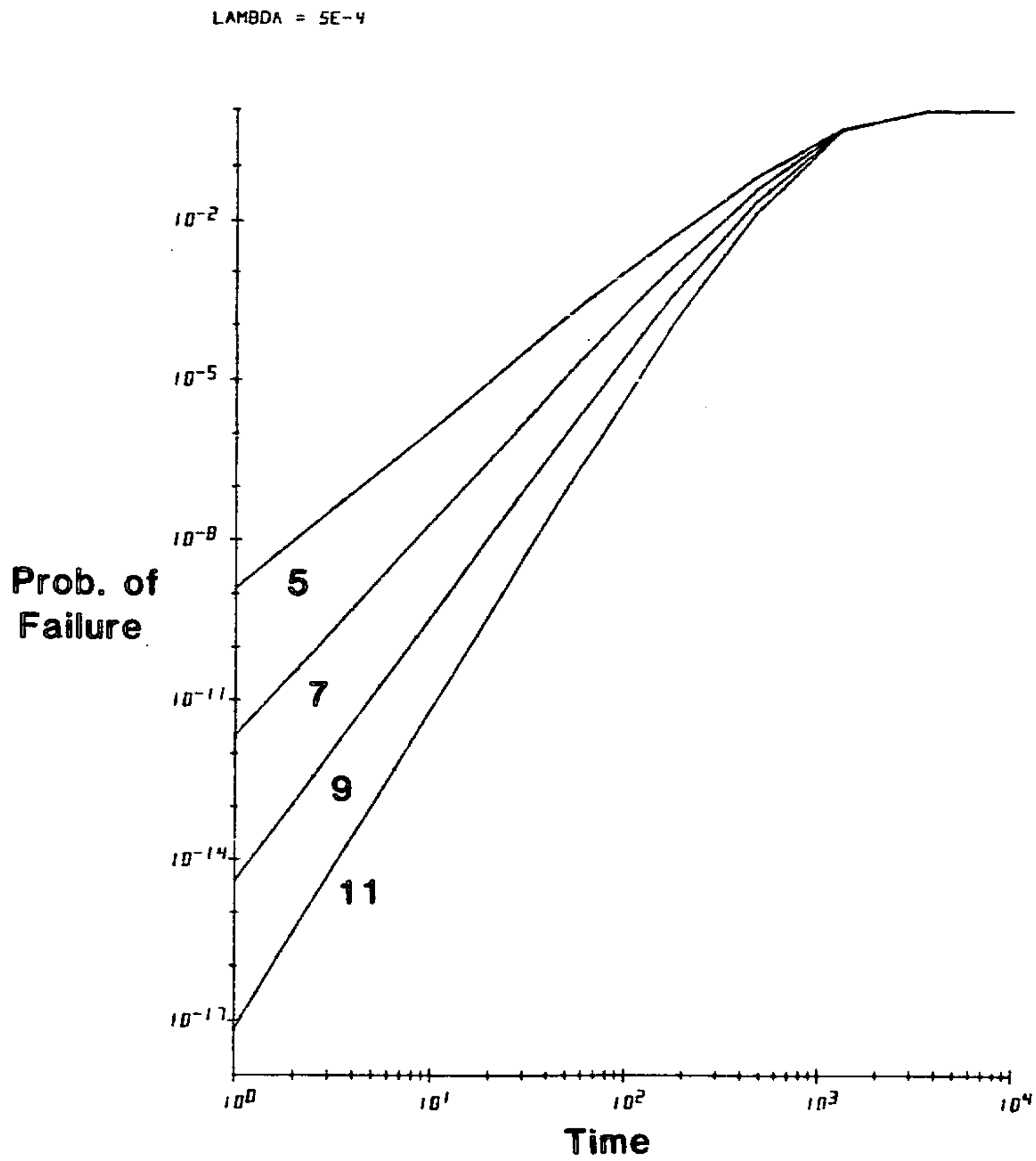
L-84-5844

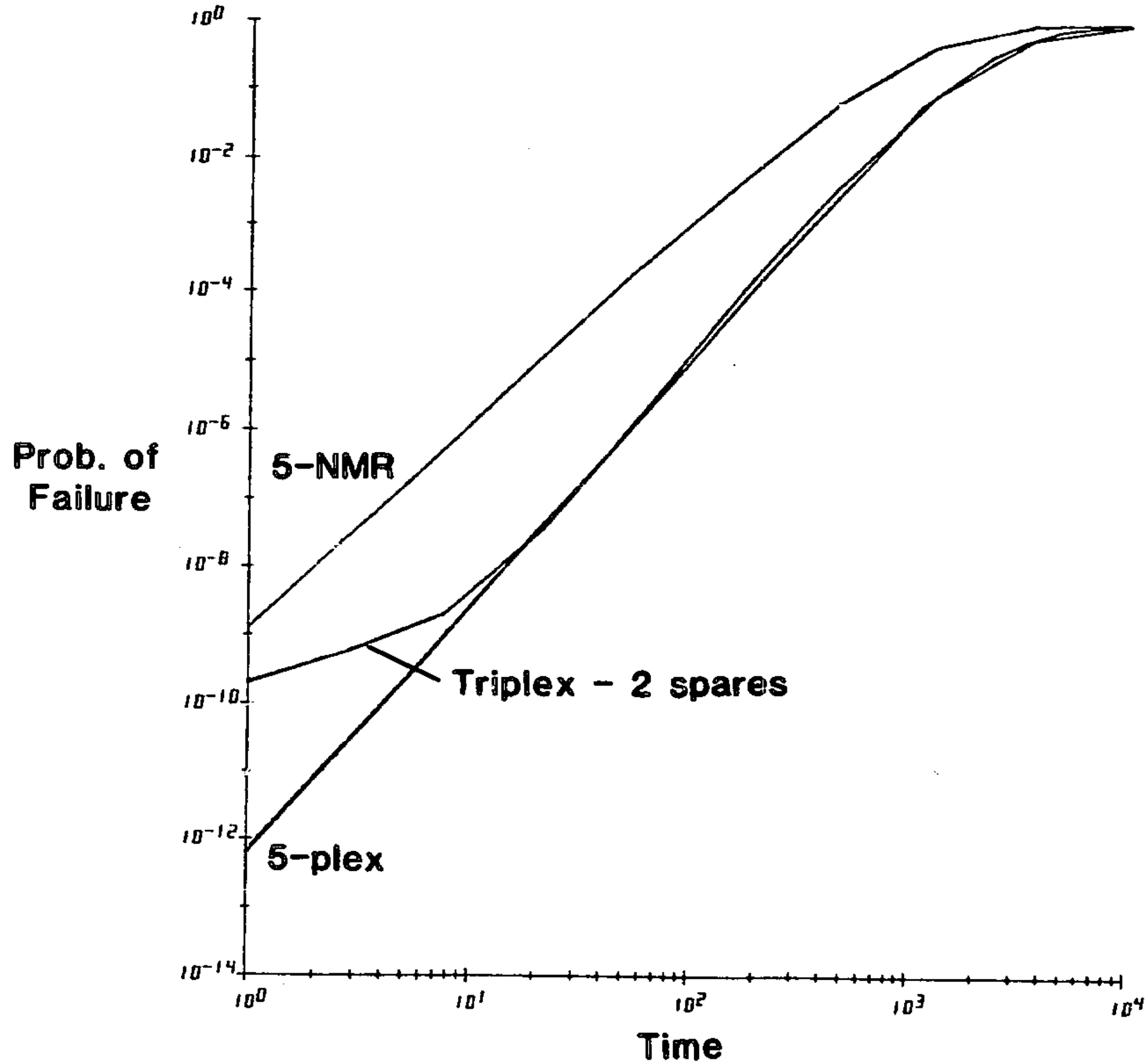
FAULT–TOLERANT SYSTEM RESEARCH



NMR RELIABILITY VERSUS MISSION TIME



HYBRID RELIABILITY VERSUS MISSION TIME



FAULT-TOLERANT DESIGN FEATURES AFFECTING MAINTAINABILITY

GRACEFUL DEGRADATION

- Component loss → Function set
- Function loss → Safety, performance, operational change
  (degraded levels of performance may not constitute failure)

FAULT DETECTION, ISOLATION & RECONFIGURATION

- Increase autonomy
- Reduce test equipment required
- Reduce unconfirmed removals
- Identify elusive symptoms

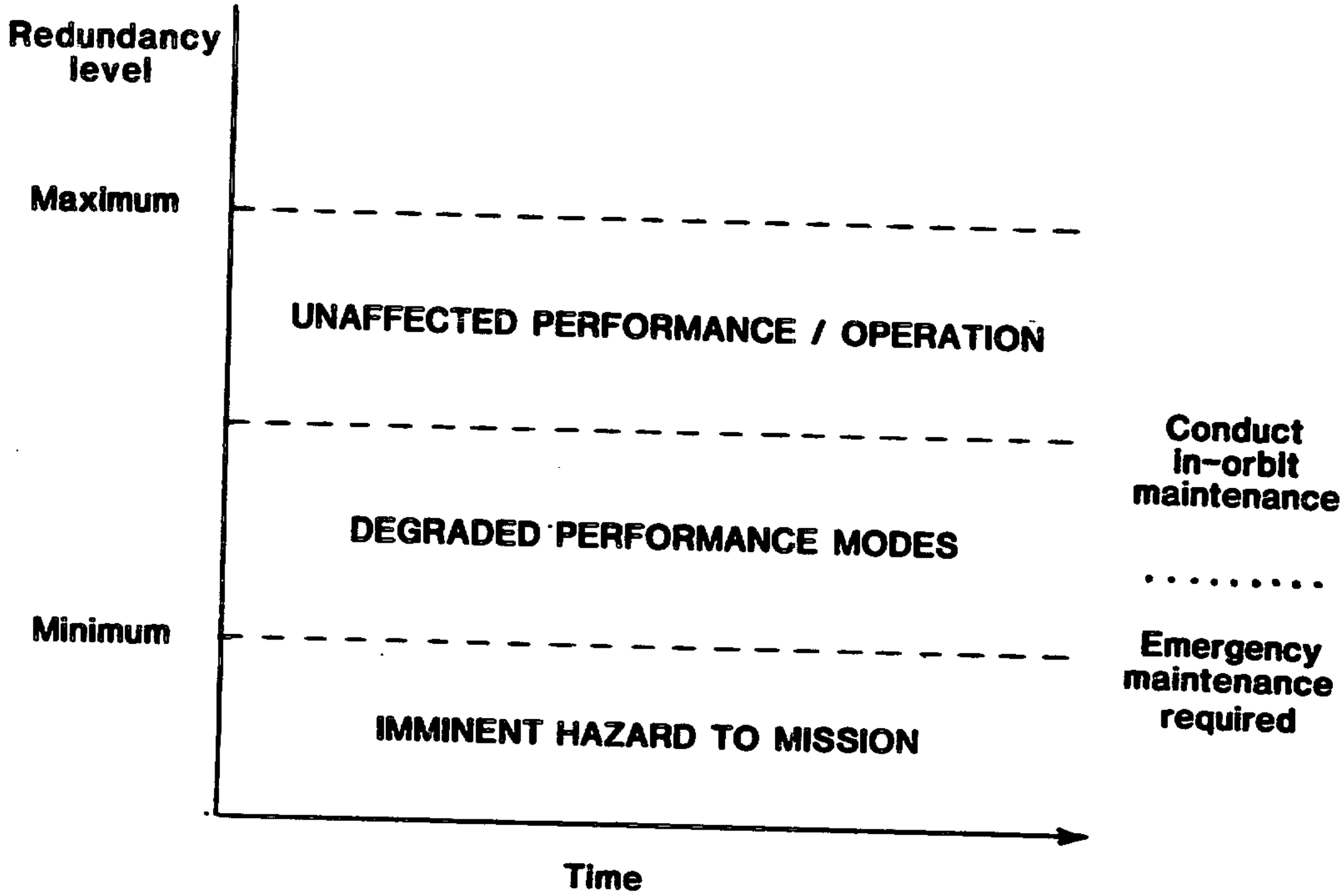
TRADE-OFFS IN FAULT-TOLERANT SYSTEM IMPLEMENTATION

AS		INCREASES		
	REDUNDANCY (above minimum dictated by system req.)		• COST	↑
			• EMERGENCY MAINTENANCE	↓
			• SCHEDULED MAINTENANCE	↓
			• IN-ORBIT SPARES	↓
			• GROUND SPARES	↑
			• REPAIRS	↑
			• WEIGHT	↑
	MAINTENANCE (# of scheduled actions)		• COST	↑
			• REDUNDANCY	↓
			• AVAILABILITY	↑
			• SPARES	?
			• REPAIRS	?

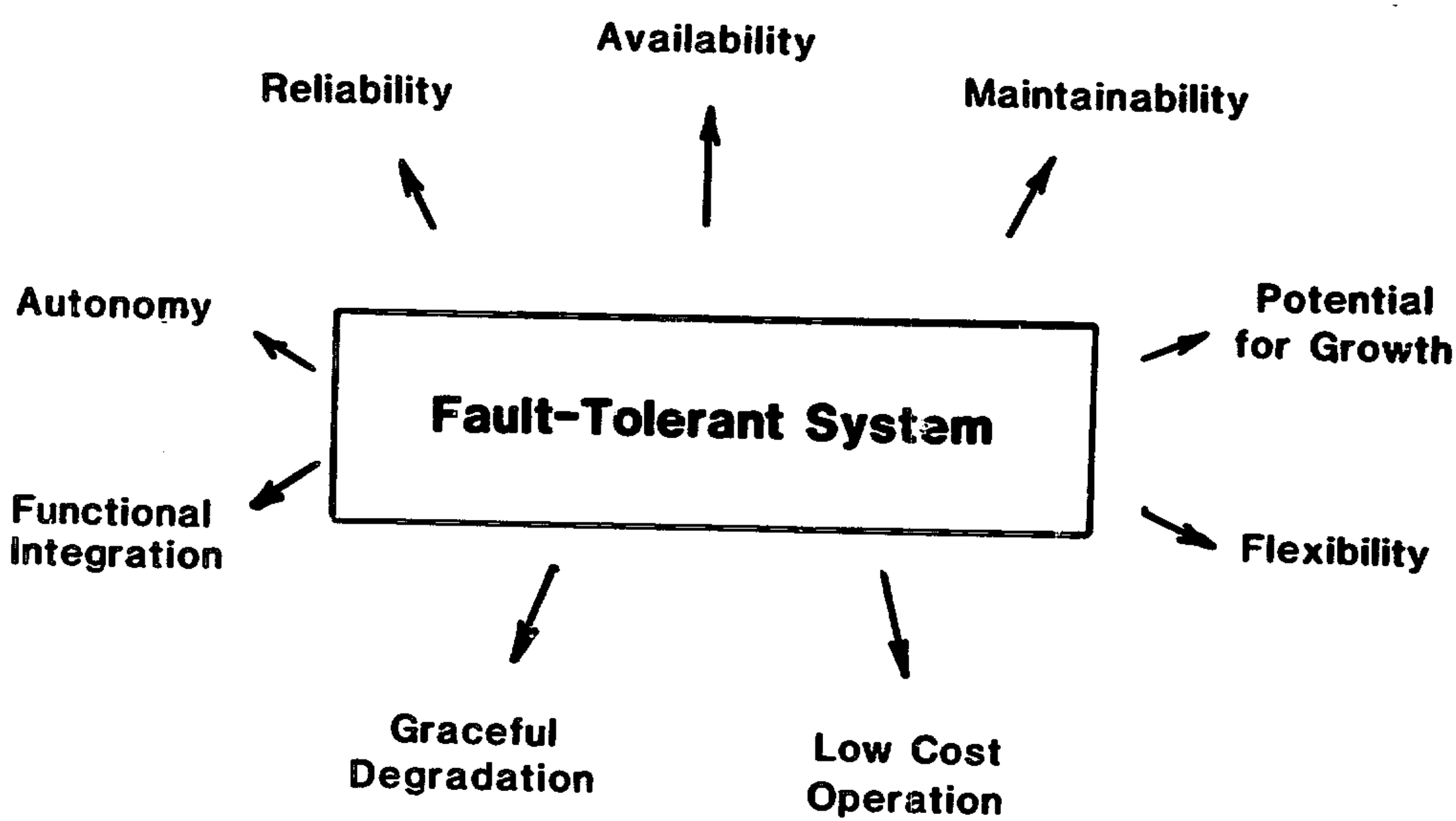
TRADE-OFFS (Continued)

AS		INCREASES		
	PACKAGING (# of dissimilar components per package)		• COST	?
			• REDUNDANCY	↑
			• SPARES	?
	COMPONENT RELIABILITY		• COST	↑
			• REDUNDANCY	↓
			• MAINTENANCE	↓
			• SPARES	↓
	SPARES PROVISIONING		• COST	↑
			• REDUNDANCY	↓
			• EMERGENCY MAINTENANCE	↓

FAULT-TOLERANT SYSTEM OPERATIONAL LEVELS



BENEFITS OF FAULT-TOLERANT SYSTEMS



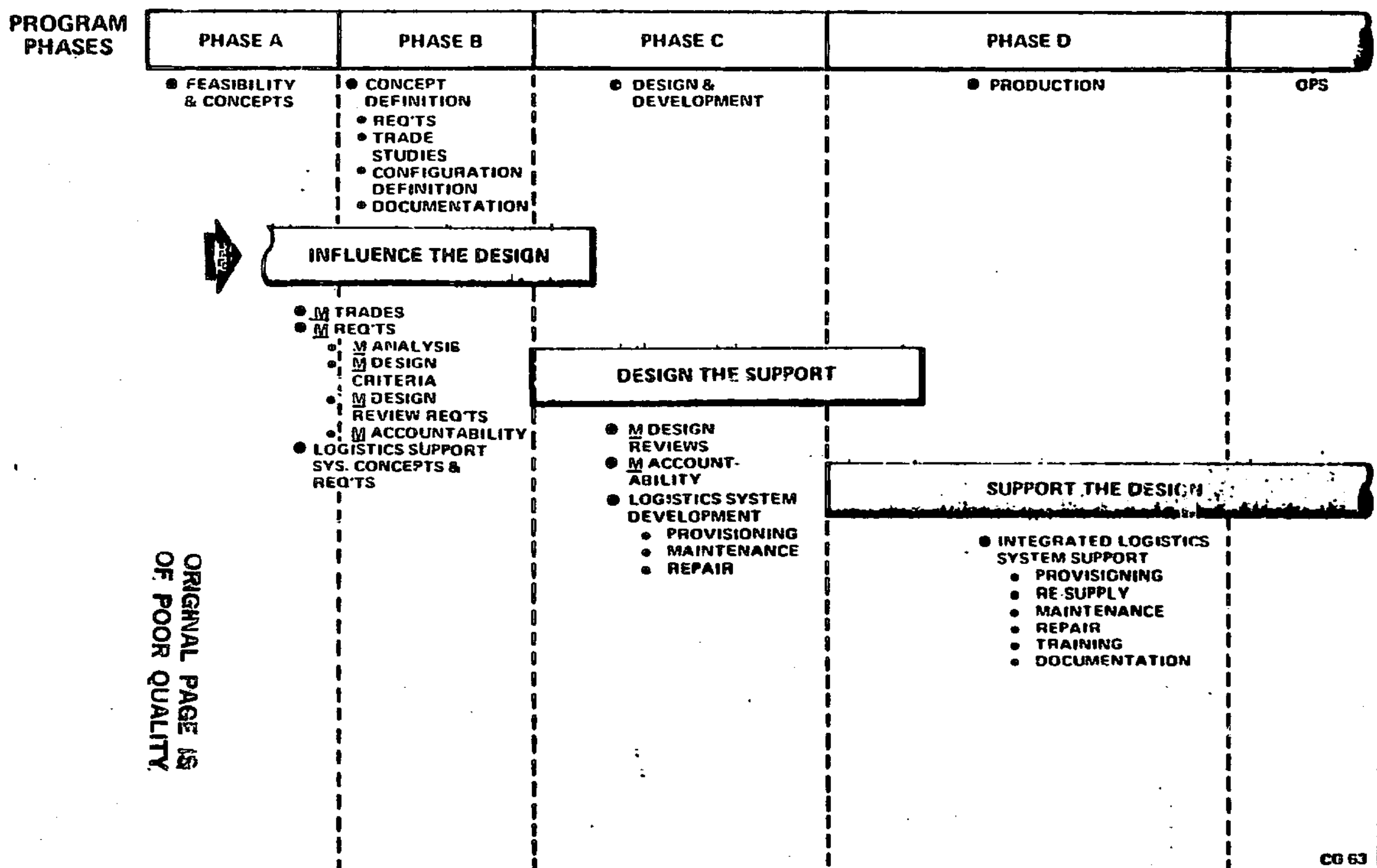
KSC SPACE STATION
FUTURE PROJECTS TECHNOLOGY

ASEB
MAINTAINABILITY PANFL
ROUND TABLE
MARCH 20, 1985

J. H. LEET
LOGISTICS MANAGEMENT OFFICE
PT-LMO
KENNEDY SPACE CENTER

Space Station Program Development

Maintainability/Maintenance



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KSC SPACE STATION FUTURE PROJECTS TECHNOLOGY

ASEB
MAINTAINABILITY
ROUND TABLE

J. H. LEET

MARCH 20, 1985

- MAINTAINABILITY PHILOSOPHY
  - RESPONSIVE TO MISSION & OPERATIONAL REQUIREMENTS
  - SYSTEMS OPERATED AND MAINTAINED ON-ORBIT
  - MINIMIZE NEED FOR EXTENSIVE TRAINING
  - EVOLUTIONARY DEVELOPMENT IN GROWTH AND CAPABILITY
  - CREW UTILIZED PRIMARY TO SUPPORT USERS
  - MINIMIZE REQUIREMENTS IMPOSED ON USERS
  - COMMON STANDARD HARDWARE AND SOFTWARE
  - MAINTAINABILITY IMPLICATIONS ADDRESSED THROUGHOUT ALL PROGRAM PHASES
  - MAINTAINABILITY INTEGRATED INTO CONFIGURATION, SUPPORTABILITY, AND LIFE-CYCLE COST DECISION

KSC SPACE STATION
FUTURE PROJECTS TECHNOLOGY

ASEB
MAINTAINABILITY
ROUND TABLE

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MARCH 20, 1985

- <u>APPLICATION OF "LESSONS LEARNED"</u>
  - PAST NASA PROGRAMS
    - APOLLO/SKYLAB
    - STS
    - SPACE LAB
    - SPACE TELESCOPE
    - OTHER
  - DOD/INDUSTRY
    - TRIDENT/ATTACK SUBMARINE
    - AF/NAVY AVIATION
    - AIRLINES
  - INTEGRATE INTO PROGRAM "LESSON LEARNED" DATA BASE
  - APPLY "LESSON LEARNED" TO CONTRACT SOW'S
  - MONITOR PROGRAM IMPLEMENTATION

ASEB
MAINTAINABILITY
ROUND TABLE

- EXAMPLES - "LESSONS LEARNED"
  - STRESS MAINTAINABILITY AND ACCESSIBILITY DURING THE DESIGN PHASE
  - PROVIDE MOCK-UPS AND TEST BEDS OF ADEQUATE FIDELITY
  - ISOLATE CRITICAL SYSTEMS - ELECTRICALLY, FLUIDS, ETC.
  - ELIMINATE COMMON INTERFACE BETWEEN PRIMARY AND SECONDARY SYSTEMS
  - CERTIFICATION OF SPARES -- COMMONALITY WITH INDUSTRY SPECIFICATIONS
  - COMPATIBLE SOFTWARE LANGUAGE FOR BOTH IN-FLIGHT OPERATIONS AND TEST PROCEDURES
  - USE OF ASTRONAUTS AND LAUNCH SITE PERSONNEL IN THE DESIGN EFFORT
  - STRONG REVIEW BOARDS TO ENSURE INPUTS FROM ASTRONAUTS AND LAUNCH SITE PERSONNEL
  - OPTIMIZE ENGINEERING/DRAWING CHANGE CONTROL AND RELEASE SYSTEM FOR LONG TERM USE
  - TIME/CYCLE COST CONSIDERATIONS NEED TO BE CONSIDERED IN THE DESIGN STAGE -- VERIFY PROJECTED LIFE EXPECTANCY OF COMPONENTS (PROBABILITY ANALYSIS)

KSC SPACE STATION
FUTURE PROJECTS TECHNOLOGY

ASEB
MAINTAINABILITY
ROUND TABLE

J. H. LEET

MARCH 20, 1985

- <u>CONSIDERATIONS</u>
  - MAINTAINABILITY <u>MUST</u> BE ADDRESSED THROUGHOUT ALL PROGRAM PHASES ITERATIVELY
  - PROGRAM LEVEL POLICY MUST BE ESTABLISHED EARLY-ON ADDRESSING LONG-TERM MANAGEMENT AND SUPPORT
  - STRONG MANAGEMENT ADVOCACY REQUIRED
  - DEVELOP AN APPROPRIATE CRITERIA FOR MAINTAINABILITY (I. E. CREW HOURS REQUIRED FOR MAINTENANCE)
  - REVIEW AND APPLY APPROPRIATE "LESSONS LEARNED"
  - ASSESS NEW TECHNOLOGIES WITH RESPECT TO MAINTENANCE/MAINTAINABILITY
  - DEVELOP A METHODOLOGY TO MEASURE "EFFECTIVENESS" OR "GOODNESS OF IMPLEMENTATION" ACROSS THE PROGRAM

APPENDIX C

Code Designator for Group Described:_______________

Commission on Engineering and Technical Systems	Committee on Fault Isolation
ASSEMBLY OR COMMISSION	COMMITTEE
Air Force Studies Board	
DIVISION, OFFICE, or BOARD	SUB-UNIT

Staff Officer: Vernon H. Miles

STATEMENT OF TASK

The ability of the United States Air Force to generate and sustain wartime sortie rates or up time of non-flying systems is severely affected by the ability of maintenance personnel to rapidly isolate and subsequently replace or repair malfunctioning components. Self repairing and self reconfigurable systems of the future are absolutely dependent on an ability to isolate malfunctions in order to respond with an optimum alternative. Requirements for maintenance manpower and training depend on the effectiveness of fault isolation systems and techniques ranging from Built in Test (BIT) and Automatic Test Equipment (ATE) to technical data for troubleshooting and manual test equipment. Among the Air Force systems and subsystems of interest are avionics, flight control systems, propulsion equipment, secondary power systems, ground communications-electronics, and missile systems, both tactical and strategic. Modern technology offers the opportunity to improve the power, accuracy and reliabilty of fault isolation systems.

The study will essentially consist of four tasks:

1. Determine the United States Air Force's present use of fault isolation, the present state-of-the-art of fault isolation, and assess them against the requirements for fault isolation capability out to the year 2000.

2. Analyze the potential for advancing the present state-of-the-art and potential pay-off for various levels of improvement.

3. Assess the possibility of reducing the Air Force's requirements for skilled maintenance personnel through improved fault isolation systems, with particular attention to the application of artificial intelligence technology.

4. Recommend future research and exploratory development that will achieve the necessary improvement in fault isolation for the United States Air Force's equipment and systems.

The Air Force Studies Board will conduct a three week summer study on Fault Isolation.

The Air Force Studies Board is supported by Contract No. F49620-83-C-0111 with Headquarters, Air Force Systems Command, Andrews Air Force Base, Maryland.

November 13, 1984
(date of Statement)

COMMITTEE RECORDS FORM #1

APPENDIX D

Further Deliberations

Statements by J. W. Schaefer and P. E. Partridge

J. W. SCHAEFER
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WHIPPANY, N.J. 07981
AREA CODE 201 386-6900

March 25, 1985

Mr. L. R. Greenwood
Mission Planning & Program
Development Director
Fairchild Space Company
Century 21 Blvd.
Germantown, MD 20874

Dear Ron,

Since our meeting in Huntsville last Wednesday and Thursday, I have thought more about the suggestions I made on maintenance of the Space Station. In particular, I think that the Remote Maintenance and Test System concept is important to the success of the Space Station. In retrospect, I should have done a better job in describing the manner in which it could be used to save crew-time and training as well as provide comprehensive and continual monitoring of the status of the equipment on-board the Space Station. My description was certainly too general to adequately convey the potential utility of the remote maintenance facility and the similarity to the one that we provided for the Dimension PBX. I will summarize my thoughts below.

A computer based terminal on the ground would be used by an expert maintenance craftsman who would dial-up the "address" of the equipment he wishes to test. The ground-based computer would interrogate the test points of the on-board equipment via a digital transmission link between the ground station and the Space Station. A programmed sequence of tests would be administered automatically to verify that the equipment is working properly. The tests would be designed so that, if any step in the sequence fails, the failure would be isolated on a printout to the smallest replaceable unit.

The remote maintenance system's capability to perform software maintenance would be just as important as its ability to test and diagnose hardware operations. Program "bugs" could be detected and fixed from the remote keyboard. Software updates and other program changes would be inserted in the same manner. Of course, any changes in the program would have been thoroughly checked out in identical processors on the ground before being transmitted and inserted in the processor aloft.

The use of a ground-based remote maintenance system would (1) reduce the time the crew need spend working on the equipment, (2) reduce the software and diagnostic training required by the crew, and (3) provide more comprehensive preventative maintenance and failure analysis.

Even though there seemed to be general agreement at our meeting with the attributes of remote maintenance as outlined above, I believe that the need for early action was not fully appreciated. The design of the maintenance system affects every circuit board and sub-assembly. The test points that need to be monitored must be made accessible at connectors and the transmission system must be standardized. To accomplish this, maintenance must be treated as a single system and its design must be started at least as early as any of the rest of the equipment.

The various design organizations will each have their own priorities and will tend to worry about maintenance only after their primary role has been satisfied. From my experience, maintenance systems cannot be an afterthought or overlay at the end of the design process.

The organization responsible for the maintenance system design will need some authority to assure that their requirements are honored by the rest of project. It is important that they get started now. It will be difficult to implement such procedures in the Space Station project because of the way NASA has it organized.

If there is interest within NASA to pursue this concept further, I will be happy to arrange for a more complete discussion of the remote maintenance systems that are used in the telephone plant.

Sincerely,

J. W. Schaefer

J. W. Schaefer
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CC: Bernard Maggin
National Research Council

AFTER THOUGHTS ON SPACE STATION MAINTAINABILITY

Peter E. Partridge
Johns Hopkins University
Applied Physics Laboratory
April 10, 1985

If the Space Station is truly to have an indefinite life with evolutionary growth then a fundamental assumption in developing a viable maintainability philosophy is that eventually, at one time or another, every element of the station will be replaced due to wearout, failure, or obsolesence. Therefore, every element must be replaceable either as an individual item or as a part of a larger replaceable assembly. Furthermore, a rationale must be developed that determines when and how replacement will occur under the constraint of maximum safety and continuity of mission operations at minimum cost.

The concept of minimum cost needs further development and definition. It is difficult to define life cycle cost for a system that is evolutionary with indefinite life. For life cycle costing purposes, it may be desireable to define the system life as IOC + ten years, for example.

Based on my own experience I wish to strongly endorse the concept that cost can be minimized by using, wherever possible, existing proven hi-rel designs that utilize currently available standard hi-rel parts adding redundancy where needed for critical functions. In addition, I strongly endorse the use of Failure Mode and Effects Criticality Analysis (FMECA) or alternatively, Fault Tree Analysis, as powerful design analysis tools for establishing cause and effect relationships and their probabilities. These analysis techniques should be extensively utilized in the development of any new designs that may be required.

If maintainability is important to the Space Station, as it properly should be, then it needs to be made a first level requirement, be given strong emphasis and high visibility, and receive top level management attention and advocacy. Contractors must be provided with a clear statement of maintainability objectives and an overview of the important issues, concepts and suggested approaches associated with maintainability. They must be encouraged to use their initiative to find imaginative and creative solutions to maintainability problems and incentivised on the basis of how well they perform against maintainability objectives. Reviews at all levels must include maintainability as a specific topic to be addressed and must judge the proposed maintainability approach on the basis of its consistency with overall program objectives.

Of possible peripherial interest to NASA and its contractors with regard to maintainability technology is the 40th Meeting of the Mechanical Failures Prevention

Group being held on April 16-18, 1985 at the National Bureau of Standards in Gaithersburg, Maryland. This meeting is featuring a symposium on the Use of New Technology to Improve Mechanical Readiness, Reliability and Maintainability. The symposium is sponsored by the National Bureau of Standards, the Office of Naval Research and the Army Materials and Mechanics Research Center with participation by the IEEE Reliability Society. A copy of the symposium announcement and program schedule of technical presentations is enclosed. A review of the presentation titles indicates that there may be some material applicable to Space Station maintainability.