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MSFC SKYLAB LESSONS LEARNED

Skylab Program Office

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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16. ABSTRACT

Key lessons learned during the Skylab Program that could have impact on on-going and future programs are presented. They present early and sometimes subjective opinions; however, they give insights into key areas of concern. These experiences from a complex space program management and space flight serve as an early assessment to provide the most advantage to programs underway. References to other more detailed reports are provided for the individual's specific area of interest.

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1.0 Foreword

The lessons learned in the Skylab Program are described in five basic documents prepared by, and representing the experience of, Headquarters, Johnson Space Center, Kennedy Space Center, and the Skylab and Saturn Program Offices at the Marshall Space Flight Center. The documents are intended primarily for use by people involved in other programs who are presumed to be familiar with the disciplines covered. The format thus favors brevity over detailed treatment.

Authors of the lessons have been encouraged to be candid and the reader may detect apparent differences in approach in some areas. This illustrates the fact that equally effective management action in a particular area frequently can be accomplished by several approaches.

Recommendations and actions described are not necessarily the only or the best approaches. They reflect Skylab experience which must be tailored to other situations and should be accepted by the reader as one input to the management decision-making process. As such, they should be used to help him identify potential problems and to benefit from the approaches that were found to be effective in Skylab.

Many of the lessons are subjective and represent individual opinions and hence should not be interpreted as official statements of NASA positions or policies.

In addition to the Lessons Learned Documents, Skylab Mission Evaluation Reports are being issued by JSC, KSC and MSFC to provide detailed evaluation results. Experiment scientific results will be disseminated by the principal investigators.

Skylab Program Office
NASA Headquarters

1.1 MSFC Introduction

The MSFC responsibility for design and integration of the Skylab systems dictates that this document convey the fundamentals of how this effort was successfully accomplished. Some of the more generalized material may not be new to all readers, but is necessary for continuity. Additionally, short descriptions of specific problems or findings are included, with related conclusions and suggestions.

The following reports, all to be available from the MSFC Respository by mid-1974, will provide the detailed historical record of the MSFC role in the development and operation of the Skylab space station.

TMX-64808	MSFC Skylab Final Program Report
TMX-64809	MSFC Skylab Corollary Experiments Final Technical Report
TMX-64810	MSFC Skylab Airlock Module Final Technical Report
TMX-64811	MSFC Skylab Apollo Telescope Mount Final Technical Report
TMX-64812	MSFC Skylab Multiple Docking Adapter Final Technical Report
TMX-64813	MSFC Skylab Orbital Workshop Final Technical Report
TMX-64814	Skylab Mission Report - Saturn Workshop
TMX-64815	MSFC Skylab Apollo Telescope Mount Summary Mission Report
TMX-64816	MSFC Skylab Mission Sequence Evaluation Report
TMX-64817	MSFC Skylab Attitude & Pointing Control System Mission Evaluation Report
TMX-64818	MSFC Skylab Electrical Power System Mission Evaluation Report
TMX-64819	MSFC Skylab Instrumentation & Communication System Mission Evaluation Report
TMX-64820	MSFC Skylab Corollary Experiment Systems Mission Evaluation Report
TMX-64821	MSFC Skylab Apollo Telescope Mount Experiment Systems Mission Evaluation Report
TMX-64822	MSFC Skylab Thermal & Environmental Control System Mission Evaluation Report
TMX-64823	MSFC Skylab Apollo Telescope Mount Thermal Control System Mission Evaluation Report
TMX-64824	MSFC Skylab Structures & Mechanical Systems Mission Evaluation Report

TMX-64825	MSFC Skylab Crew Systems Mission Evaluation Report
TMX-64826	MSFC Skylab Contamination Control Systems Mission Evaluation Report

Skylab Program Office
Marshall Space Flight Center

1.2 Skylab Orbital Assembly

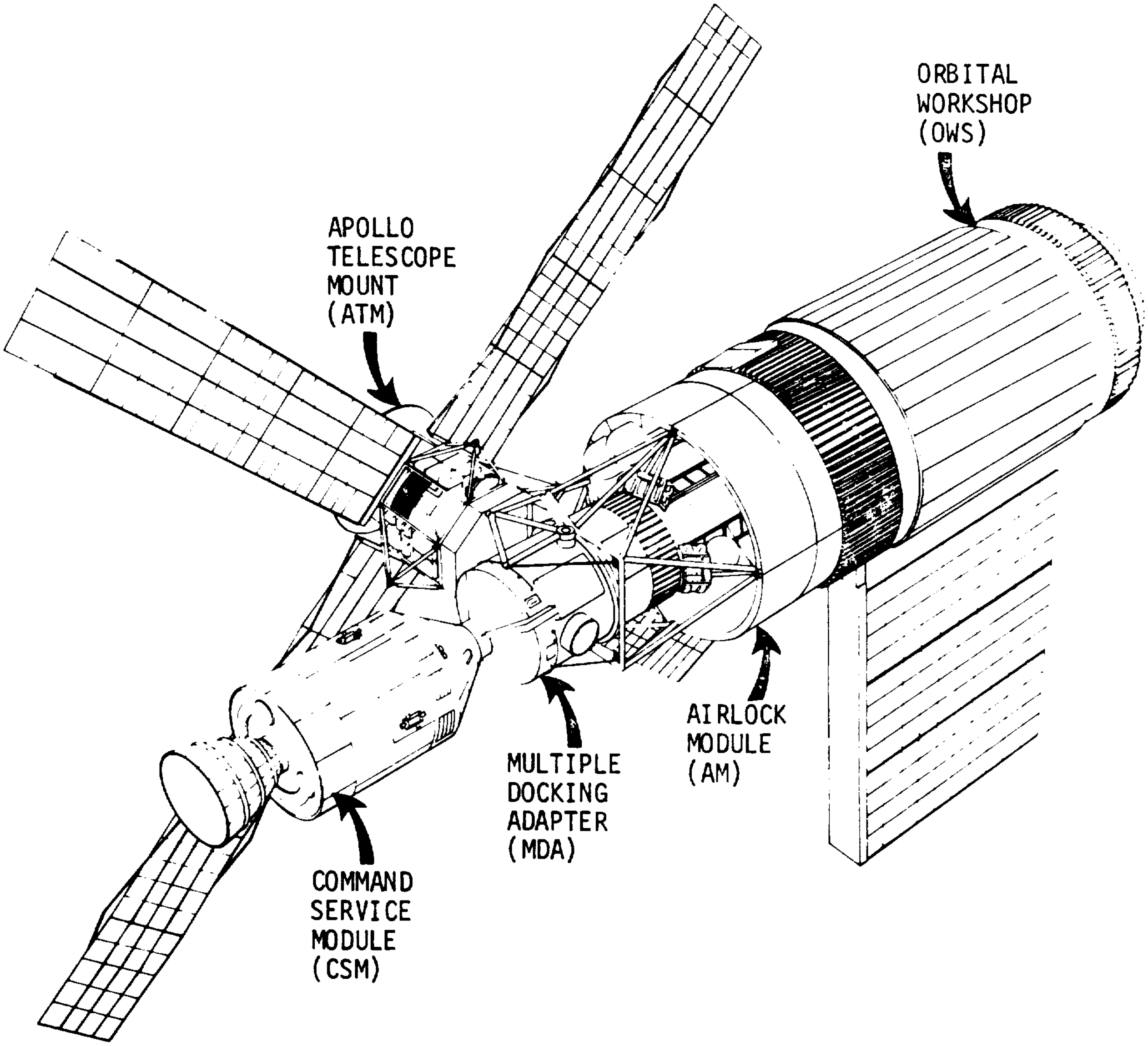

FIGURE 1.

1.3 Glossary

1.3.1 List of Acronyms

ACE	-	Acceptance Checkout Equipment
AGC	-	Automatic Gain Control
AM	-	Airlock Module
APCS	-	Attitude and Pointing Control System
ASEP	-	Automated Sequences of Event Processor
ATM	-	Apollo Telescope Mount
ATMDC	-	Apollo Telescope Mount Digital Computer
CBRM	-	Charger Battery Regulator Module
CCB	-	Configuration Control Board
CCWG	-	Contamination Control Working Group
C&D	-	Control and Display
CDF	-	Confined Detonating Fuse
CDR	-	Critical Design Review
CEI	-	Contract End Item
CIWG	-	Change Integration Working Group
CMG	-	Control Moment Gyro
COCOA	-	Computer Oriented Communications Operational Analysis
CRB	-	Change Review Board
CRS	-	Cluster Requirements Specification
CSM	-	Command Service Module
DCR	-	Design Certification Review
DQM	-	Data Quality Monitoring
EBW	-	Exploding Bridgewire
ECE	-	Experiment Compatibility Engineer
EIE	-	Experiment Integration Engineer
EITRS	-	Experiment Integration Test Requirements Specification
EMC	-	Electromagnetic Compatibility
EPS	-	Electrical Power System
EREP	-	Earth Resources Experiment Package
ESE	-	Electrical Support Equipment
EVA	-	Extravehicular Activity
FAST	-	Fast Access System Terminal
FRR	-	Flight Readiness Review
GFP	-	Government Furnished Property
GN_2	-	Gaseous Nitrogen
GSE	-	Ground Support Equipment

I&C - Instrumentation and Communication
ICD - Interface Control Document
IVA - Intravehicular Activity

JSC - Johnson Space Center

KSC - Kennedy Space Center

MDA - Multiple Docking Adapter
MSFC - Marshall Space Flight Center
MSG - Mission Support Group

OWS - Orbital Workshop

PATRS - Post Acceptance Test Requirements Specification
PCG - Power Conditioning Group
PCM - Pulse Code Modulation
PCN - Program Control Number
PI - Principal Investigator

QA - Quality Assurance
QCM - Quartz Crystal Microbalances
QD - Quick Disconnect

RF - Radio Frequency
RID - Review Item Discrepancy

S&E - Science and Engineering
SL - Skylab
SOCAR - Skylab Systems/Operations Compatibility Assessment Review
STDN - Spacecraft Tracking and Data Network
SWS - Saturn Workshop

TACS - Thruster Attitude Control Subsystem
TCN - Test Change Notice
TCP - Test and Checkout Procedure
TCRSD - Test and Checkout Requirements and Specifications Document
TM - Telemetry
TV - Television

2.0 Systems Engineering

2.1 Systems Engineering and Integration

2.1.1 Cluster Requirements - One program document to be utilized as a single authority and baseline for all integrated system level design, build, test and performance is considered mandatory. This document should result from a systems integration working group representing all NASA centers and contractors involved in the program. Likewise, the document should be baselined, placed under change control at each center and imposed contractually (or equivalent) on all centers and contractors. This document should be the foundation for all systems engineering and integration activities throughout the program and, therefore, must be a viable working document under strict level 2 (intercenter) change control. The scope of such a document reduces the need for a large number of other program documents which may be consolidated into this one document. It should serve as the controlling document for development of Contract End Item Specifications (CEIs), Interface Control Documents (ICDs), and associated performance criteria to assure fully integrated systems that will accomplish mission objectives.

The Saturn Workshop represents the culmination of a complex program involving several major hardware elements and contractor design efforts. The performance of the SWS was directly related to the success or failure of integrating the various contractor design requirements into a single hardware entity to function in such a way as to satisfy Skylab mission objectives. The need for a single specification to define cluster design and performance requirements was recognized and implemented on the program in the form of the Cluster Requirements Specification (CRS). The document resulted from a joint MSFC/JSC effort to provide a single, viable working document to be used by all involved contractors and NASA centers. The document was successfully controlled by the Level 2 Configuration Control Board (CCB) at MSFC and JSC. This included the review of Level I direction for CRS impact and subsequent incorporation of necessary changes by Level 2 CCB directives.

The CRS placed emphasis on the following areas:

a. The integration of all ground systems with the launch vehicle, payload and orbital assembly.

b. Performance, design and integration requirements for the SWS.

c. Interface requirements between the SWS and the CSM and between the SWS and Saturn V launch vehicle.

d. Interfaces between the crew, experiments and the SWS.

e. The CSM stowage requirements for data/film return.

2.1.2 Interface Requirements - The tremendous complexity of Skylab interfaces, with the dispersion of development and production activities across the country, demanded accurately defined and tightly controlled interfaces. It was soon learned that third-party custodianship of ICDs could not accomplish this task in a timely manner. ICDs between modules were defined after detailed system requirement ICDs had been agreed to between centers. Systems ICDs were necessary where significant portions of the hardware were furnished by more than one center. The systems level ICDs also proved to be an effective way of doing a systems engineering evaluation of changes late in the program and served as catalysts to initiate compatibility testing between the ground and airborne systems. Maintenance was assigned to one party of the interface, under configuration control board management. ICD changes were coordinated with all other affected interfaces by the responsible party. Contractual requirements should ensure that this work and related engineering change processing is accomplished expeditiously with management visibility.

2.1.3 Configuration Control - Comprehensive configuration management implemented early is essential for any program, and particularly for one with complex interfaces and a variety of hardware and documentation sources.

Configuration management and change integration for the Saturn Workshop (SWS) was a basic responsibility of the systems engineering and integration activity at MSFC. A change integration group was established early in the program to develop necessary guidelines and support all level 2 and 3 configuration control board activities.

A basic system used by the Saturn program was successfully modified and implemented for the SWS program. This system called for the assignment of a single program control number (PCN) and a responsible change integration engineer to each change. A computerized tracking and accounting system also developed for the Saturn program, became the basic working tool of the group. This system provided daily reports on the status of changes, pointed out delinquencies, identified all affected interfaces and modification kit status once hardware was delivered.

An intercenter Change Integration Working Group (CIWG) was established to coordinate hardware design changes occurring early in the program. This group acted as a level 2 preboard to screen all changes and keep everyone informed of total change activity affecting SWS module interfaces, ground systems, crew operations, and so forth. A SWS Change Review Board (CRB) was implemented locally. This MSFC board met daily to review all new change requests and the progress of all changes being worked at the center.

The following observations are made based on experience gained in the SWS change integration activity.

a. Change Control - Assignment of a single program-wide tracking number and one responsible change integration engineer to each change is an absolute necessity in a complex program having many changes affecting many interfaces. This "cradle-to-grave" concept for change tracking and integration responsibility ensures positive identification and coordination between all involved centers, contractors, projects, and contract personnel.

b. Change Integration Working Group - The SWS Change Integration Working Group was made up of representatives of the various technical systems disciplines and systems engineering and integration. Such a group is a primary tool for ensuring that early design is well coordinated. This group must be established early and must represent all involved centers and hardware contractors.

c. Change Review Board (CRB) - This daily review board ensures that changes are being worked effectively and expeditiously with all affected program elements. The board chairman should have level 2 signature authority and each level 3 organization should be represented on the board by signature authority.

d. Configuration Control Boards - The SWS level 2 configuration control board was a primary function of the systems engineering and integration activity. Representatives of that group also sat on level 3 boards to ensure proper coordination of changes at level 2 and at other level 3 boards. Establish requirements for each Board, regardless of level, to convene on at least a weekly basis. Attendance discipline is mandatory for successful board operation. Alternate members must be prepared to function responsibly when principle members are absent. Working changes outside a board meeting causes delays in dispositioning and issuing directions to contractors. It would be beneficial to issue uniform direction to suppliers, especially when interfaces are involved. Configuration Control Board Directive forms used by the NASA vary, and a standard form would aid recipient contractors in complying with given direction regardless of the NASA source. The MSFC Directive form and procedures for completion are recommended.

e. Inter-Center Sub Agreements - Early development and implementation of change integration sub agreements between centers is necessary to ensure that a closed loop system exists for identifying, coordinating and tracking changes affecting more than one center. Necessary contractual direction must also be imposed as required to ensure implementation of these sub agreements.

f. Coordination, Tracking and Accounting - It should be recognized that an established, well organized change integration group having acquired and developed the fundamental skills and tools for coordinating and tracking complex systems changes is a natural source of similar support in other systems engineering and integration activities. The SWS change integration group, for example, was used to coordinate and perform program tracking and accounting in the following areas:

- ICD change status and indexing.
- Work remaining to be done in-plant, and work deferred to KSC.
- Crew procedure change status and coordination.
- Test change notice status and coordination.
- Program documentation status and change coordination.
- Levels 2 and 3 configuration control board secretarial functions.

2.1.4 Reviews

2.1.4.1 Key Milestone Reviews - The Skylab Program implemented the key hardware milestone reviews (preliminary requirements, preliminary design, critical design, design certification) as accomplished on previous programs. These reviews were on an end item or module basis. However, due to the modular construction of Skylab, end-to-end system reviews were required to ensure that the totally integrated system would satisfy mission requirements. To accomplish this, a cluster system review was instituted prior to the module critical design reviews (CDRs) to ensure total system requirements were complete and being implemented. The Cluster Requirements Specification was the foundation for this review. Additionally, module level design certification reviews (DCRs) were conducted and served as inputs to the overall systems level DCR. The foundation for certification of the cluster systems was the results of the KSC integrated systems tests.

The module and cluster system reviews were structured by system representatives from the S&E technical disciplines and Program Office co-chaired or chaired the individual system review sessions.

Skylab experience has demonstrated that an effective design review must emphasize the hardware, but should also include the review of in-flight repair possibilities, single failure points, critical mechanisms, test plans and test results. The reviews must be scheduled in a timely manner with data packages being reviewed by the pertinent disciplines prior to the actual review. Action items from the reviews were documented on Review Item Discrepancy (RID) forms. Post review followup and ultimate disposition of all RIDs was formalized and reported on regularly. High fidelity mockups have proven to be very useful for these reviews, and the importance of early availability of interface control documentation was clearly shown. Not only design personnel, but test and operations representatives should participate in design reviews.

2.1.4.2 Skylab Systems/Operations Compatibility Assessment Review (SOCAR) - SOCAR served as a mechanism for establishing dialogue and working relationships between the design, development, test and integration and the operations personnel, facilitating a smooth transferral of pertinent data such as hardware descriptions, performance characteristics, operational requirements, constraints, mission rules and test history. Review and revision of the mission plans, procedures and documentation advanced the operational readiness of Skylab significantly.

2.1.4.3 Special Reviews - The concept of review by "new eyes" was extensively exploited. These reviews ranged from a systems review team headed by the Deputy Associate Administrator to in-plant reviews of sub-tier suppliers of critical items by teams made up of specialists from MSFC and the prime contractors. Critical mechanisms were reviewed by an intercenter group of senior management and technical personnel. Engineering walkarounds of the flight modules were patterned after the Apollo practice, bringing to bear the experience of senior NASA individuals who had no direct hardware management responsibility. A comprehensive hardware integrity review by teams of MSFC specialists validated the contractor's systems of translating requirements into flight hardware; the teams' activities were audited by a blue ribbon committee chaired from the laboratory director level. Although a great deal of time was required for the preparation and execution of these reviews, there is no doubt that they contributed greatly to the overall success of the program.

2.1.5 Test Requirements and Specifications

The Skylab Program Test and Checkout Requirements and Specifications Documents (TCRSDs) were developed in the "building block" concept. The TCRSD was developed for the modules to verify system operation in accordance with the module end item specification. Additionally, experiment checkout requirements for on-module testing were included. These TCRSDs were the basis for checkout procedures and factory acceptance testing. Such documents are invaluable in establishing contractual compliance.

An integrated cluster systems TCRSD was developed to define the test and checkout requirements for the integrated Skylab cluster systems at the launch facility. This was accomplished by the formation of cluster systems test requirements review teams composed of technical experts from the NASA design organizations, systems engineering organizations, program offices, KSC test offices and contractors. Upon technical agreement by each of the system teams, the integrated TCRSD and the module TCRSDs were baselined and controlled by the Level II Configuration Control Board. These baselined TCRSDs provided the technical basis for the final test and checkout plans and procedures at KSC.

Upon delivery of the modules from the factory to KSC, representatives from each of the system teams (both NASA and contractor) were assigned to KSC to maintain the TCRSDs. Required changes to the TCRSDs were implemented and controlled by the "test change notice" system which was controlled and approved by the Level II CCB at KSC. These teams and the TCN board were responsive to the KSC test schedules.

2.1.6 Special Topics

2.1.6.1 Sneak Circuit Analysis - Sneak circuit analysis should be performed on systems to assure a high probability of freedom from undesired current paths.

The sneak circuit analysis performed on Skylab was unique in that a computer was used to help develop a simplified schematic of Skylab circuits for evaluation, following a modified Apollo technique. This program yielded the following results:

- identified 44 sneak circuits
- identified a number of components that were not necessary for circuit operation
- identified errors in documentation
- verified electrical interfaces within and between modules
- key source for verification of operational documentation (operational handbooks, schematics and crew procedures)
- provided a valuable tool for investigating real-time operational problems and work-arounds

2.1.6.2 Corona - Early development of corona suppression specifications defining pressure and voltage potential criteria can preclude many post-design problems. Equipment that cannot be designed to suppress corona requires operational constraints which may be highly undesirable.

Analysis by corona specialists early in the Skylab Program resulted in a mission with no corona failures.

Of 44 items identified as corona-susceptible during the Skylab assessment effort, 11 were flown with acceptable operating constraints. Of these 11, only one item experienced corona: the AM quadriplexer when connected to the 10W transmitter apparently experienced corona due to an unanticipated increase in pressure during a venting operation in preparation for an EVA. After the gasses dissipated the 10W transmitter again functioned normally.

2.1.6.3 Electromagnetic Compatibility (EMC) - Electromagnetic interference was not a problem with Skylab electronic devices. This was achieved by comprehensive component level testing, module system testing and a test of the total assembled system.

Early identification of EMC requirements in the hardware design and generation of a module EMC control plan gave Skylab a basis for testing to verify compatibility. An EMC control group rigorously reviewed all waivers, test results, redesigns, and retest results associated with EMC.

2.1.6.4 Skylab Mission Contingency Analysis - Premission contingency analysis can enhance real-time response to emergencies, even if the precise contingency has not been analyzed.

Certain anomalies and contingencies which occurred during the Skylab 1 unmanned activation sequence were analyzed premission. These analyses permitted rapid and accurate mission recovery action.

Before the Skylab 1 launch, the MSFC Mission Support Groups (MSGs) and affected contractors conducted the following mission contingency analyses:

Inability to:

- close MDA vent
- jettison radiator shield
- deploy ATM
- deploy ATM solar arrays
- deploy OWS solar arrays
- vent OWS habitation area
- deploy discone antennas
- release lock on ATM canister
- deploy meteoroid shield

Loss of:

- ATM thermal control
- AM telemetry
- one control moment gyro

Optimization of:

- cluster operation on 1/2 power resulting from:
  - inability to deploy the ATM solar arrays
  - inability to deploy the OWS solar arrays and meteoroid shield

For each contingency analyzed, a preliminary feasibility study was conducted. Detailed areas needing further study were supplied to each Mission Support Group (MSG). The MSGs, with appropriate contractor support, conducted detailed analyses pertaining to their particular discipline, *e.g.*, electrical power (load models, thermal models, mechanical feasibility, crew simulation).

The individual responses by the MSGs were then combined into an integrated resolution of the contingency.

The analyses were continued in sufficient depth to determine adequate workarounds and to identify any special provisions necessary to accomplish the workaround. The analyses served to provide a base for quick resolutions for the deployment anomalies and resulting power management and thermal balance requirements that occurred during Skylab 1 activation.

During the Skylab mission, real-time studies were continued in the following areas:

- OWS solar array deployment
- effect of loss of meteoroid shield on thermal balance
- power system (battery) degradation
- AM coolant loop degradation
- reserves study for the actual Skylab 1 configuration *i.e.*, electrical power available, electrical loads, thermal, commodities reserves.
- loss of cooling loop for ATM control panel and earth resources experiments.

2.2 Contamination

2.2.1 Contamination Control As A System - As a result of the Skylab program, it is evident that contamination control should be integrated into the design criteria on a level comparable to major functional systems. It should be considered from the initial stage through mission support. Future missions should consider a contamination control system which integrates the degradation effects resulting from interactions between all contributory systems.

Systems affected by contamination on Skylab were thermal, power, attitude pointing control, environmental control, crew safety, and all experiments or critical and operational surfaces such as windows and antennas.

2.2.2 Contamination Control Working Group (CCWG) - A Contamination Control Working Group was used for integrating contamination design requirements, determining systems interactions and contamination effects on all systems as well as managing technical contamination studies.

Contamination was recognized early in the Skylab program as a potential critical problem for the experiment optical systems and for other external Skylab surfaces. For this reason the CCWG was created to coordinate the technical efforts of various groups studying the contamination problem.

The CCWG was made up of members from MSFC Science and Engineering laboratories, experiment principal investigators and management personnel from the KSC, JSC and MSFC.

Under the guidance of the CCWG extensive ground testing of Skylab systems including the waste management system was performed to predict contamination levels. Design and operational procedure changes were recommended by the CCWG to limit contamination. Rigorous analyses were performed in conjunction with testing to model performance of the contamination producing systems and to predict contamination levels. Flight experience confirms that this multi-discipline approach is successful and required for complex space vehicles.

2.2.3 Contamination Modeling - Surface deposition contamination and induced cloud brightness levels can be predicted within ± 30 percent. Total contamination of the vehicle can be predicted fairly accurately if periodic updates of mission critical parameters and as flown conditions are made.

Adequate pre-mission predictions of surface deposition and induced cloud brightness around the Skylab vehicle were made. Revisions of the contamination model were made as mission changes, anomalies and contingency operations had major impacts on the contaminant environment.

The line-of-sight model for surface deposition contamination was shown to predict contamination levels within 10 to 20 percent. Modeling of the induced cloud brightness around the Skylab was found to be dependent on parameters identified during the Skylab Contamination Ground Test Program and which were mission dependent.

2.2.4 Contamination Monitors - Instrumentation to measure contamination deposition and cloud brightness is invaluable in assessing and predicting experiment degradation, contamination levels on critical surfaces and as reference points for updating contamination prediction models. Mass deposition monitors, low pressure sensors, residual gas analyzers and cloud brightness monitors are recommended for future consideration.

Quartz crystal microbalances (QCMs) were successfully used on the exterior of Skylab to monitor mass deposition rates. Cloud brightness monitors measured the brightness of the induced atmosphere around the vehicle. The accuracy of the prediction model was improved by using these measurements as specific reference points.

2.2.5 Material Source Properties - Uniform materials testing criteria were used to determine parameters required for accurate modeling and assessment.

Success of contamination modeling and subsequent countermeasures is dependent upon extensive materials testing for source rates over the range of temperatures, times of exposure and ambient environment interactions anticipated. Resultant deposition capability must be determined for major sources as a function of temperature variations of source and sink and the contaminant effects on signal attenuation.

2.2.6 Overboard Venting - The Skylab contamination ground test program demonstrated the need for testing of vent systems to determine operating parameters and to evaluate vent nozzle designs. Experience has indicated that desired particle size distribution, direction and velocity can be created by proper nozzle design and flow rates for a given liquid. Advantage can be taken of sublimation characteristics and ambient atmosphere drag effect to minimize contamination potential. Given these parameters, modeling can determine proper timelines and vent sequences. Alternative methods to venting overboard for sources unacceptable in a vent mode should be established.

2.2.7 Experiment Exposure - Proper timelines for experiment exposure or operation in relation to engine firings, outgassing levels and overboard venting are necessary to ensure low contamination levels. The clearing time of particles and molecular interactions with the ambient atmosphere should be considered.

Modeling of vents and engine firings successfully indicated periods during which an experiment or critical surface required protection on Skylab. Particles were observed when the predicted clearing time was not observed.

2.2.8 Waste Tank - Testing and flight observations have shown that discharging waste liquid into a screened waste tank, exposed to vacuum can be successful in allowing only vapor to escape.

The Skylab waste tank concept was instrumental in keeping the brightness of the induced atmosphere within the limits established for normal operation by ground testing.

2.2.9 Significant Contamination Sources - Of all the sources of contamination on a manned vehicle, materials outgassing and engine firings are major problems because of the continuous, long lasting nature of outgassing and the necessity for engine firings at times which may not be propitious for contamination control. Other major venting can be adequately designed, controlled or timelined to minimize cloud brightness or deposition potential.

Deposition rates on Skylab mass detectors confirmed that outgassing sources and engine firings were the major sources. Other vented or leaked material did not deposit significantly at the temperatures of the Skylab exterior.

2.2.10 Contamination Control During Ground Handling - Proper contamination control of experiment and vehicle components requires uniform specifications encompassing the susceptibility of critical surfaces. Documentation and monitoring by a single organization should exist from production to launch for continuity of control and a comprehensive central record.

In general, Skylab prelaunch cleanliness was well controlled and no adverse effects resulted from prelaunch contamination.

2.2.11 On-Board Cleaning and Storage of Optics - Skylab optical cleaning kits for accessible optics consisted of a mild detergent solution, distilled water, lint free cotton, brush, lens tissues and air syringe and have been successful in removing contamination from certain Skylab surfaces. However, these techniques will not remove many contaminants such as deposits outgassed from external sources. Storage of optics in both GN_2 and vacuum has been satisfactory.

The capability to clean accessible optics and the development of techniques to clean remote optics are highly desirable. New techniques for contaminant detection and cleaning include Auger spectroscopy, binary scattering, metastable beams, ion sputtering and activated plasmas.

2.3 Man-Machine Interfaces

2.3.1 Interior Layout - Although the Skylab crews adapted to zero gravity with great ease, they expressed a strong preference for an interior arrangement based on a gravity orientation (floor, table, walls, ceiling). This of course need not be precisely maintained - there was no problem in adjusting to special cases within an overall gravity-oriented design such as the Workshop. Due to the confined space of the MDA and AM, gravity orientation was not possible in the designs and crew adaptation was not as easy.

2.3.2 Translation and Stability Aids for Extravehicular Activity (EVA) - Work on the jammed Workshop solar array was hampered by the lack of emergency aids on the Workshop exterior. A handrail was devised with on-board equipment (solar shield deployment rods and a cutter head) and used as a translation aid to maneuver to the damaged area.

The EVA access area should not be limited by the lack of EVA handholds or stability aids, but should encompass the entire vehicle. These aids could either be integral to the exterior design or allow for the simple attachment of portable devices.

2.3.3 Container Latching Techniques - Lockers and stowage, regardless of size and configuration should have simple latches. The Skylab crews indicated a high preference for lift handle and magnetic latches. Difficulty was experienced with double action latches which, once released, tend to relatch partially if the container becomes nearly closed. These were particularly troublesome when used in multiple. Indications were that pip pins were not required for lockers incorporating frictional devices. Consideration should be given to launch restraint straps (similar to packing straps) which could be available for contingency use later in the mission.

2.3.4 On-Orbit Temporary Stowage Provisions - The permanently installed snaps and Velcro were very useful. Adequate Velcro, snaps, and permanent bungees should be installed at work stations where task analysis shows a high probability of use.

2.3.5 Lighting - Spacecraft illumination design requires careful attention to light locations, the characteristics of lighting to be used, provisions for convenient portable lights, and adequate ground testing. The flight hardware test program should allow early crew review of the flight lighting in the flight-type environment. Auxiliary lighting should be completely portable and flexible with respect to use by the individual crewman. Spot illumination should be available at work locations.

2.3.6 Airflow Retrieves Loose Objects - The ventilation system on Skylab included debris collection screens on air inlets. The circulation in the entire vehicle was such that airflow directed all loose objects to the debris screens. A vehicle airflow system should be considered as a "lost and found" device during the design phase. Nooks and crannies should be closed (mesh is adequate) to prevent entrapment of loose hardware.

2.3.7 Switch Guarding - As a corollary to the discovery by the Skylab crews that virtually any piece of equipment had its uses as a restraint, toes and fingers penetrated more universally than had been planned. Thus the mechanical protection provided for switches, while adequate to prevent accidental tripping by hands working a console, was not adequate against toes blindly seeking support.

2.3.8 High Fidelity Mockup (Contractor) - A high fidelity crew systems mockup situated at the contractor's facility from program inception provides for optimized crew interfaces and operations. The mockup is used to develop interior layout, EVA/IVA workstations, lead flight article engineering, develop operational procedures and ultimately to be utilized as a mission support tool.

2.4 Mission Operations

2.4.1 Skylab Mission Simulations - Simulation preparations and activities should begin early enough to perform simulator checkout, to start technical disciplines planning for mission support, and to check out support facilities and data flows.

a. In the Skylab Program, a number of early simulalations were halted due to simulator or data problems. Early planning is required for an end-to-end data flow test that involves many program elements which are engaged in important activities at any given time. An alternative would be to generate an output tape from one element which could be played as an input tape for the next element, but a comprehensive test is much more useful. Adequate time should be allowed for the software changes which will inevitably result from any testing.

b. The mission personnel and procedures were not always the same used as those for the simulations. Longer duration missions and diversified mission objectives will dictate more personnel turnover and therefore condensed training courses will be needed for rapid familiarization of new personnel.

c. All technical disciplines should be in simulated problems to identify interfaces between systems; between systems and experiments; and interactions which are not otherwise obvious to those involved in design problems, who will be required to support the mission. This situation could be improved by use of operations/systems engineering personnel working directly with each technical discipline.

2.4.2 Data Management - Future spacecraft instrumentation and information (data) systems design considerations should include the impact on ground data handling systems.

a. The Skylab on-board data system configuration was a combination of previously-qualified flight systems with limited data management capabilities. The inability to perform on-board data processing required that additional processing of data be performed by the ground network remote sites in order to accommodate data flow rates with the existing network capabilities.

A total integrated design effort should consider sensors with data compression capabilities, on-board processing systems that will only transmit key parameters and analyzed results, information systems with decision making capabilities as to what constitutes valid data for transmission, and on-board data compression techniques.

b. For Skylab, the planning and implementation of data systems were accomplished assuming nominal operations. It was within this assumption that both flight operations and scientific data were combined into one major system. The system that resulted is not totally adaptable to handling continuous scientific data as well as contingency operations data.

Future ground data systems should provide capabilities for independent processing and handling of data for flight operations and scientific functions. The output from these systems though flexible to accommodate the user's processing capabilities, should be standardized to minimize the various types available. A data user's handbook listing the outputs and constraints is recommended to be provided to users prior to requirements definition.

c. In developing and implementing future ground data systems where multi NASA centers are involved, a total integration function is desirable. The responsibility and authority should be assigned to a single entity and it in turn should be responsible for task assignments, requirements integration, resources commitment and definition, scheduling, statusing, reporting and implementation. To accomplish this function, data management planning should have level 1 configuration control.

d. Since the Skylab Program utilized existing and proven data systems (from other programs), extensive ground data processing testing and control analyses were not performed. Air-to-ground capability was tested to determine quality of data at the site, but wasn't carried through to user. An end-to-end data flow verification testing program should be implemented to perform complete simulations and tests of data systems and interfaces associated with the flow of data. This is required to assure an effective integration of the ground data system with the flight system. The program should be included as an integral part of the overall mission test planning with reviews and controls similar to those imposed in other test areas.

e. Due to inherent and imposed data distortions, a Data Quality Monitoring (DQM) program should be provided to identify the data quality to users. DQM program capability should be provided at each point in the data flow stream that imposes some form of data handling (e.g., transmission and reception systems, line capability switching, data formatting, data compression, production processing, etc.). The program should specify special data tags, computer programs, data sampling and validation techniques, and data enhancement capability.

f. At the time of the initial Skylab launch, the data system readiness was not equivalent to that of the flight hardware and software. To assure readiness, the development and operational aspects of ground data systems should be under the same formal control as flight hardware, with similar design reviews and configuration management.

2.4.3 Console Displays - Early mission simulations should be scheduled for full-up display utilization and maximum console engineer participation.

This training should be completed before pre-launch test participation and simulation start.

2.5 Experiment Integration and Compatibility

2.5.1 Experiment Integration Engineer (EIE) - As each experiment was approved for Skylab an EIE was assigned to document the experiment integration requirements. The EIE worked closely with the experiment hardware developers, principal investigators and Skylab system designers to ensure that the experiment and the Skylab systems were compatible. The EIE took the lead in performing tradeoffs and other studies. As the requirements evolved, the EIE ensured that the interfaces were properly defined and understood by all concerned. The EIE was responsible for his experiments through all phases of the program, and as a result, experiment integration problems were minimal during the mission.

2.5.2 Experiment Compatibility Engineer (ECE) - A system engineer was assigned to each system pertinent to Skylab experiments to provide detailed support in the various disciplines. These Experiment Compatibility Engineers were particularly useful in class areas of interest such as scientific airlock utilization. They acted as focal points for consolidating experiment status reports, and were single points of contact between the experiment group and other Skylab project groups.

The efforts of the Experiment Compatibility Engineers were summarized in a monthly Experiment Compatibility Report which documented the results of a systematic review of pertinent program documentation, information and activities to permit orderly identification, visibility and resolution of experiment incompatibilities with Skylab systems, test programs and operational usage.

2.5.3 Design Reviews - Design reviews for experiments followed the pattern outlined in 2.1.4.1.

2.5.4 Ground Support Equipment

a. An attempt was made to track GSE by kits composed of several pieces of equipment required to perform a particular function. The approach proved to be ineffective since in many instances the kits were delivered on a piece by piece basis. As a result, control and management visibility of the GSE were difficult until adoption of the more realistic approach of tracking individual pieces of equipment rather than groups.

b. Test support requirements should be identified and placed under control early in the program. Experiment Integration Test Requirements Specification (EITRS) meetings and Post Acceptance Test Requirements Specification (PATRS) meetings, conducted early in the program to discuss and identify tests and test support requirements, were exceptionally fruitful. It was found that the results should be baselined and placed under control immediately.

c. Module and GSE flow planning should be closely monitored throughout the program to ensure compatible experiment planning.

2.5.5 On-Site Support of Integrated Testing - On-site support of integrated testing by experiment integration personnel proved to be effective in maintaining continuity and visibility of experiment hardware development testing, operating history, and integrated testing. This experience proved very helpful during the mission in generating malfunction procedures, abbreviated checklists, and other real-time activities.

2.5.6 Mission Support

a. The science planning conferences at JSC proved to be an extremely useful tool for advance flight planning. These semi-weekly meetings were attended by representatives from each discipline with the authority to make firm commitments with regard to the performance (or non-performance) requirements for their particular discipline through the following seven-day period of the mission.

b. Mission support was effectively provided by the several teams of the Corollary Experiment Mission Support Group, on-site at Huntsville. This support took the form of reviews of all flight plans, execute packages, action requests, and crew voice transcripts for impact assessments on, or relevance to, experiments; resolution of in-flight anomalies; initiation of action requests in support of the experiments; preparation of mission problem summaries, malfunction procedures, and mission evaluation reports.

2.6 In-Flight Maintenance

2.6.1 Criteria for Design - Initial design concepts should include in-flight maintenance provisions, with the necessary design features to facilitate failure detection, isolation, corrective action and verification of repair. Provisions should be made for tools, spares, maintenance equipment and space for maintenance work.

Accessibility to equipment attaching hardware, electrical connections and plumbing is imperative, even in areas where maintenance is not planned. All contingencies cannot be anticipated, but corrective maintenance action can be taken if the general design is consistent with this approach.

In much of the unplanned Skylab repair work, it was necessary to remove cover plates held in place by an inordinate number of fasteners, which were not always of the design best suited for operational removal. Allen head screws and hexagon head bolts were much preferred over other types by the crew.

A substantial effort had to be spent in identifying, to and by the crew, components, cables, and tubing to be repaired or replaced. A simple system of identification decals should be used to facilitate identification.

2.6.2 Selection of Tools - Tools initially selected for Skylab were primarily those required for specific tasks. A few contingency tools were included such as a pry bar, a hammer and the Swiss Army knife, which proved to be valuable assets. Wrenches were provided only for specific applications. The crew activities and evaluation indicate a tool kit should contain all the tools normally found in a tool collection for comprehensive home usage, as well as the special tools required for special aerospace hardware. Good quality off-the-shelf hand tools are adequate and no special features are required for use in space. An improved tool caddy for carrying tools from place to place should be developed for easy location of the needed tool after arriving at the work station. Transparent material would be desirable. The caddy should also hold small parts in an accessible manner as the work is done, since containing and locating these items was a problem in zero gravity.

2.6.3 Selection of Spares - Spares selection should include repair parts for critical items whose design permits in-flight bench repair, as well as replaceable assemblies. Skylab has proven that the crew, when provided the proper tools, procedures and parts, is capable of performing bench repair of failed assemblies beyond prior expectations. Although there were initially no repair parts aboard, these were provided on subsequent revisits and used successfully.

A good example is the tear-down of tape recorders by the crew of SL-3 and the subsequent furnishing of repair parts and repair by the SL-4 crew. This reduced the volume requirements for resupply by providing a few repair parts instead of an entire new assembly. This philosophy could reduce the number of primary spares required on board initially, if the capability to repair the failed items is provided.

Other examples of detail repair on Skylab were the repair of the teleprinter and replacement of the printed circuit boards in the video tape recorder.

The flight backup and test units on limited-production programs should be considered as spares sources within reasonable refurbishment effort, launch delay, and reprocurement time considerations.

2.7 Thermal Control

2.7.1 Integrated Thermal Analysis - A specialized team responsible for thermal and environmental control assisted in solving interface problems, verified thermal designs by defining realistic operating conditions and interactions, and allowed optimum solutions to problems involving more than one interface such as mission operations evaluations and contingency analyses.

Thermal interfaces are not readily defined by use of module boundaries. Heat that transfers across an interface is highly dependent on conditions on each side. The interface evaluation must be considered as part of a total system in order to define limiting conditions. If each module or experiment is designed on limiting conditions on the other side of the interface, overdesign or underdesign is possible. Experimenters designing to module requirements could create over and underdesigned systems since to be able to define the experiment interface, the entire area of the module and the experiment needs to be evaluated. Without this approach local temperatures would be unrealistic because of boundary interface temperatures influenced by the experiment, space blockage and waste heat.

Having thermal models simulating overall cluster systems, not limited by interface requirements, allowed rapid assessment of project changes.

2.7.2 Fast Response Math Models - Thermal math computer models and facilities for expediting computer studies should be streamlined, organized and designed for mission support. The tools should be exercised in the planned operating mode prior to the actual mission.

Mission support thermal math models should be designed for rapid response and easily adaptable to solving mission problems. Direct input/output/control computer terminals are desirable in mission support group work area for maximum capability.

During the OWS sun shield problem period, hundreds of thermal computer runs were made possible by use of a Fast Access System Terminal (FAST) located in the thermal work area and providing direct access to the large computers. Without the thermal analyst leaving the terminal, thermal models could be run, changes made, programs or arrays merged, runs remade at new conditions, inputs checked, progress statused during the run and finally the results taken from the display tube before printing so as to be able to start the next case or problem.

With this capability, numerous studies could be carried on simultaneously without punching, changing or handling any computer cards. The time saved, and being able to have more than one engineer working on the same problem, greatly increased accuracy and efficiency.

2.7.3 Mission Support Hardware - Test hardware, breadboards, mockups, etc., along with hardware specialists should be maintained and available for mission problem resolution assistance.

Flight backup hardware, breadboards, mockups and experienced hardware specialists became very valuable in malfunction problem solving. These resources were used many times to evaluate off nominal conditions, determine the nature of a failure mode and to evaluate potential corrective actions. Examples follow:

When the AM coolant loop valves became stuck, contaminants were injected into an AM coolant loop test setup. It was found that contamination in the system could cause valves to stick in a similar manner to that seen in flight.

When it was suspected that Coolanol was leaking into the cabin, a test was run with test hardware to provide information to aid in the analysis of returned CO_2 cartridges and to verify the Coolanol removal capability of the atmosphere purification system. The CO_2 cartridges were found to contain Coolanol and it was concluded that the condensing heat exchanger removed most of the Coolanol from the atmosphere. Preflight tests had shown extensive Coolanol removal capabilities for the condensing heat exchanger and for the molecular sieve.

Support hardware was used to provide information to aid the evaluation of flight data relative to the AM Coolanol loop leakage. Tests were also conducted to establish the behavior of the various types of joints in the AM coolant system when subjected to temperature variations.

A test setup was used to provide data on the behavior of the ATM C&D/EREP coolant loop in a variety of abnormal operating conditions to evaluate the flight behavior of that system after flow oscillations were seen.

Ground support hardware was used to simulate the failure of the radiator bypass in the OWS refrigeration system, to provide verification of malfunction procedures and to aid the prediction of future system performance under flight conditions.

When condensate collection system problems during SL-3 raised the possibility that free water would have to be injected into the molecular sieve, ground tests were conducted to provide information on the resulting sieve performance and to verify that the bed could be baked out to recover proper performance.

2.8 Attitude and Pointing Control System (APCS)

2.8.1 APCS Integration - The extremely accurate APCS performance requirements led to a concept which dictated close coordination of all major system designs and dependence on several technical disciplines. In particular, mass properties, structural flexibility characteristics, electrical system constraints, environmental control, thermal properties, and human factors all formed portions of the design criteria.

It was particularly significant that the diverse pointing requirements of the EREP experiments and the ATM experiments were accomplished through the same set of sensor-actuator-computer hardware systems.

2.8.2 APCS Verification - Design verification of high performance attitude control systems controlling large vehicles such as Skylab to a stability of arc-seconds or sub-arc-seconds, can be performed by software simulation supported by limited hardware testing. The software function is to simulate the entire control system including detailed sensor and actuator dynamics, vehicle rigid and flexible body characteristics, digital computer interface, and the environment in which the vehicle operates. The function of the hardware testing is to obtain analytical models that adequately represent a given piece of hardware over the range of operational interest. It is, therefore, apparent that hardware testing will be limited mainly to the testing of sensors (sun sensor, gyros, etc.) and actuators (reaction wheels, thrusters, etc.) that constitute a particular control system, in order to aid in obtaining high fidelity analytical models of these components. Vehicle rigid and flexible body characteristics should be obtained by detailed analytical modeling of a given structure with the possibility of vibrational testing to verify the accuracy of the structural model obtained. Since vehicle flexibility characteristics are obtained primarily by analysis, appropriate tolerances should apply to the knowledge of various vehicle structural parameters (i.e., stiffness, damping, etc.) and the techniques used to model a particular vehicle. Once the tolerances on vehicle dynamic characteristics are established the attitude control system would be required to yield satisfactory performance throughout the range.

a. Skylab was probably the first large space vehicle where the primary means of performance verification of the attitude control system was solely based on computer simulation supported by limited hardware testing. This was a departure from past programs where hardware testing was the major system verification technique. The software verification approach used in Skylab was dictated due to the difficulty in testing a vehicle of such large size and the fact that measurement of arc-second pointing performance is not independent of test equipment errors. This approach yielded satisfactory system verification in a cost-effective manner that would be even more applicable to future missions where performance requirements transcend those of Skylab for vehicles of similar or possibly larger size.

b. Flight data indicated that structural bending properties differed significantly in some respects from predictions. However, the control system design had sufficient margin to meet both pointing and stability requirements. The lesson learned is obvious: realistic tolerances should be provided in the design when complete preflight verification is not possible.

c. APCS verification continued throughout the flight for purposes of anticipating control difficulties and for monitoring subsystem performance such as sensors and actuators Deviations from expected performance were evaluated to determine whether procedures or control laws required changes (either by the crew or through the computer uplink) to improve system performance.

d. Experience has shown that control system adaptability was greatly enhanced by use of a digital computer as the main sensor data and command processor. If practical, future applications should have sampling rates with common multiples for control variables and telemetry. This feature was precluded on Skylab by use of existing capabilities.

2.8.3 ATM Error Analysis - A satisfactory total system error model can be provided for complex large vehicles by the application of computer programs accounting for all system effects combined with a statistical error analysis.

Because of the extremely high accuracy required for the ATM experiments, it was necessary to account for systems other than the APCS in predicting the final experiment pointing errors. The analysis began with the APCS itself, including the vehicle pointing control system and the ATM canister pointing system. Other factors were considered, such as ATM-to-vehicle alignment, experiment alignment in the ATM canister, accuracies internal to the experiments, and alignment changes resulting from changing thermal gradients. Computer programs were generated to determine the magnitude of each of the error sources on a deterministic basis. Finally, the individual error contributions were combined statistically to arrive at a total system error model. Results indicated that the total error model was somewhat conservative, allowing for errors up to 30 arc-seconds, worst-case. Although some data taken under high disturbance conditions indicate errors of this magnitude, the large bulk of ATM data show pointing errors well within the design goal of 2.5 arc-seconds, mostly about 1 arc-second.

2.8.4 Crew Motion Disturbance - The control system was consciously designed to accommodate significant disturbances from crew activities. The design effort held particular significance in view of the pointing requirements of ATM experiments and because of the requirements for other simultaneous crew activities. Mathematical models of typical crew activities were constructed from limited experimental data. These crew motion models of both a statistical and deterministic nature were applied in conjunction with the APCS models to predict the impact on experiment accuracy. The results led in part to the decision to provide a separate isolated control system for pointing the experiment canister. This in turn made it possible to achieve the required ATM pointing accuracies. An additional lesson grew out of the realization that man adapts quickly to new environments. Life in Skylab presented an acrobatic challenge to the crew, who responded with such agility as to render some of the crew motion models slightly obsolete.

2.8.5 Generation of APCS Functional Schematics - Coordination of the design, build, test, and operation of the APCS was effected by functional schematics covering all major internal and external interfaces. These gave individual hardware design groups a comprehensive overview of the entire APCS operation and ensured that correct polarity was observed between internal interfaces. The schematics provided the uniform coordinate system definition and control which is mandatory for any complex space systems. Finally, the schematics served as the common ground of communication between design engineers and flight operations when it came time to verify the operational status of the Skylab APCS.

2.8.6 APCS Control Law and Compensation Filters - Control moment gyros (CMGs) can be successfully used to stabilize a large space vehicle against transients, store momentum and generate maneuvers of limited magnitude. For future use of this system prime consideration should be given to momentum storage capacity and the minimization of all vehicle and space suit vent propulsion effects.

a. The use of a digital computer as the primary sensor data and command processor permitted design of a control law which used the actuation devices (control moment gyros) to their fullest capability. Control compensation filters eliminated most of the undesirable effects of structural flexibility. Additionally, the logic governing the drive of the control moment gyro gimbals minimized the amount of propellant used for accumulated momentum disposal and for high rate maneuvers.

b. Skylab is the first large space vehicle controlled by gyroscopes, large double gimballed wheels spinning at a constant speed. Torques are generated by changing the direction of the spin vectors with respect to the vehicle. A cold gas thruster system is available on board to augment the CMG system when required.

c. CMGs have been successfully used in the mission to:

- stabilize the vehicle against transients such as crew motion and canister roll
- store the momentum accumulated due to gravity gradient and vent torques

- reorient the vehicle with respect to the gravity field during the night portion of the orbit in such a way as to reduce the stored CMG momentum.

- generate large maneuvers such as those required for thermal control in the first week of Skylab before solar shield deployment, and the rates required for Earth resources passes.

d. Vehicle venting torques were less than predicted with the exception of a vent mode made more propulsive by the loss of the meteoroid shield. Astronaut suit vents were more propulsive than expected and caused thruster usage during periods of EVA. Space suits for future missions should be designed with non-propulsive vents.

2.8.7 Contingency Operation - A digital control system, with ground reprogrammable computer, proved invaluable during contingency operations. Shortly after lift-off the APCS demonstrated the capability to compensate for discrepancies in other systems. The thermal-electrical attitude-time profiles which were flown prior to installation of the sun shade and deployment of the jammed solar wing were possible because of the versatility design of the APCS. The extreme flexibility of a digital control system and particularly of the computer itself made the Skylab control system most adaptable to contingency operation. For example, the computer was used at one time or another during the mission to adapt as follows:

- Software changes were made to compensate for excessive gyro drift.

- Compensation was made for variable gyro scale factors resulting from different gyro temperatures.

- An additional star was accommodated in the software for better roll update information.

- Provisions were made and a program, loadable from the ground, was developed which would have allowed vehicle control by derived rates if the rate gyros had failed.

- Mass property updates were made in the computer allowing more accurate momentum management.

- Provision was made in the software for improving experiment data accuracy if necessary.

- Maneuver command granularity was improved to facilitate viewing of the comet Kohoutek.

In summary, Skylab has shown that a redundant general purpose computer, reprogrammable from the ground and backed up by an extremely versatile group of support personnel using a variety of simulations made it possible to meet every contingency situation which arose.

2.9 Electrical Power System (EPS)

2.9.1 General

This system, the most complex every flown, included two separate solar array systems which converted sunlight into electrical energy. This energy was supplied to two energy storage and conditioning systems, one related to each array. These systems are termed power conditioning groups (PCGs) and charger battery regulator modules (CBRMs), respectively.

The power systems were designed to be operated independently of each other as well as in an electrically paralleled state where load sharing is the normal mode of operation.

2.9.2 Solar Array Systems

Each of the two systems was similar in function but different in design detail. These differences provided a good engineering comparison of the two designs while operating in the total space environment. In addition, this mission was unique in subjecting the vehicle (and solar arrays) to over 4000 day-night temperature cycles.

Degradation of each solar array with regard to micrometeoroids, ultra violet and charged particle radiation was well within premission planning for both array designs.

Thermal cycling dictates a close match between solar cell interconnector material and silicon (solar cell) with respect to thermal expansion. The OWS solar array used Kovar as the interconnector material and exhibited no temperature cycling failures. Since the OWS used single string (electrical) design detail, any failure would result in significant power loss. The ATM solar array, an earlier design, used copper interconnector material. Copper and silicon have significantly different expansion coefficients, thus the ATM solar array experienced several open circuited modules (power loss) apparently due to this failure mode.

The ATM array was not shadowed (normally), permitting a circuit design that ties each solar cell into both series and parallel with adjacent cells, permitting a significantly higher number of open solar cells before power loss is detected. The single string design of the OWS array was imposed by partial shadowing from structure.

The OWS concept of combining modules throughout each wing and between each wing into a single output is a desirable approach, as was demonstrated when wing 2 of the Workshop was lost at launch. Thus, loss of a complete wing of modules only slightly reduced the energy producing capability for each of the 8 PCGs.

Shadows from structure should be eliminated from future designs, permitting use of the most reliable circuit design while minimizing area loss and analysis complexity.

2.9.3 PCGs and CBRMs

The ampere-hour integrator concept is desirable, however, the circuit design should allow ground crew updates to permit deviations from predicted performance.

The nickle-cadmium batteries flown in the ATM system were subjected to system ground tests and were trickle charged over long periods. This stressing along with early mission-imposed stresses apparently reduced ATM battery capacity. The AM system received new batteries just prior to launch and did not experience significant loss in capability.

2.9.4 Parallel Operation

If a power system is composed of more than one independent subsystem, those subsystems should be able to operate in parallel (i.e., any one power system capable of equally sharing loads or of supplying one or both sets of loads, by adjustment of bus voltages). This design feature was at least partly responsible for the long duration of the Skylab mission.

2.9.5 Special Documents

a. A power allocation document should contain:

- Power required for each operational mode at the required range of input voltages. For resistive loads the difference in the electrical load between 24 volts input voltage and 30 volts is very significant. For some devices, such as inverters, a constant power is required over the range of input voltages. Therefore, it is very important that this characteristic be understood for each component. Peak loads should also be identified.

- The bus (or source) from which each component will receive power should be identified.

- The resistance of the distribution system wiring from the bus (or source) to each component should be defined.

- The nomenclature and reference designators used for each component in the power allocation document should be consistent with those of other contractual documentation.

- The resistance of the interconnecting wiring between the distribution system buses and the power source should be defined.

b. A loads assumption document should contain:

- The duration of the operation of each component at each operational power level.

- The factors affecting the operational sequence such as temperature, ground track, etc.

- The relationship of the operational sequence to that of other components.

c. A clear understanding of the EPS configuration requires functional schematics.

The functional schematic should present all circuitry to a level of detail sufficient to display the interaction between all major components in the EPS.

2.9.6 Power Management

This requires load profile and EPS capability analyses.

The load profile analysis consisted of collating the predicted astronaut activity timeline with a prepared list of loads to provide a load profile for each one-tenth hour of the mission. The power capability analysis was performed using the large EPS computer prediction program to calculate the individual power system (ATM and AM/OWS) power capability for a specific orientation. The capability was compared to the calculated load profile. If the margin was positive (capability exceeds load) no further action was required. If, however, the margin was negative, the power management group determined the required off-loading or adjustment of the load sharing capability.

In addition, a critical loads list and a candidate off-load was maintained.

2.10 Instrumentation and Communication (I&C)

2.10.1 Skylab I&C Integration - In reviewing the design of the Skylab Instrumentation and Communication (I&C) system against nine months of orbital operation, several experiences are worthy of consideration for future applications.

a. In the SWS, the television subsystem requires the combination of the SWS and the CSM communication equipment for an operating subsystem. If a backup transmitter were located in the SWS, visual surveillance of the SWS as well as the possibility of down-linking ATM TV camera images during the unmanned mode would have been possible. On future vehicles that mate in orbit, thorough systems trade-offs on equipment location should be made in designing a subsystem; i.e., (television and audio) where part of the subsystem hardware is in one vehicle and the rest in another and both are required to operate in the system. The study should evaluate which vehicle should have an autonomous subsystem with capability of extending its services to the other.

b. The lack of full definition of the functional role of the TV subsystem at an early stage of conceptual design resulted in continual add-ons during the later stages of the program. This yielded a design difficult to implement, especially with respect to crew interface. Incompatibilities of the individual pieces were difficult to detect and correct, and may have resulted in some compromises that would not have been necessary, otherwise. The total desired subsystem functional requirements should be thoroughly defined first, independent of schedule and cost. The subsystem can then be created on a building-block basis, as dictated by schedule and cost restraints.

c. The interfaces between crew systems, I&C subsystems, and the vehicle should be thoroughly tested under all modes of operation as close to the actual environment as practical, using simulators and mockups. Special attention should be given to hardware location, ease of operation, and environmental conditions within the vehicle. Regardless of the amount of ground analysis and testing, it is difficult to predict flight results in all respects. Flexibility should be built in to allow the crew to move some hardware; for example, intercom boxes based on crew preference for location. A duplex portable wireless intercom system should be considered for part of future communication systems. The accumulation of crew experience, sound level measurements obtained in the Skylab atmosphere, and maximum distance of normal voice propagation in a 5 PSIA atmosphere should be of immeasurable value on future design.

d. Extensive compatibility tests were conducted between the airborne data and command systems with the corresponding ground equipment. The lack of any command problems during the mission attests to the thoroughness of the prelaunch test program. Although a variety of interface problems were uncovered and resolved during ground tests, most of the problems encountered during the mission were primarily related to the ground computer's data processing capability. Testing between interfacing airborne and ground equipment is mandatory and should be extended through ground data processing. The peculiarities of the airborne data train should be thoroughly evaluated and tested with the ground equipment and its software programming to preclude development of problems.

2.10.2 RF System Analysis and Verification - Early program direction can ensure standardization of the measurement techniques, such as the use of standard coordinate systems, which in turn will reduce later data processing. Furthermore, the cost of range measurements can probably be reduced if only the predominant polarization patterns are completely documented, such as circular polarization in the case of linear antenna elements.

a. Premission Analysis - The application of computer analysis techniques began several years prior to the Skylab launch with development of the COCOA family of computer programs specifically oriented to supporting Skylab communication system analyses. These analyses primarily addressed two technical areas; SWS antenna data processing and documentation, and the computation of RF link circuit margins.

Although computer processing was applied to standardize antenna pattern formats and compute isotropic levels and cumulative gain curves, even further application is recommended in the documentation of a large number of antenna patterns in the standard theta-phi (θ-ϕ) format. Minor additional processing of raw antenna pattern tapes could facilitate and automate the process of indicating specific gain contours on the patterns.

Premission analysis of the SWS telemetry and command links included the utilization of COCOA programs to generate RF link circuit margins, taking into consideration five sets of antenna data, RF system parameter variations, differences between STDN site RF systems, and variations in SL trajectory and attitude. These data were generally used to verify overall RF system compatibility, i.e., the spacecraft to network interface. It proved that substantial signal level differences will occur from pass to pass dependent upon spacecraft attitude, but that antenna coverage was sufficient to provide satisfactory long term link performance in either the solar inertial or Z axis-local vertical attitudes. In addition, telemetry link circuit margins were computed in order to recommend appropriate recorder tape dump opportunities and optimum RF link selection.

b. RF System Verification - Premission RF link performance predictions were verified during the mission with the assistance of telemetry receiver automatic gain control (AGC) recordings made at the ground sites. The recordings at four U.S. sites were analyzed to determine received signal strengths to ensure that the RF systems were operating properly. A profile of link performance was plotted for each of the five telemetry links in order to highlight long term variations in performance.

A long term mission such as Skylab presented an unusual opportunity for the collection of sufficient data to partially reconstruct actual spacecraft antenna radiation patterns and compare these with premission pattern measurements. This rather complex procedure was achieved by first processing STDN site tracking data along with mission attitude profiles to accurately arrive at spacecraft antenna look angles (θ and ϕ), and associated measured antenna gain levels. Available receiver AGC recordings were then used to determine received signal levels and actual antenna gains, which were compared with ground measured pattern data.

2.10.3 Special I&C Documentation - The Skylab I&C subsystems required operation of a number of complex electronic subsystems ranging from the audio frequency spectrum to S-band. Integration activities were complicated by the number of contractors (four) and NASA centers (four) involved, when it was essential that each should not only fulfill his responsibilities, but be kept abreast of the the total I&C status as well. The following experiences are included for consideration by future programs:

a. The status of over 2000 SWS measurements, 900 commands and hundreds of digital computer inputs were controlled via level I interface control documents (ICDs). Measurement and command channelization were controlled by these ICDs, which required inter-center agreement before changes could be made. The success of this type of control was evidenced by the lack of problems in this area during the mission. With more complex and variable format suggested on future missions, a well disciplined documentation control is required.

b. The SWS TV subsystem is an example of a complex system provided by five entities: the MDA, AM, OWS, CSM and the ATM. The entire TV system was not operated together until after rendezvous and activation of SL-1 and SL-2 in orbit. The development and implementation of the Skylab TV Test Plan and Test Requirements Document provided uniform and consistent technical direction in the successful ground testing of the TV subsystem components.

c. The Skylab to STDN ICD was a technical document which proved to be valuable in making visible the communication link interface between the SWS, launch vehicles and the ground. The functional performance characteristics of both the SWS, launch vehicle and ground equipment were detailed. In addition, it controlled such details as the PCM data formats (real-time and delayed time), command coding formats and ground antenna masking data. The value of this document lay in its use as a common source for parametric data used by all technical organizations analyzing the Skylab RF communication system.

d. Based on the SL experience, future I&C integration effort should include development and maintenance of the total I&C subsystem functional schematics and detailed technical descriptions, from the inception of the program. This information would enhance design reviews at the module level for systems that extend through multi-modules. For example, the AM PCM, SWS television and audio subsystems operate into three modules, i.e., MDA, AM, and OWS. During a module review, module electrical documents were supplied to all reviewers, but the unavailability of the total system diagrams made it difficult to critique the module's design.

2.10.4 On-Board Displays - Measurements required for on-board display should be defined in conjunction with measurement requirement definition for telemetry.

The displays on board Skylab were selected to permit monitoring of critical parameters by the crew. Prior to launch, the calibration data for the displays was obtained so that any differences with the TM data could be resolved. Problems in documentation made obtaining the original calibration data and the cross checks with the TM readings very difficult on the majority of the modules.

In obtaining the data, there were several items that indicate the need for a systems design concept to define the relationship of the display and the TM readings. For example, is the display to supplement (have an expanded or decreased range), or is it to be backup (should not have any common equipment)?

An accuracy requirement should be defined before any of the system components are selected and the calibration requirements of the individual components and the system should be made at the beginning of a program. Depending on the severity of the accuracy requirement, this could result in end-to-end test requirements just prior to launch and/or an inflight calibration system for very critical measurements.

There were different meters used in the various modules of Skylab, but this did not create problems. Some Skylab designs used one meter for several parameters, switching in the parameter required. This seemed to operate very well and should be used extensively on future programs.

2.11 Structures

2.11.1 Dynamic Analysis Modeling - Vibration analysis for a large structure such as Skylab should contain frequency definition which includes all the fundamental modes of the uncoupled structure prior to implementing the modal coupling technique.

The formulation of a complex model for Skylab involved idealization of an actual structural member or assembly of members into a series of discrete or finite elements. These elements were considered to be connected at node points to form a network or model from which stiffness characteristics were obtained for the structure, using a digital computer program. A stiffness matrix was formed for each discrete element (axial member, beam, plate, etc.) and the element stiffness matrices were merged to form the overall stiffness matrix for the entire assembly represented by the model. To obtain good representative stiffness characteristics of a complex structure, the original model was formed in more detail than that used in the dynamic model. The large stiffness matrix was then reduced or collapsed to one of more manageable proportions. The effect of all intermediate, or collapsed, stiffnesses was retained in the final stiffness matrix.

The technique used to compute the modes was modal coupling, with the modes of the various components being computed separately, then mathematically coupled and transformed to form a set of coupled modes. During this coupling process, a frequency cutoff criterion was defined for the coupled mode set. The frequency limit then determined the number of component modes required in the coupled analysis. The total degrees of freedom which made up this model, prior to any reduction, approached 20,000.

It was known that some component modes were more effective than others in modal coupling. The method for selecting the important component modes involved selecting the modes which had the largest effect on the main beam response.

It was recognized that the vibration analyses used for the loads analyses were not necessarily sufficient for control system analyses. The concept of uniform frequency cutoff was used for the controls model. This concept is to retain all modes of each component to a specific frequency determined by the size limitation of the computer program. The modal selection technique did not guarantee maximum control moment gyro (CMG) or rate gyro motion. Of course, this limited the frequency definition in the controls model to slightly less than 5.0 cps. As one might suspect, this was not an adequate model for loads calculations. Here again, the modal selection technique was employed to increase the frequency definition of the loads model above 10 cps.

The decision was made to assess the accuracy of the loads versus the controls modes, to assess the validity of modal selection techniques, and to determine an acceptable frequency fidelity for vibration analyses. It was concluded that all future vibration analyses would contain individual component frequencies equal to or greater than 15.0 cps. A single model for both loads and controls analysis, determined in accordance with the aforementioned criteria, is considered more accurate than vibration analyses based on consecutive modes and frequency cutoff for a limited number of coupled modes. The final mathematical models were run using over 200 degrees of freedom.

The modal selection technique provides a tool for selecting important elastic modes and eliminating others to increase the frequency fidelity of the mathematical model. Even so, it is recommended that all modes within the frequency realm of the control system be included in the vibration analysis.

Care should be exercised in modeling the junction of beam and finite element stiffness properties in order not to constrain the expected motion artificially. This may indicate apparent load problems where none exist.

2.11.2 Vibroacoustic Testing - Vibroacoustic payload assembly tests should be conducted to verify acoustic criteria. Skylab tests were completed which provided:

- significant updates of the acoustic criteria, improved resolution of zonal properties and refined criteria levels;
- correlation of launch configuration analytical structural models;
- refinement of the orbital configuration analytical model associated with the ATM deployment assembly.

This effort resulted in test-verified structural models and associated analyses.

2.12 Integrated Electrical Support Equipment

2.12.1 Program Management

2.12.1.1 Close Coordination Between Government and Industry - Weekly meetings between MSFC and contractor personnel permitted in-depth visibility of all problems or potential problems which could affect the Skylab integrated checkout program.

This very close coordination contributed significantly to the success of the Skylab checkout program in meeting assigned schedule milestones within program cost allowances.

2.12.1.2 ICD Maintenance - Maintenance and custodianship of ICDs was a responsibility of the prime contractor, who also provided the ESE design function. This dual function allowed a unique insight into a traditionally difficult area. Many problems were avoided and others resolved more easily than would otherwise have been possible.

2.12.1.3 Timely Design Baseline - The Skylab ESE and Software Design was baselined (placed under formal configuration control) at a relatively early time, as compared with some previous programs. The effect was to focus timely attention on incompatibilities existing between vehicle documentation, the associated ICDs, and ESE design. This early baselining allowed changes to be fully evaluated for total program impact and documented prior to implementation.

2.12.2 Hardware Design

2.12.2.1 Multi-Site Usage of Apollo Telescope Mount (ATM) ESE - This ESE, by far the most complex used in the Skylab program, was designed to be semi-portable. Two sets of ESE were required to support testing at four sites. A set could be moved and activated in about 30 days.

2.12.2.2 Factory Checkout of ATM ESE - Prior to delivery, ATM ESE was subjected to an evaluation test which exercised as much of the system as practical. Several problems were found and corrected which otherwise would not have been found until installation and checkout of the ESE at the test site.

2.12.2.3 Delivery of Spares Concurrent with ESE - More than 90 percent of the logistics spare items were delivered concurrently with the ESE. Prior to actual test start 100 percent of the spares had been delivered. This is attributable to early baselining and planning.

2.12.3 Software Design

2.12.3.1 Computerized Programming Requirements for Automated Testing - The initial programming requirements data base was established for ATM post-manufacturing checkout at MSFC. This computerized data base allowed a rapid turn-around for anomalies, and also provided the basis for generating follow-on data bases for checkout activities at the thermal vacuum test site and the launch site. This technique allowed utilization of a similar data base for generation of a unique ACE test file tape and test and checkout procedures for each test cycle. The use of a computerized data base resulted in a minimum of ACE station reconfiguration requirements, test checkout procedure modifications, and test file tape updates with the ultimate benefit being greatly improved response time and reduced overall cost.

2.12.3.2 Computerized Automated Test Sequences - The initial automated sequences of event processor programs (ASEP) were established to reduce lengthy test procedures to automated computer operated sequences and meet stringent test schedules for ATM checkout at MSFC. The ASEP routines provided the capabilities of performing lengthy and exacting checkout procedures in minutes instead of hours. They also provided a hard-copy printout of test results for post-test analysis. ASEP routines were then updated for each follow-on test cycle to further reduce test procedures and test time. This resulted in improved test checkout reliability.

2.12.4 Test and Checkout Procedures

2.12.4.1 Automated Production of Test and Checkout Procedures (TCPs) - Test and checkout procedures (TCPs) were computer-produced, utilizing the ACE program reference file (computerized data base) as the primary control. This process assured that spacecraft software (ACE), TCPs, and ESE were in exact configuration.

3.0 Other Experience

3.1 Design

3.1.1 Contact Resistance - An explosive bridegwire (EBW) firing unit procured to Apollo specifications and modified to prevent cable outgassing by application of S-13G paint failed during a functional test. Analysis of the unit indicated the polyurethane used to coat the printed circuit boards had flowed into the interconnection of a stud diode causing electrical interruption and failure. The mechanism of failure was aggravated by the modification to the EBW firing unit cable to prevent outgassing which required a number of temperature and vacuum bake cycles. A change in design of the stud diode connection was made to maintain a close tight fit between the electrical interfaces and eliminate the flow of the conformal coating insulation from the contact surfaces. Close in-process controls and inspection were maintained in follow-on fabrication, and operations requiring thermal applications were kept to a minimum. Hardware design for conformal coated stud diode connections should specify:

a. A compressible lock on star type washer in contact with the nut and solder lug surfaces.

b. Nuts with a minimum of five threads in contact with the diode stud.

c. Contact surfaces coated with a conductive epoxy prior to conformal coating.

d. A masking compound to cover the interconnecting parts.

3.1.2 304 CRES Corrosion - During vendor acceptance lot testing of confined detonating fuse (CDF) assemblies, an end fitting made from 304 CRES material split in the crimped area during firing. Functional performance was otherwise successful; however, for Skylab the release of combustion products could result in contamination of deployed optical surfaces. CDF assemblies were used on OWS and ATM for a variety of system functions.

The primary cause of failure was found to be intergranular corrosion in the 304 CRES material. This occurred as a result of carbide precipitation of the 304 CRES grain boundaries and exposure to moisture during the temperature humidity exposure of the test specimens.

Carbon precipitate was attributed to the bright annealing process specified for the end fittings which required a gas quench and resulted in low cooling rates. Slow cooling allowed the chromium carbide to precipitate at the grain boundaries.

CDF assemblies subjected to low cooling rates for bright annealing were reinforced with test-qualified metal sleeve clamps and successfully flown on Skylab.

Future procurement of CDF assemblies should specify 304L CRES material for improvement of micro structure. Manufacturing Processes should include annealing in an inert atmosphere and assurance of a rapid quench. Necessary precautions should be taken to maintain shipment of the CDF assemblies and storage of the units under dry conditions.

3.1.3 Prevention of False Stars - Explosive components located on the exterior of Skylab Modules had adhesive-backed metallic nameplates and identifying tapes which were found to be capable of coming off when the explosive device was fired and becoming "false stars" which could confuse the star tracker.

A method of securing these by wrapping with transparent tape was qualified and implemented. Future designs should ensure that adhesive-bonded labels and nameplates will adhere under operational conditions in vacuum.

3.1.4 Pressure Switch Diaphragm - Several pressure switches failed during development and qualification testing. One failure was attributed to imperfections on the diaphragm mating surface, another to fatigue. The switch was considered poorly designed since the diaphragm was not being fully supported and the backside not being evacuated, thereby causing the diaphragm to be worked in the opposite direction during the vacuum cycle.

3.1.5 Transducer Welds - Temperature transducers leaked out of specification, during checkout, from a 90 degree miter weld joint. Investigation revealed that the weld joint was not intended as a pressure seal since there were redundant seals upstream. Clam shell structural members were successfully bonded over the miter weld joints on all production hardware. This problem could have been avoided if the miter weld joint had been properly specified.

3.1.6 Liquid Dump Freezing - During tests where 150 to 200 pounds of liquids were dumped to vacuum, it was found that if the stream of dumping liquid was allowed to impinge upon any surface before the liquid had changed into ice, an ice bridge would form which would eventually freeze the flow. If the stream of dumping liquid does not strike anything until it is completely converted to ice crystals, a bridge will not form.

3.1.7 Iodine Absorption From Water System - During tests of the water system deionization hardware, it was discovered that the organic resin in the deionization container removed the iodine from the water passed through the container. The resin could be somewhat passivated by soaking it in a strong (200 mg/l) iodine solution. However, after removing the concentrated solution from the container the resin (still in the container) had to be flushed with a low concentrated solution because the "passivated" resin continued to release iodine into the water for a while. The strength of the soaking solution, length of time in soak and amount of flush after soak must be juggled to arrive at the desired iodine level wanted in the effluence. As a minimum for biocidal action 0.5 mg/l of iodine is required and anything over 6.0 mg/l is a taste problem. The volume of the deionization resin was 220 cubic inches and the flow rate of the water was very low, i.e., 24 pounds per day in the three 8-pound slugs (one for each meal). The water sitting stagnant in the container between meals would lose iodine to the resin. Therefore when water was discharged from the container the iodine content would be below the 0.5 mg/l acceptable minimum. The solution was to reduce the resin volume to 66 cubic inches.

3.1.8 Portable Fans - Crew comfort required little use of the portable fans, but they were useful to cool the rate gyros and to increase mass flow to the workshop heat exchangers. Such functions should be considered in future applications.

3.1.9 Seals - The Viton seals in the water system cold flowed or took a set with age and the steam used to sterilize the system accelerated this deformation thereby allowing some static seals to leak at a later date. The Viton seals were replaced with silicone seals and the leak problem was solved. The silicone seals did not take a set with time nor did steam cause them to fail. Qualification plans should take care to consider non-operational environments such as this steam sterilizing process.

Caution: The slight water permeability of silicone rubber should be considered in electrical or other applications where a more complete water seal is required.

3.1.10 Urine Separator Check Valve Screens - The umbrella check valve used with the centrifugal separator operated as a strainer. As the separator flow gradually decreased, small particles were trapped between the lip and the seating surface, which in turn caused backflow leakage. This problem was resolved by placing a 500 micron screen above the check valve. The large screen was selected to minimize the clogging effect of colloidal urine solids.

3.1.11 Solar Cell Environments - Covered solar cells are quite resistant to damage from heat and humidity. The temperature and moisture limits for a specific application should be determined by test of the actual configuration to be flown, including all wiring, soldering, plating, etc.

3.1.12 Rain Leak Control - Over-pressurizing an enclosure such as a payload shroud with purge gas is inadequate to prevent leaks under typical KSC weather conditions if leak paths exist. Structure must be water-tight.

3.1.13 Welding Distortion - Extensive welding of fittings, longerons, etc., to thin-shell structures should be held to a minimum to avoid warpage.

3.1.14 Relocation of Components - A positive system should be established for comparing before-and-after launch and operating environments of components which are relocated by design change on a vehicle. All aspects of the mission profile should be systematically considered.

3.1.15 Paint - Avoid the use of paint wherever possible, due to problems of wear and flaking. Excellent space-qualified adhesive-backed metallic labels are available, together with a wide selection of permanent finishes, such as anodizing, for metals.

3.1.16 Flexible Metal Hoses - Bellows-type braid-covered flexible hoses should not be used for stationary bends in rigid tubing. When installed between two hard points, with no possibility of adjustment, hose length is critical to avoid deformation. Deformation may be encountered if a short section of hose is bent in more than one plane.

3.1.17 Gas Storage Technology - Skylab produced a significantly improved approach to storing a large quantity of oxygen for long duration flight. A small scale laboratory idea was turned into full scale production, saving considerable funds and 11,700 pounds of lift-off weight through use of a relatively thin metal tank wrapped with glass fibercord.

The metal liner offers a non-permeable oxygen-compatible barrier to satisfy long duration minimum leakage rates. It also provides a non-shattering failure characteristic which greatly enhances safety.

3.1.18 Regenerative CO2 Removal System - To support long duration manned space flight, the weight, storage volume and inflight crew time were saved by utilizing a regenerative CO_2 and odor removal system. Skylab utilized this method successfully for the first time.

By incorporating this compact system into the spacecraft a large volume of disposable absorption material was eliminated. It simplified crew housekeeping chores due to its automatic cycling and self-purging capabilities. Its basic design should be considered for future applications in manned space flight.

3.1.19 Fluid System Integrity - The Airlock coolant leakages were probably attributable to the many "B nuts" and flange seal connections used in its design. This contrasts with the OWS refrigeration subsystem, which has given no indication of leakage and which maximized brazed-joint connections. Long term exposure to vacuum conditions and severe thermal environments will tend to overstress any system; therefore, use of mechanical torque-fastened connectors should be minimized in favor of brazed or welded joints in future applications.

3.1.20 Cabin Heat Exchanger Performance - During the mission a gradual reduction of cabin atmosphere circulation was noted and traced to an accumulation of dust on the cabin heat exchangers that restricted the flow of gas. Although the problem was easily corrected with the vacuum cleaner, it could have been serious if this measure had failed to remove the contamination. Gas circulation systems should incorporate protective, replaceable filters upstream of all heat exchangers and other contamination-sensitive equipment.

3.1.21 Optical Spaceship Windows - Large single pane high optical quality windows can be successfully utilized in pressurized spacecraft by giving proper attention to sources of contamination, thermal control, mounting techniques, and glass processing.

3.1.22 Sensitive Expendables - Design to facilitate last-minute loading of sensitive expendables requiring a controlled environment.

3.1.23 On-Board Calibration - Design on-board calibration capability into experiments or other equipment requiring calibration.

3.1.24 Off-The-Shelf Components - Use conventional, well-proven piece parts with generous tolerances whenever possible. Be especially careful about scaling up size, rating, or other characteristics of a proven part for a special application without thorough requalification by analysis, test, or both.

3.1.25 Provisions for Handling - Designers should ensure that all practical design features are included to facilitate safe handling of bulky items during installation, maintenance, or replacement. These could include handles, lifting lugs or eyes, tapped holes for attachments, etc. It should be remembered that at one time or another most flight items will have to be put into two slippery bags, a task every designer should have to perform at least once.

3.1.26 Cross-Connection of GSE - Positive measures should be taken to prevent errors in connecting fluid lines and electrical cables from GSE or the facility to flight hardware.

3.1.27 Jamming of Strip Recorders - Any instrument which records on paper, or equivalent, should be in-flight serviceable at least to the extent of clearing a paper jam and resuming operation.

3.1.28 Conductive Adhesive - Electric heaters were bonded to the structure with a silver-filled adhesive. The bonds were accidentally wetted by atmospheric condensation, and galvanic action damaged the heater cases. Overcoating of the conductive adhesive with a waterproof compound would have prevented the damage.

3.1.29 Caution and Warning System - It is easy to compile a long list of "requirements" for displaying housekeeping parameters on the caution and warning system, when large numbers of disciplines and interests contribute to the design. After the list is scrubbed down to a minimum, consideration should be given to on-board adjustability of limits for crew convenience in the event of borderline or extended off-nominal performance.

3.1.30 Alarm Power Source - An alarm to indicate loss of ground power to the food freezers was isolated to the same ground power source, and automatic switching was not a design feature. Power was lost during a weekend, but thermal lag prevented food damage before it was restored. While automatic switchover might justifiably be ruled out (as in this case, where ample recovery time was obviously available due to the large heat sinks involved), alarms and other emergency indicators should always be independently energized.

3.1.31 Optical Grating Materials - An optical efficiency degradation in an experiment was traced to time-and-temperature related diffusion of the metallic thin films of the reflectance grating. The inferior Au-Al-MgF_2 gratings were replaced with Al-Al-MgF_2 gratings which showed suitable stability. The failure report recommended against coating Al directly over Au for optical surfaces.

3.1.32 Contamination from Detonating Fuse - Confined detonating fuse (CDF) assemblies with a braided glass fiber cover were used in the deployment sequences. Testing showed that the firing shock released a substantial cloud of glass fibers that could have been quite detrimental to the ATM experiments. Taping the assemblies reduced the contamination by 97 percent.

3.1.33 Nickel-Cadmium Battery Short Circuits - Dendrites associated with normal cadmium migration pierced the fibrous material separating the plates and caused shorts.

A third electrode had been added on the broad side of the plate assembly, causing decreased clearance between plates at that point when the cell was assembled into the case. Dendrite growth in that area was thus stimulated by increased pressure and temperature.

The problem was eliminated by moving the third electrode to the edge of the assembly, where there was more room.

3.1.34 Electrical Brush Material - Brush material selected for a vacuum application was found to develop a nonconductive film during systems thermal vacuum tests. Fortunately, this was corrected without undue difficulty by selection of a more suitable material for new brushes. Materials compatibility with use requirements should be established prior to incorporation in a design.

3.1.35 Photo Tube - During the early design stage, problems were experienced from thermal expansion and high voltage arcing.

The encapsulation of the photo tube and high voltage power supply tended to prevent thermal expansion causing breakage of the tube. An improved technique of supporting the tube and a change in encapsulation material solved this problem.

Arcing of the high voltage power supply (5000v) was accomplished by encapsulation in stages to eliminate air bubbles which are conducive to arcing. A layer of encapsulating material was applied and allowed to cure before the next was applied.

3.1.36 Film Storage - Cameras, film canisters, storage containers and film processing equipment should not utilize non-anodized aluminum or copper where Schulman type films are employed.

Film fogging was observed during the testing of ATM film types SWR and S0114. All of the severely fogged films were found to have been stored in non-anodized aluminum test containers. The degree of fogging was found to be a function of storage time and temperature. Films stored in black anodized aluminum test containers evidence no such fogging. The above films are non-overcoated Schulman type emulsions. The absence of a gelatin overcoat on the emulsion surface may make those films more susceptible to chemical fogging than the other conventional overcoated films used in the Skylab program. A review of the fogging phenomena with the manufacturer resulted in their identification of comparable contaminant problems with copper.

3.1.37 Draining Hollow Structural Members - At one point a question arose as to whether the large hollow members of the ATM deployment assembly might contain liquid. This was resolved (negative findings) by removing bolts from the end fittings. Consideration should be given to providing such members with weep holes or plugged holes at low points to avoid disturbing structural fasteners.

3.1.38 <u>Thermal Uses for Portable Fans</u> - Access should be provided to liquid systems and temperature sensitive components so that portable fans can be used directly to help heat or cool in off-nominal situations.

3.1.39 <u>Reservicing Capability for Fluid Loops</u> - In-flight reservicing capability should be provided for critical fluid systems, especially in long-duration missions.

3.1.40 <u>Tolerance for Particulate Contamination in Fluid Systems</u> - Avoid small clearances that could bind from particulate contamination. Pay particular attention to filter locations, capabilities, and servicing potential. Assure that pressure transients cannot crack filter bypass relief valves, possibly contaminating the system and even preventing the valve from reseating properly.

3.1.41 <u>Moisture in Window Cavities</u> - Provide positive means for removing moisture from the spaces between multiple window panes, regardless of how "perfect" the seals may be.

3.1.42 <u>Redundant Fluid Systems</u> - Identically redundant fluid systems have not always provided the expected backup capability, being naturally subject to the same anomalies. While completely different dual systems would not usually be cost-effective, consideration should be given to such features as manual or ground capability in parallel with one or both automatic functions.

3.1.43 <u>High Structural Safety Factors</u> - Three major Skylab structural assemblies, the ATM deployment assembly, the fixed airlock shroud, and the jettisonable shroud, were designed with safety factors of 2.0 to 3.0, thus obviating the requirement for an expensive static structural strength qualification program.

3.1.44 <u>Valves Vs. Orifices</u> - Avoid moving parts in fluid systems by using fixed orifices instead of flow control valves wherever the operating range permits. Use of such valves should be rigorously justified.

3.1.45 <u>Gas Purges</u> - Dry air rather than an inert gas should be the purge medium. Two cases of anoxia associated with nitrogen purges occurred during the program, one when a man inserted his head into a relatively open structure under purge. In the other, nitrogen flowed from a compartment under purge through a pressure equalization valve (which was supposed to be closed) into a compartment where a man was working. The relatively modest decrease in contamination potential does not justify the risk of large-volume inert gas purges.

3.1.46 Ultrasonic Cleaning of Fluid Systems - Fluid systems that are improperly cleaned may release particles under launch and operational conditions which can jam close tolerance valves and other components. It was learned that many components, such as heat exchangers with small parallel passages, cannot be cleaned with standard flushing procedures unless accompanied by ultrasonic vibration.

3.1.47 Component Thermal Data - Thermal data requirements should be included in component development programs to support timely, reliable thermal analyses.

3.1.48 Corona From Multilayer Insulation Outgassing - Multilayer film-type insulation, adequately protected by purge during ground operations, vents readily in orbit to provide the required thermal protection. However, its use in conjunction with electrical equipment subject to corona at pressures much lower than those of thermal interest should be carefully examined. Residual outgassing could delay operation of high voltage equipment for several days.

3.2 Manufacture

3.2.1 Urine Bag Fabrication - Urine bags, which were laid up over an aluminum mandrel that was subsequently dissolved with a caustic solution, experienced an early high rejection rate for leaks while the process was being developed. Sharp edges produced on the mandrels while they were being dissolved were primarily responsible. Minor adjustments to the caustic flow rates and bag/mandrel positioning sequence during the dissolving process reduced the number of holes. However, the hole problem was not eliminated and 10 to 20 percent of the bags had leaks and were rejected. Ultimately, a patching process was developed and all the bags rejected for holes were repaired and used.

3.2.2 Mercury Contamination - Several pressure switches were contaminated with mercury by the supplier, as a result of a mercury spill which had occurred months earlier. Close inspection of vendors' facilities, manufacturing and test methods should be made to preclude the possibility of mercury contamination. Where doubt exists, testing of delivered items for the presence of mercury is not difficult.

3.2.3 Manufacture of Qualification Units - Qualification and flight units should be built to the same documentation system and in the same facilities insofar as practical.

3.2.4 <u>Cables</u> - Cable assembly is greatly facilitated and installation is easier and safer if a three-dimensional manufacturing assembly is used. This can be a mockup used for engineering development as well.

Massive cables such as those developed on Skylab present special problems in restraint due to their weight and the slipperiness of insulation. Where the topography permitted, such as where the ATM cables traversed the deployment structure, complete restraint was not attempted. More positive control, such as using compartmented clamps, was necessary in congested areas of the airlock module, where six-inch cables were routed near structural members.

3.2.5 <u>Cleanliness</u> - Orbital experience confirms that an extremely high level of spacecraft cleanliness can be maintained during manufacture if the proper controls are enforced. Even though the size of the Skylab modules precluded a practical "shake-rattle-and-roll" exercise and inspection before flight, the crew reported a virtually immaculate condition at initial entry in orbit.

3.3 Test

3.3.1 <u>Qualification Environments</u> - As flight systems and mission time lines become more complex, it is essential that all component or other qualification programs are systematically developed and validated against all ground and flight environments which will be encountered. Flexible closed-cell foam material was extensively used for contoured packing in stowage lockers. During the altitude test of the airlock-multiple docking adapter with 5 psi internal pressure, the foam expanded so that it was difficult to remove items from their cavities. Upon reflection, it was realized that, with pressures required in the workshop during launch for structural integrity, the foam would have been compressed and at least partly failed to do the primary job for which it was intended. Neither condition had been considered in the qualification program.

3.3.2 <u>Water Tank Ground Handling</u> - The water supply was stowed in ten tanks approximately 23 inches in diameter and expelled by gaseous nitrogen behind a metal bellows with one end enclosed by a metal dome. Movement of the metal bellows inside the tank during ground handling was prevented by mechanically restraining the bellows in a fully collapsed position by a metal strut from the opposite tank end to the bellows. In this design, a slight temperature change could cause the gas trapped behind the bellows to expand and deform the bellows dome at the point of attachment with the strut. This problem was resolved by removing the metal restraining rods from all tanks and pulling a slight vacuum behind the bellows and sealing the tank.

3.3.3 Gas Leak Control - Using an extremely accurate mass-decay detection system developed at MSFC, cabin leak rates were determined at ambient external pressure for all MSFC Skylab pressurized modules, and the airlock-multiple docking adapter combination was also checked in an altitude chamber. All leakage was well below allowable rates, and such was the case in flight as well. The cross-check of leak rates at ambient and altitude indicates a larger conversion factor for altitude difference than previously established.

3.3.4 Megger Test - Megger tests should be performed on all cabling after installation in the space vehicle.

3.3.5 Test Teams - The program benefitted greatly from the "traveling test team" concept. Each module was followed by a dedicated NASA-industry test team from factory checkout through launch. The readily available experience thus accumulated was invaluable in troubleshooting and implementing changes.

3.3.6 Test Procedures - Develop and use launch site and orbital test procedures as much as possible for factory checkout. This required early participation by launch and operations personnel in planning requirements.

3.3.7 Prototype Unit - Include an all-systems prototype in the program so design, procedure, or facility problems can be identified with adequate lead time for correction. This unit can be refurbished for flight or real-time mission support.

3.3.8 Problem Close-Out - Trace any and all problems encountered in qualification or systems testing to clear and proven conclusions, and file for quick reference.

3.3.9 <u>Crew Participation</u> - Plans for crew participation in factory checkout or other tests should be made in time for procedures to be developed which are acceptable for crew use. This requires a learning period for an organization not experienced in writing such procedures.

3.3.10 <u>Thermal Vacuum Testing</u> - Skylab has shown that full-scale thermal vacuum testing of even a quite complex spacecraft is not mandatory for thermal design verification. This can be accomplished by thoroughly integrated thermal analyses and a sound test program involving components, materials and partial configuration tests (such as individual reflective panels and segments of cabin walls).

3.3.11 <u>Nonfunctional Test Activities</u> - Water hoses were damaged by three hours of steam cleaning at the test site as opposed to one hour at the manufacturing site. Nonfunctional activities related to the test program (cleaning, handling, preparing for storage, repair) should be defined and reviewed with as much care as the functional verification requirements.

3.3.12 <u>Quick-Disconnects (QDs)</u> - Ground QD leakage in one case was attributed to high side loads which accelerated wear during making and breaking connections. QDs should be qualified not merely for the required number of cycles under nominal operating conditions, but also should be subjected to representative factors such as side loads and misaligned engagement, which could increase wear.

3.3.13 <u>Integrated Testing</u> - The Skylab program demonstrated the feasibility of developing separate space station building blocks, or modules, at different locations, for assembly and integrated design verification testing at the launch site or other central location. A very slight extrapolation of this experience indicates that in-orbit assembly and checkout of such modules is well within present capabilities.

The success of this approach is attributable to an extremely comprehensive system of intercenter reviews in every discipline throughout the program, clear interface definition and tight control of those interfaces, and flowing experienced personnel through the hardware buildup and checkout sites into the KSC activities.

3.3.14 Checkout of Redundancy in Orbit - Knowledge should be maintained of readiness of redundant capability which is not on-line, so that malfunction procedures can be initiated in a timely manner if needed.

3.4 Product Assurance

3.4.1 Redundancy - A high degree of redundancy in critical Skylab systems was an essential factor in mission success. Critical rotating equipment was either redundant or replaceable in flight, and the same was generally true of critical electronic equipment. All ordnance and other critical activation (deployment) features were redundant.

3.4.2 Human Errors - Minimize opportunity for human error by designing parts that cannot be installed backward, etc. Critical parts should be inspectable (physically or functionally, as required) after installation in the final launch and flight configuration. Establish mandatory inspection points early.

3.4.3 Control of Special Items - Receiving inspection and in-plant control should be carefully planned and maintained for materials not subject to ready visual identification. Examples are springs, non-metallic seats and seals, and fasteners.

3.4.4 Safe Handling - Special handling fixtures with "load leveling" features should have positive provisions to prevent load-bearing members from separating as could happen if threaded members completely unscrewed during adjustment. Existence of these protective measures should be confirmed before use.

Most handling incidents involved intermediate-sized items whose weight or bulk placed them near the limit of ready handling by one or two men. One experiment was dropped while being bagged by two men when the cart supporting it rolled away; the cart should have had brakes or the operation should have been performed on a table. Items fell from sideless carts because of rough or discontinuous floors; articles should be secured to sideless carts before movement, and travel routes should be maintained in good condition. Special care should be exercised with rolling loads having high centers of gravity.

3.4.5 Recording Specific Test and Inspection Data - Where fine mechanical adjustments or critical clearances are involved, component or system trends are of interest, and in other cases as applicable, consideration should be given to requiring that actual measurements be recorded by the inspector, not merely that the observed value was within the allowable tolerance.

3.4.6 Clarity of Procedures - Procedures must be as brief as practical, but adequate information should be provided. In one operation, a torsion rod was to be twisted, with a wrench, in the "wind up" direction to relieve the force on a keyed keeper so the latter could be removed. The procedure was silent on the direction of twist, the technician guessed wrong, and the rod was sheared between the wrench and the keeper.

3.4.7 Witness Samples - Witness samples of critical materials and components with possible time-dependent degradation should be maintained at conditions similar to the flight hardware for times representing flight hardware life before launch. Proper functioning should be verified in time for corrective action to be taken if required. Particular attention should be paid to one-shot activation devices such as liquid-filled actuator dampers, springs, and ordnance assemblies.

3.4.8 Storage Conditions - After calibration, it was decided to store oxygen partial pressure sensors in nitrogen to "rest" them until required for use. When rechecked before installation, they were out of calibration because of prolonged lack of contact with oxygen. While they were not permanently damaged, this is another good example of an apparently innocuous factor which caused a completely unexpected result.

3.5 Other

3.5.1 Government Furnished Property (GFP) - Skylab module contractors were provided GFP both for installed hardware and stowage. The majority of installed hardware selected as GFP required development and qualification. Delays in qualification of these components and associated modifications required additional module installation and checkout. The GFP stowed flight hardware was delivered late and required the use of non-flight hardware during manufacturing checkout.

Program management should establish a central office to coordinate GFP requirements for all project offices. GFP procurement requiring long lead time, project priorities, best or most economical buy, logistics and other overall program considerations should not be left to the individual projects who may eventually compete with other projects for common GFP components.

3.5.2 Development Specialists - Managers should encourage their contractors to take advantage of specialty capabilities (such as heater development) which exist within the industry, rather than building up new efforts inhouse.

3.5.3 Prior Program Hardware Usage - Many individual hardware items used on Skylab were chosen because their design had already been proven on other programs. Some items were actually removed from museum articles, refurbished and flown. Although some design changes were found to be necessary to adapt the original design for Skylab, and requalification was necessary in most cases, it was found that the majority of these items proved to be quite adequate.

Examples are: The Saturn S-IVB stage basic structure was used for the OWS, Saturn ten-watt transmitters, ordnance ignition systems; Gemini tape recorders, hatch, CO_2 and O_2 sensors, two-watt transmitters, PCM programmer, multiplexers, many instrumentation sensors, heat exchangers, coolant pumps, switches, circuit breakers, relays, and digital command system; Apollo post-landing ventilation fans and docking system.

A clear understanding should be maintained of the basis for projecting lifetimes for refurbished items: there may be more than one level of refurbishment possible for a given item, justifying resetting the clock to zero or not, depending on the specifics.

3.5.4 Joint Observing Programs - Until fairly late in the development of Skylab, the five ATM Principal Investigators (PIs) planned to operate their experiments according to their own individual observing program. This approach had the following shortcomings:

- Non-optimum use of allocated ATM flight plan time.

- Very difficult if not impossible to correlate data between experiments.
- Inability to use all ATM film.
- Each individual observing program was written without proper consideration for the objective of other observing programs.
- PIs discovered that many scientific gaps would exist in the data if this approach was used.

At that time, they began working toward a joint observing program with the following objectives:

- Define a set of problems to be solved on ATM as an observatory, not as six individual experiments.
- Write the joint observing program such that all experiments are working on the same problem at the same time.
- Define the joint observing programs so that maximum utilization of ground based observatories can be made.
- In constructing the joint programs, provide maximum capability for the PI to make real time changes in order to optimize his data return.

This approach was achieved and has been proven through highly efficient and successful orbital operations.

3.5.5 Mission Support to Experiments - In some cases the principle investigator's knowledge of the experiment hardware design was inadequate to provide the necessary mission support, especially in contingency situations. If such essential knowledge resides other than with the principle investigator (e.g., with the experiment developer or manufacturer), measures should be taken to ensure its availability during operations.

3.5.6 Award Fee Contracts - Milestones for which performance is evaluated should span key program events, such as CDR, DCR, FRR, launch, etc. The period of time covered by a specific milestone should not end when that event occurs, but it should include adequate time for full accomplishment of the event.

3.5.7 Contracting for Scientific Experiments - The qualifications of a Principal Investigator for managing a hardware development and procurement contract should be carefully examined. Also to be weighed is the ability of the Government to control changes in activities under direct contract to another party.