NASA TECHNICAL MEMORANDUM

NASA TM X-73073

NASA TM X-73073

SKYLAB LESSONS LEARNED AS APPLICABLE TO A LARGE SPACE STATION

William C. Schneider
Office Of Space Flight
Headquarters NASA

April 1976
Report On Period 1967-1974

National Aeronautics And
Space Administration
Washington, D. C. 20546

INDEX

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TMX-73073		
4. Title and Subtitle Skylab Lessons Learned As Applicable To A Large Space Station		5. Report Date April 1976
		6. Performing Organization Code
7. Author(s) William C. Schneider		8. Performing Organization Report No.
9. Performing Organization Name and Address NASA Headquarters, Office of Space Flight		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum (1967-1974)
		14. Sponsoring Agency Code

15. Supplementary Notes

Report prepared for variety of purposes; History records; reference; training; dissertation for Doctoral Thesis at Catholic University of America.

16. Abstract

The space program in the past decade has given mankind a third dimension in which solutions to many world's problems may be sought. Weather, communications, and earth resources, satellites have demonstrated the benefits of the exploitation of space; Projects Mercury, Gemini, and Apollo have shown no restriction on man's use of space; and Project Skylab has shown that a multipurpose manned space station, is a useful and practical means of utilizing this relatively new capability. We can assume that resources will eventually be made available for the building of a permanent earth orbiting space station.

A permanent space station will require the consolidation of efforts and knowledge of a diverse group of engineering, scientific, and technical talents. It will be a challenge to design, build, and manage. Skylab, the world's first experimental space station, was a significant engineering and fabrication task, involving a nationwide distribution of organizations.

This report records some of the lessons learned during Skylab development.

The approach taken in this report is to list lessons which could have wide application in development of a large space station. The lessons are amplified and explained in light of the background and experiences of the Skylab development.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Skylab Lessons Learned Space Station Program Management Management	Unclassified - unlimited STAR Category 81

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22151

SKYLAB LESSONS LEARNED AS APPLICABLE TO A LARGE SPACE STATION

by William C. Schneider

National Aeronautics and Space Administration

SUMMARY

The Skylab Program was established as a precursor space station with the multiple objectives of proving the worth of a permanent space station, of exploring the physiological limits of man's endurance in space flight, and conducting a series of space oriented experiments. The program has been successfully concluded and, in addition to the above, has left a legacy of lessons, of a technical and managerial nature, to be followed by the developers of the next space station. It is the purpose of this report to record some of the lessons from Skylab to be added to the previous reports as well as to document the observations of the Program Director.

The technical and scientific results of the Skylab experiments have been documented and published by the individual investigators as a part of their experiments. From the point of view of the value of a manned space station in the achievement of scientific objectives, numerous examples are chronicled in those reports. In summary, the value of a continually manned space station has been shown in the solar observations (where fine-grained geometric and color details were observed when none had been anticipated), in the medical experiments (where subtle additions to the experiments added to the scientific results), in the ground observation programs (where the trained observers detected phenomena not predicted), and in the general conduct of the experiments where the trained operator was able to correct, adapt, and change the experiment procedures and, thus, improve the scientific output.

The unique capabilities of man to repair and fix equipment and experiments is well known and in Skylab proven to be true in space as well as on the Earth. The primary advantage of a manned space station as compared with an automated spacecraft is the ability to respond to previously unforeseen anomalies. The ability of the manned operator to respond to unprogrammed events was clearly demonstrated during the 9-month operating period of Skylab. Beginning with the difficult activities associated with the deployment of the thermal shield and the freeing of the solar panel, and continuing on through the repair of the coolant system, the Skylab crews repeatedly demonstrated that the ability of man to repair, fix, and correct the flight systems was invaluable and essential.

The value of man in space exploration was clearly demonstrated.

The inherent value of a long-duration space observation platform is almost axiomatic and has been demonstrated repeatedly in the automated satellite programs. Skylab reinforced that conclusion and added the dimension of manned flexibility. The presence of the trained astronauts gave the ground-based scientists the freedom of changing their desired observation program to respond to earlier results. Unmanned programs are limited in the ability to reprogram events by the size and capabilities of the spacecraft computer. Having a man onboard permits a flexibility of operation comparable to that available to an investigator in a ground-based laboratory.

The medical experiments on Skylab were designed to produce data which would permit the detailed analysis of the response of the body functions to long-duration flight. All of the experiments performed properly and the data has been analyzed. It is beyond the scope of this paper to report the details of the medical experiments, but is appropriate to record that, for the 84 days of Skylab, no physiological limitation to manned flight was found.

A manned space station has no serious physiological limitation, although obviously the presence of man must be taken into account in the system designs.

The development of a space station is a complex problem which requires a variety of technical and managerial expertise. Skylab pointed the way in a variety of areas: habitability results point toward the correct designs; the control moment gyros proved that this type of attitude control is practical and possible; the integrated solar power systems demonstrated the principles needed for a large, solar-powered electrical system, and the principles of the passive/active thermal control system have been shown; the principles of management for a complex and far-reaching development program have been evolved and demonstrated. This paper intends to record and explain some of these technical and managerial lessons.

In summary, Skylab has proven that a long-duration, manned space station is a practical and desirable step in space exploration. The experiences and lessons of Skylab have pointed the way to design, develop, and manage a large space station project.

INTRODUCTION

A. Purpose and Scope of Paper

The development activities of a major space project are generally hectic, filled with crises and trauma, and rapidly paced. The records left behind for follow-on programs tend to be factual reports (i.e., References 1, 2, 3, 4, 5, 6, and 7), reports of accomplishments (i.e., References 8, 9, and 10), or results of investigations (i.e., Reference 11). The files are generally filled with the records of the day-to-day activities. Little or no time is set aside for analysis and reflection on the lessons which were learned (frequently the hard way). Such lessons are generally confined to personal experiences and are used by the individuals involved as they move on to the next project.

Skylab was destined to be no exception. However, near the conclusion of the program the Program Director recognized that since no follow-on space station projects were planned in the near future, the unique experiences of this development might never be passed on to future generation developers. Consequently, a series of "Lessons Learned" documents were requested and developed. These documents (References 12, 13, 14, 15, and 16) represent the view of the development engineers. This paper is an attempt to summarize and record the major program development lessons learned by the Program Director, and as such, represents his personal views. Some of the experiences mentioned in References 1 through 16 may be repeated herein, if similar lessons are applicable. In particular, many of those included in Reference 13 were those of the Director, although most of the lessons contained here are recorded for the first time.

These experiences, while primarily aimed at lessons applicable to space station development, should have a wider application in the development of many large, complex projects.

B. General Description

The Skylab (Figure 1) was the Free World's first experimental space station preceded only by a far less sophisticated space station, also experimental in nature, the Salyut of the Soviet Union. Both vehicles were similar in many respects--both contained working areas, the experiment descriptions were similar, both were revisited. However, the space stations were dissimilar in size, Skylab containing

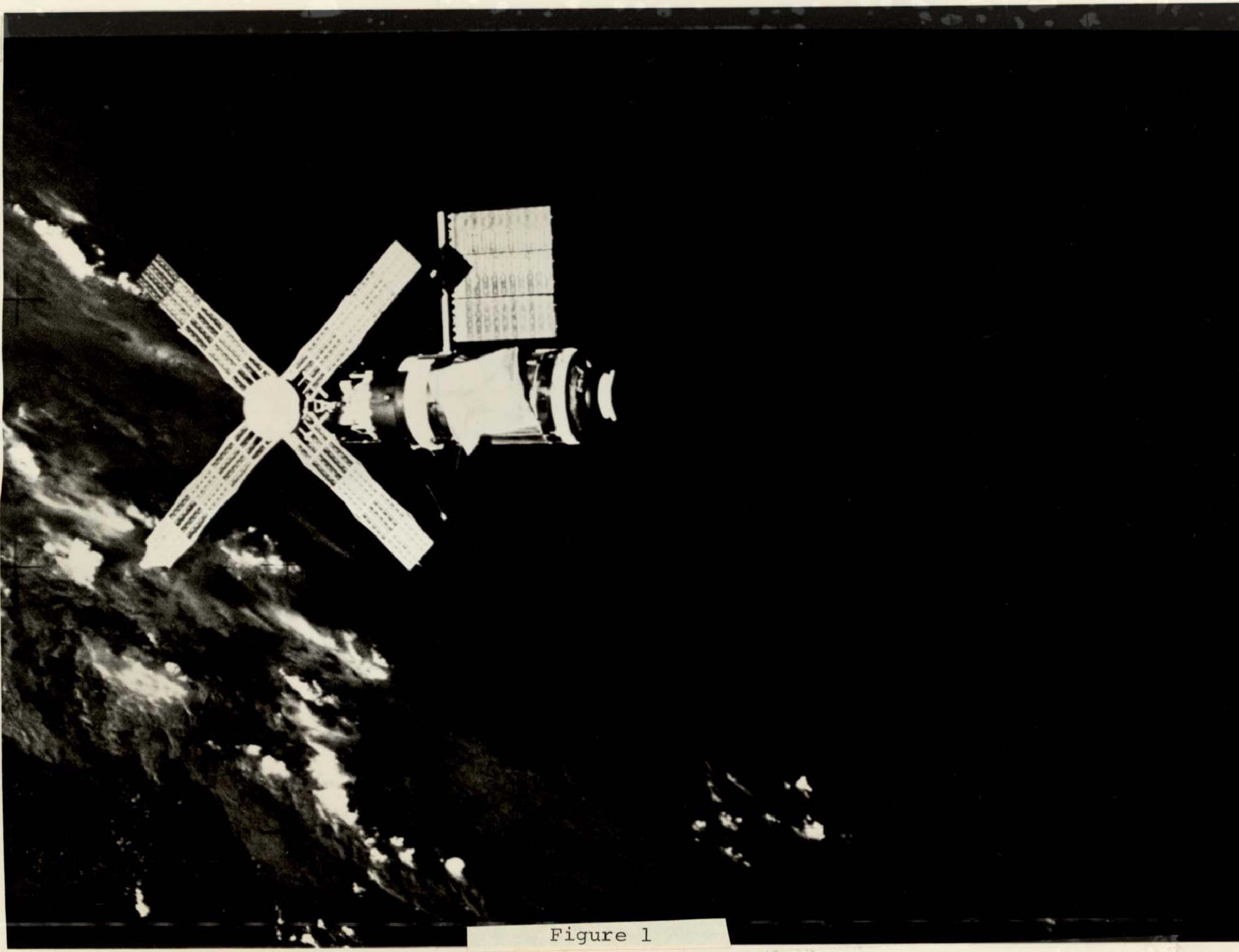


Figure 1

SKYLAB SILHOUETTED AGAINST EARTH, DARK SKY, AS VIEWED FROM COMMAND/SERVICE MODULE

11,300 cubic feet and Salyut 3,500 cubic feet. Salyut apparently has a propulsion system, whereas Skylab did not. The maximum mission duration for Salyut was 26 days, whereas Skylab extended manned space experience to 84 days. Skylab was stabilized by attitude thrusters. Skylab proved the utility of long-duration manned flight in low earth orbit.

A complete description of the Skylab hardware and facilities will be given later (Appendix I), but a brief outline is in order here to set the stage for what follows. The space station, Skylab (Figure 2), consisted of several modules, each with a specific function (at least originally) and each manufactured by a different industrial organization. The largest segment, the orbital workshop (Figure 3), served as the main living area and contained eating, sleeping, and waste management facilities. In addition, the workshop contained the medical experiment area and storage of several other experiments. Attached to this section was the section known as the Airlock Module (Figure 4). This section served as the "engine room," with the controls for the electrical power and environmental control systems located here. It also contained the hatch for the flight crews to egress the space station in orbit for extravehicular activities, hence the name, Airlock. Connected to the Airlock Module was the Multiple Docking Adapter (MDA) (Figure 5), which contained the docking mechanism for accommodating the repeated visits of the ferry module (the Apollo Command and Service Module), as well as the auxiliary docking mechanism needed for potential rescue missions. The MDA also contained the majority of the earth resource experiments as well as the control panels for the solar observation experiments. The final module which contained these solar instruments was designated the Apollo Telescope Mount (ATM) (Figure 6). In orbit the ATM was solar oriented with its axis perpendicular to the major axis of the space station. (During the launch phase, the ATM was oriented along the major axis and was covered, along with MDA and the Airlock, by a protective shroud (Figure 7).)

The space station, that is the workshop, A/L, MDA, ATM, all supporting equipment, all consumables and experiments, was placed into orbit using the first two stages of the Saturn V rocket (Figure 8). The launch was from Pad A, Complex 39, Kennedy Space Center, Florida, on May 14, 1973, at 17:30 GMT (Greenwich Mean Time).

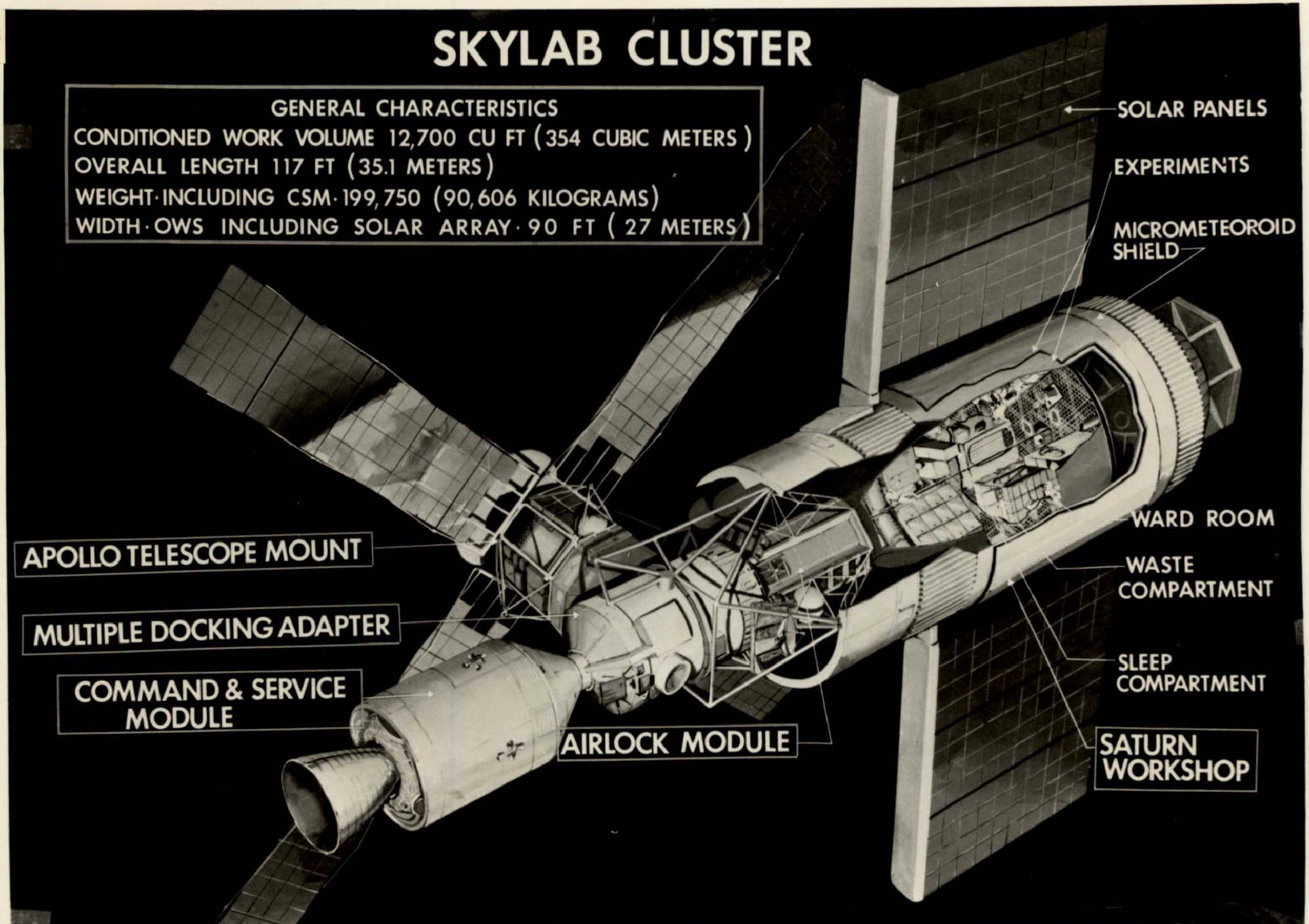

SKYLAB CLUSTER
GENERAL CHARACTERISTICS
CONDITIONED WORK VOLUME 12,700 CU FT (354 CUBIC METERS)
OVERALL LENGTH 117 FT (35.1 METERS)
WEIGHT·INCLUDING CSM·199,750 (90,606 KILOGRAMS)
WIDTH·OWS INCLUDING SOLAR ARRAY·90 FT (27 METERS)
SOLAR PANELS
EXPERIMENTS
MICROMETEOROID SHIELD
WARD ROOM
WASTE COMPARTMENT
SLEEP COMPARTMENT
SATURN WORKSHOP
APOLLO TELESCOPE MOUNT
MULTIPLE DOCKING ADAPTER
COMMAND & SERVICE MODULE
AIRLOCK MODULE
MSFC·70·IND·7200·062J

Figure 2

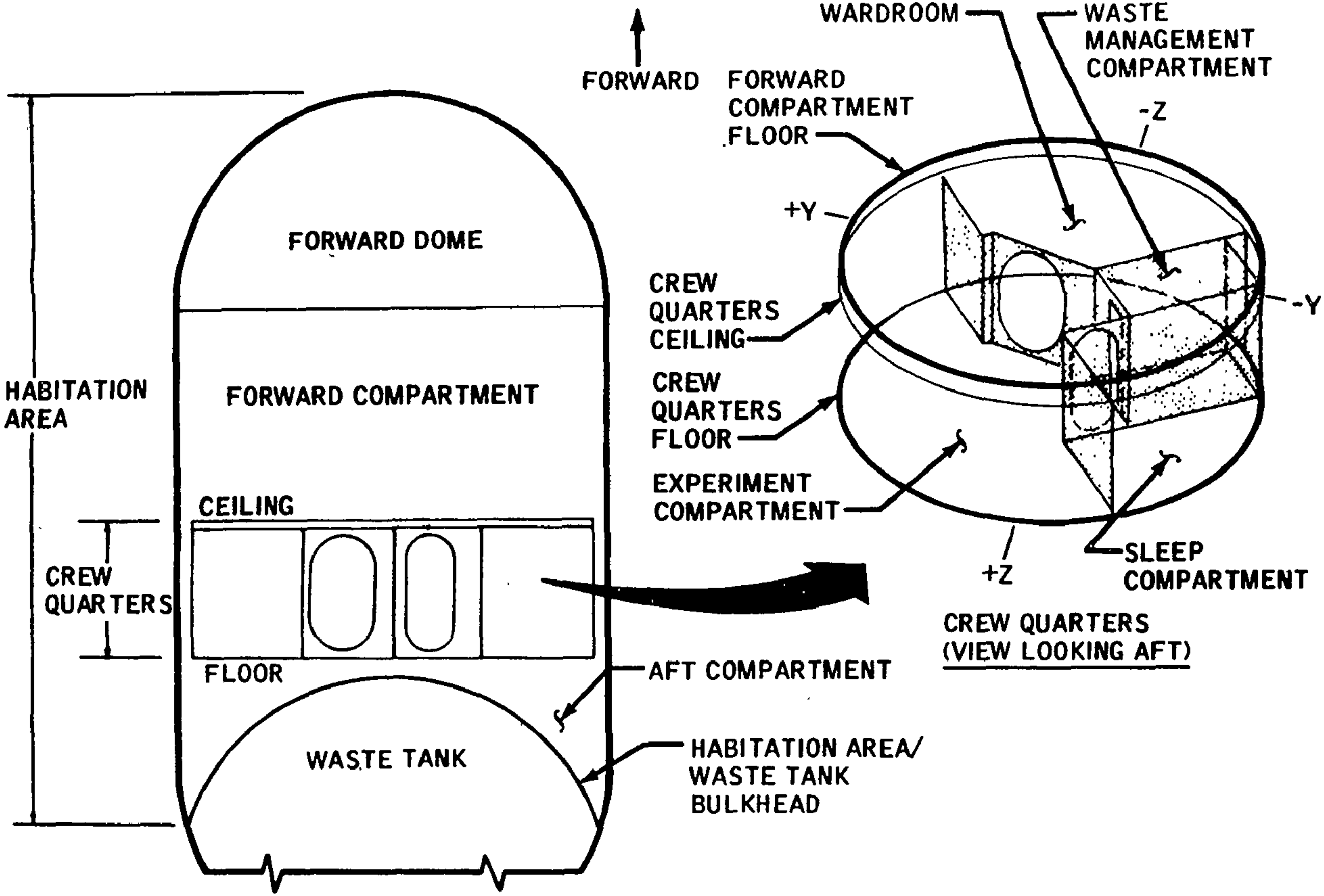


FIGURE 3 **OWS Habitation Area**

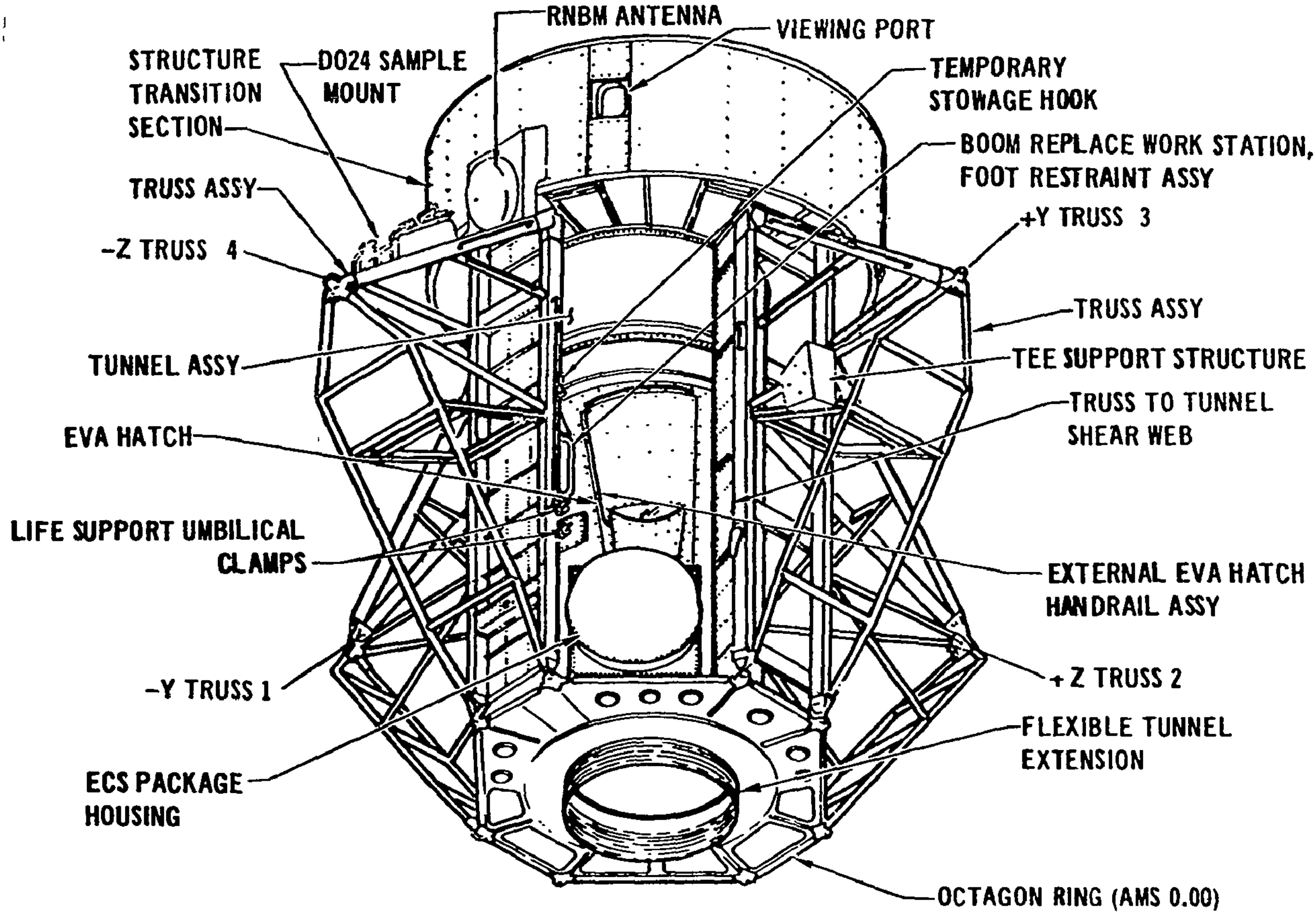


FIGURE 4 **Airlock Module**

- PROVIDES CSM DOCKING CAPABILITY
- CREW WORK AREA
- PROVISIONS FOR EXPERIMENTS
- CONTAINS THE ATM C&D AND EREP PANELS
- ECS RADIATOR MOUNTS
- STOWAGE

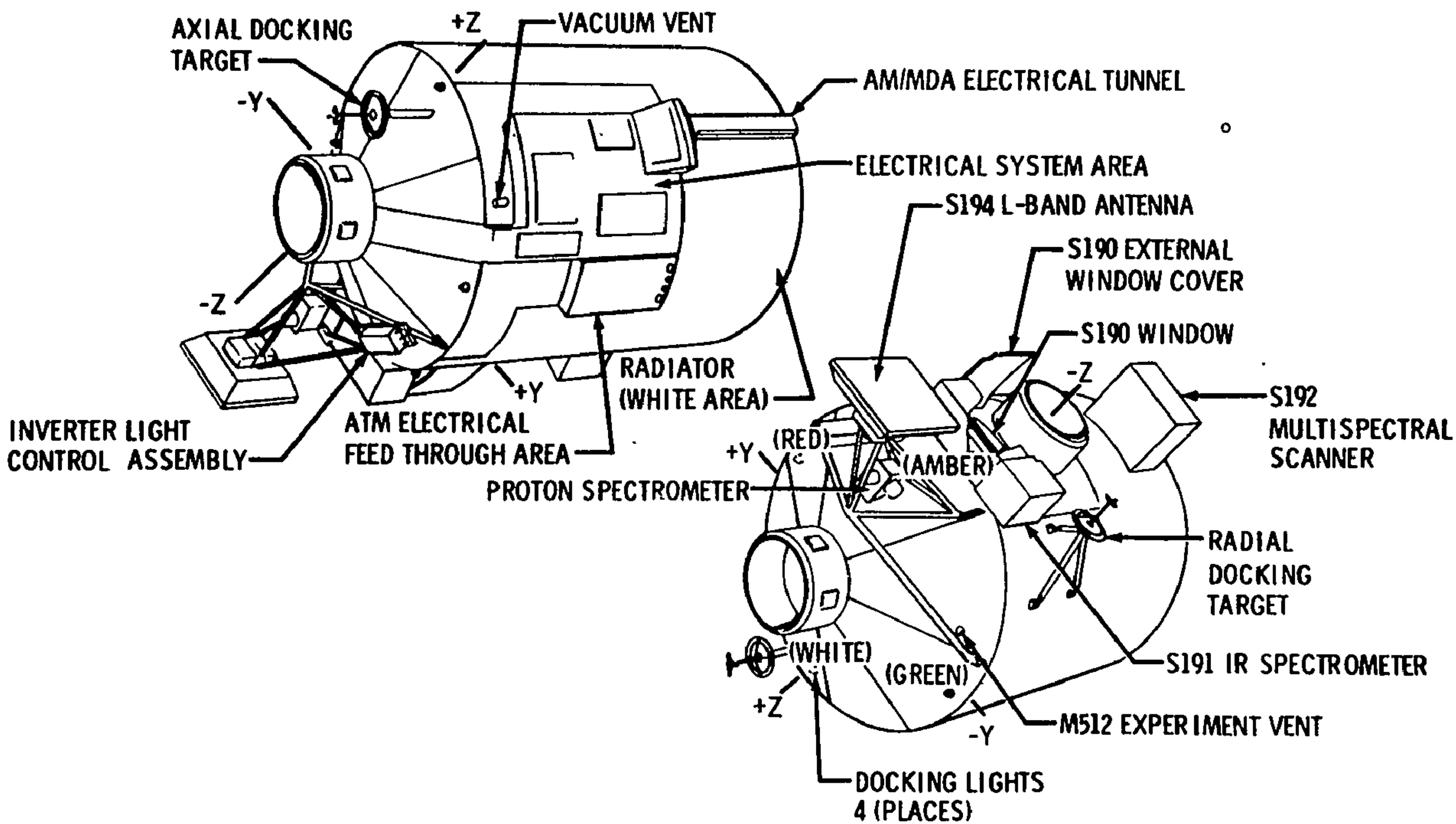


FIGURE 5 **Multiple Docking Adapter**

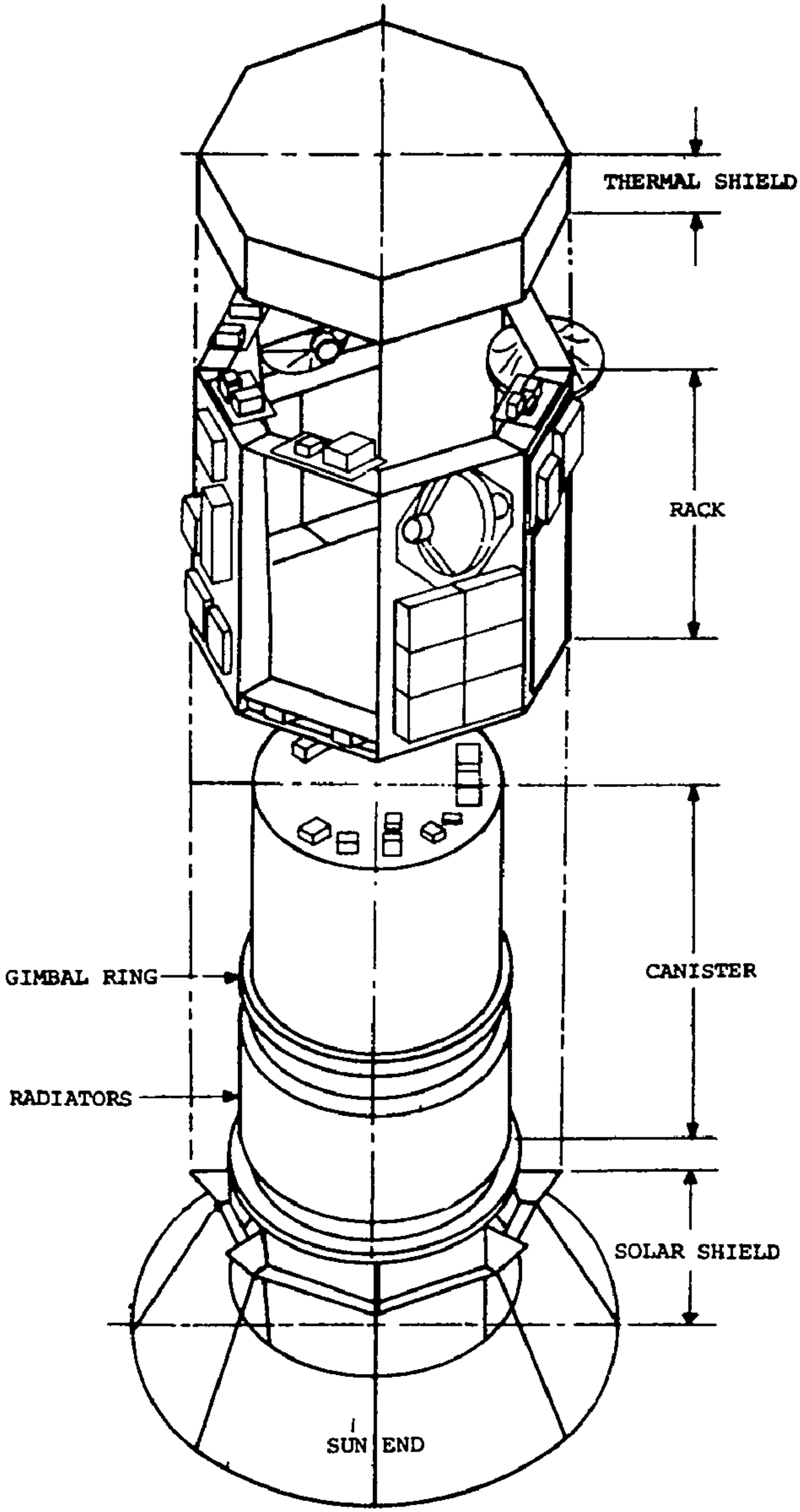
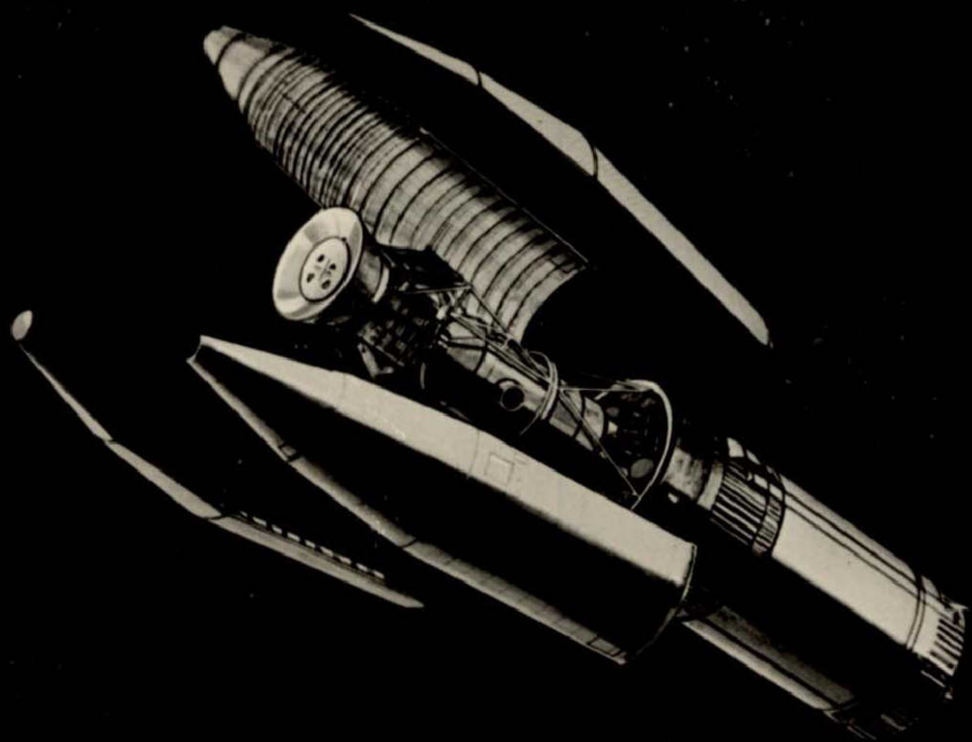


FIGURE 6 **ATM Major Structural Components**

PAYLOAD SHROUD



CHARACTERISTICS

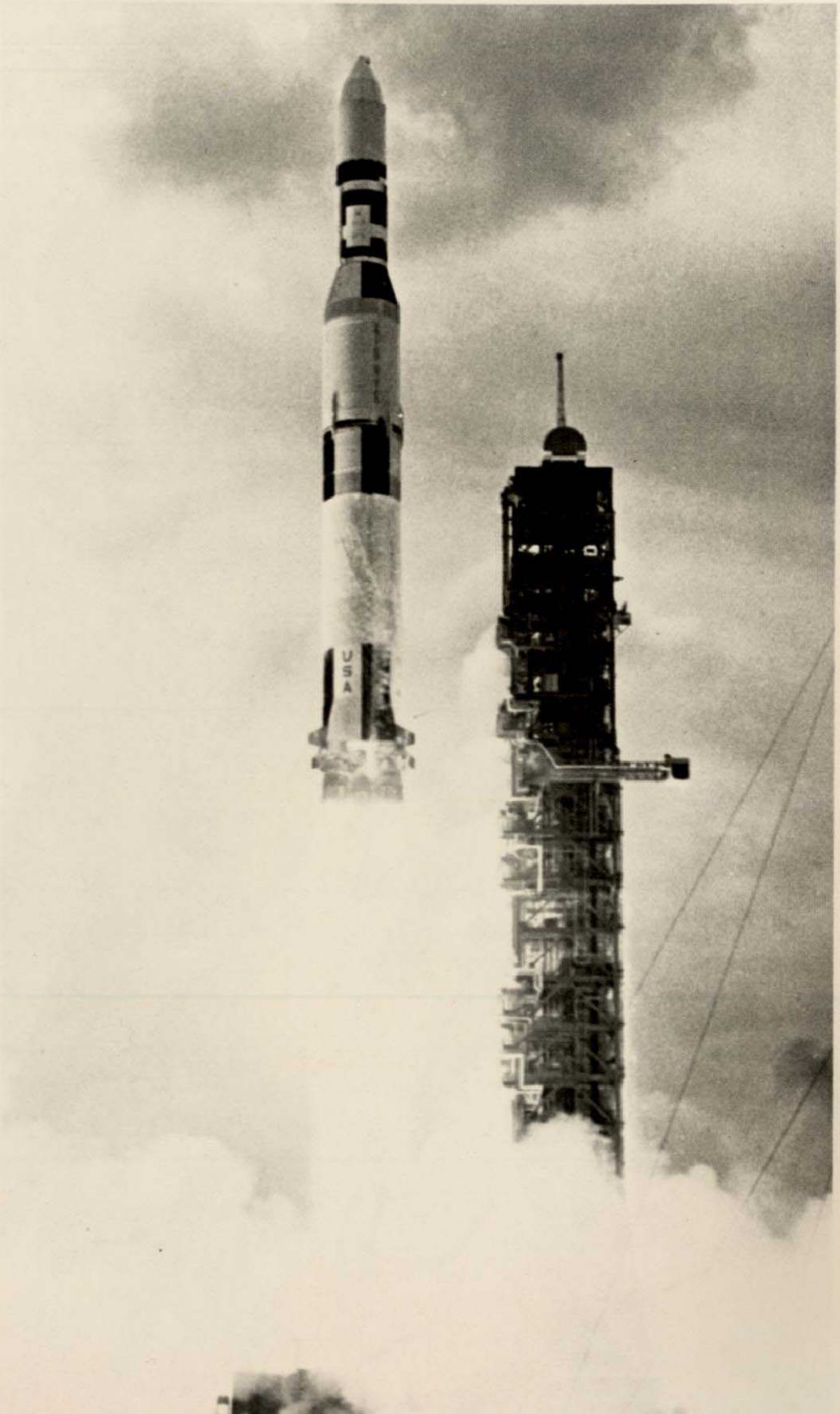
- WEIGHT
  26,000 LBS.
- DIAMETER (MAXIMUM)
  21 FT. 8 IN.
- LENGTH (OVERALL)
  55 FT. 9 IN.

OTHER

JETTISONED IN FOUR SECTIONS AT 5 MIN. AFTER ORBITAL INSERTION

NASA HQ ML71-5131
2-18-71

Figure 7



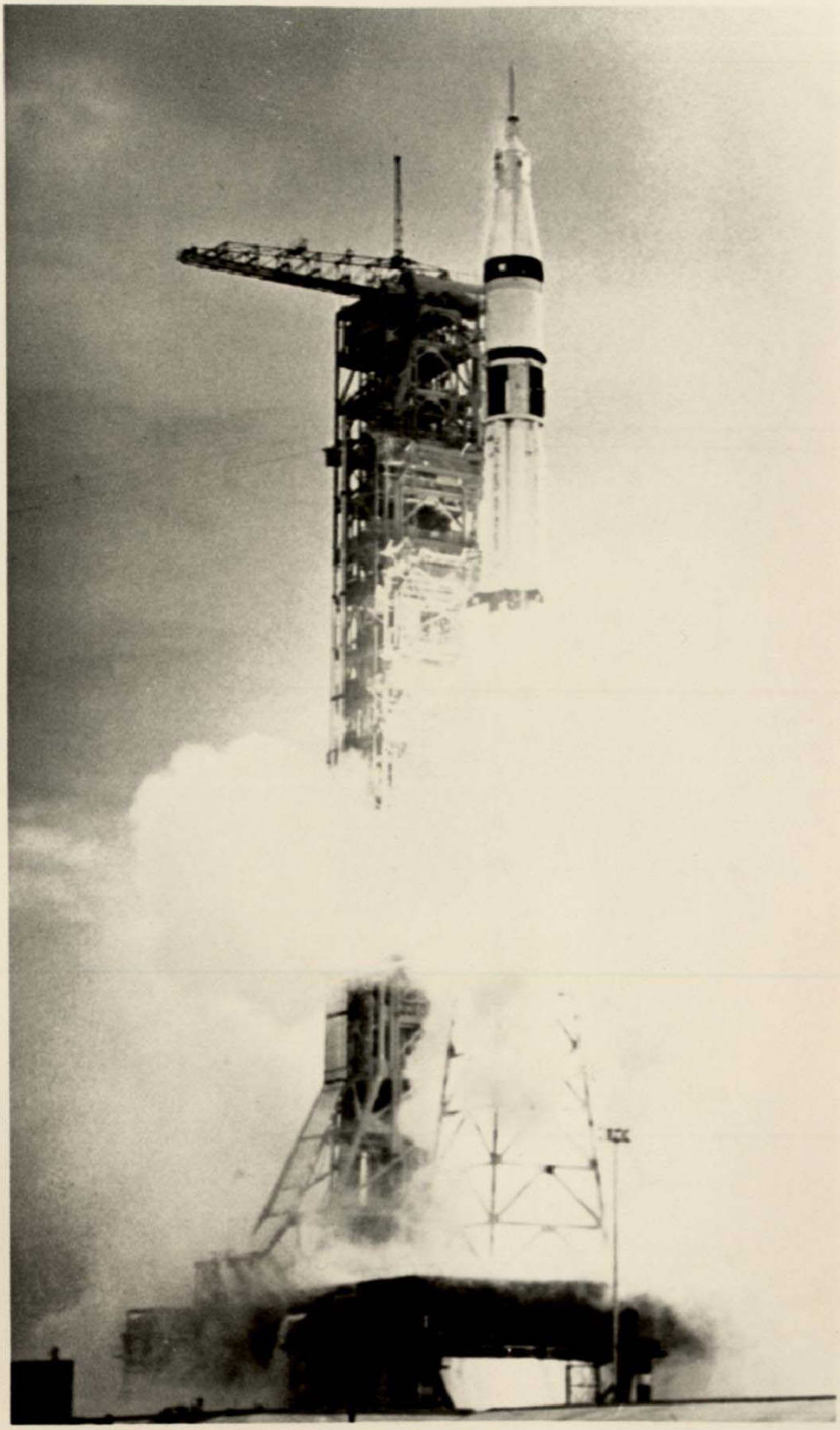
SKYLAB 1 LAUNCH

FIGURE 8

Skylab was manned for three periods by separate three-man crews. The periods of occupancy were 28, 59, and 84 days, all of which occurred during a 9-month active life of the spacecraft. The crews were launched in a modified Apollo Command and Service Module (CSM) using a Saturn IB launch vehicle (Figure 9). The Saturn IB, a two-stage booster, was launched from Pad B of Complex 39. Recovery of the Command Module, the crews, and the returned experimental data was in the Pacific Ocean in an area west of San Diego, California. Launch of the first manned mission was at 13:00 GMT on May 25, the second launch was at 11:10:50 GMT on July 28, and the final manned launch was at 14:01:23 GMT on November 16, 1973.

The achievements of Skylab are well documented and, when viewed in retrospect, are noteworthy and significant. With respect to the statistics, Table I lists the achievements by experiment group. A total of 69 experiments were planned preflight, and of these, 66 were performed during the missions. Four experiments were added during the life of Skylab. In addition, 20 detailed test objectives (DTO's) were performed, as well as 25 student investigations and 20 science demonstrations. A total of 238,600 feet of magnetic tape and 46,146 frames of film were used to record the results of the earth resources experiments. One hundred and seventy-five thousand, forty-seven frames of film were used for data recording for the solar experiments.

The length of the manned periods of Skylab, 28, 59, and 84 days, was selected to investigate the effects of the space environment on the physical and psychological well-being of man. Previous long-duration manned flight, the 14-day Gemini VII flight, showed that the proposed 14-day duration of the Apollo lunar flights posed no problem for the crew, but medical data from this mission and from later Apollo missions gave confusing indications when extrapolated to very long missions. The Skylab missions, with the step-by-step increase in duration, were planned to give evidence of any physical limitation of man when exposed to zero gravity. (This paper will not cover the results of the experiments, however, it is worthy to note that no serious physical limitation on manned missions was found through the 84-day missions.) Not only were the crew examined soon after the completion of a flight, but also for the first time, through the medical experiments, the behaviors of the body systems were monitored at regular intervals throughout the missions.



SKYLAB 2 LAUNCH

FIGURE 9

TABLE 1 - Experiment Summary

Experiment group	Manhours				Number of investigations		
	Crew 1	Crew 2	Crew 3	Total	Planned	Actual	Percent deviation
Solar physics	117.2	305.1	519.0	941.3	880++	941++	7.1
Astrophysics	36.6	103.8	133.8	274.2	168	345	105
Earth observation	71.4	223.5	274.5	569.4	62	99	60
Life science	145.3	312.5	366.7	824.5	701	922	32
Engineering and technology	12.1	117.4	83.0	212.5	264	245	-3.4
Materials science and manufacturing in space	5.9	8.4	15.4	29.7	10	32	220
Student	3.7	10.8	14.8	29.3	44	52	18
Totals	392.2	1081.5	1407.2	2880.9	++Manhours		
*Film, frames	28,739	24,942	73,366	127,047			
**Film, frames	9,846	16,800	19,400	46,046			
Magnetic tape, feet	45,000	93,600	100,000	238,600			

The technology required to accomplish Skylab was also a significant legacy to future designers. Very few critical systems represented significant advances in the technological state-of-the-art (notable among these were the control moment gyros which stabilized the workshop). However, many critical systems were unique simply because of their size and reliability requirements. Others, such as the waste management system, represent innovative and imaginative applications of relatively simple technology.

The third achievement of Skylab is in the area of technical management of diversified groups of engineers, scientists, and technicians into an effective team--a team which responded to the challenge and created the success of Skylab in the face of seeming disaster.

At about 1 minute after liftoff, the micrometeorite shield was torn from the workshop. This in turn caused one workshop solar array to be ripped off and the other array to be jammed in the stowed position (Figure 10). As a result, the underpowered, overheated workshop (the meteoroid shield served also as a part of the thermal system) seemed destined to be a $2.4 billion hulk in space. The Skylab operations team was able to stave off total disaster for 10 days while the development team conceived, designed, built, tested, and launched the equipment needed to correct the problems. (Further details follow under Mission Summary.) The outstanding performance of the flight crew in these critical operations is well known and well documented. This ability to respond quickly by the ground and flight teams was repeated several times throughout the mission and saved the Skylab workshop several times.

Skylab was not completed without a considerable investment in both costs and resources. A total of over $2.4 billion dollars was appropriated by Congress for Skylab over a 12-year period.

The first activity leading directly to Skylab began in 1961 with studies of the usage of Apollo hardware and the final activity is expected in 1977/1978 with the completion of the analysis of the Skylab experiment data. The efforts required to develop and operate Skylab included major efforts by three of the NASA Centers, the George C. Marshall Space Flight Center, the Lyndon B. Johnson Space Center, and the John F. Kennedy Space Center. In addition, corollary activities were located at the Langley Research Center, the Ames Research Center, the Goddard Space Flight Center, the Wallops Flight Center, and the Lewis Research Center. The direction of this national activity was centered at the Office of Manned Space Flight, NASA Headquarters, Washington, DC.

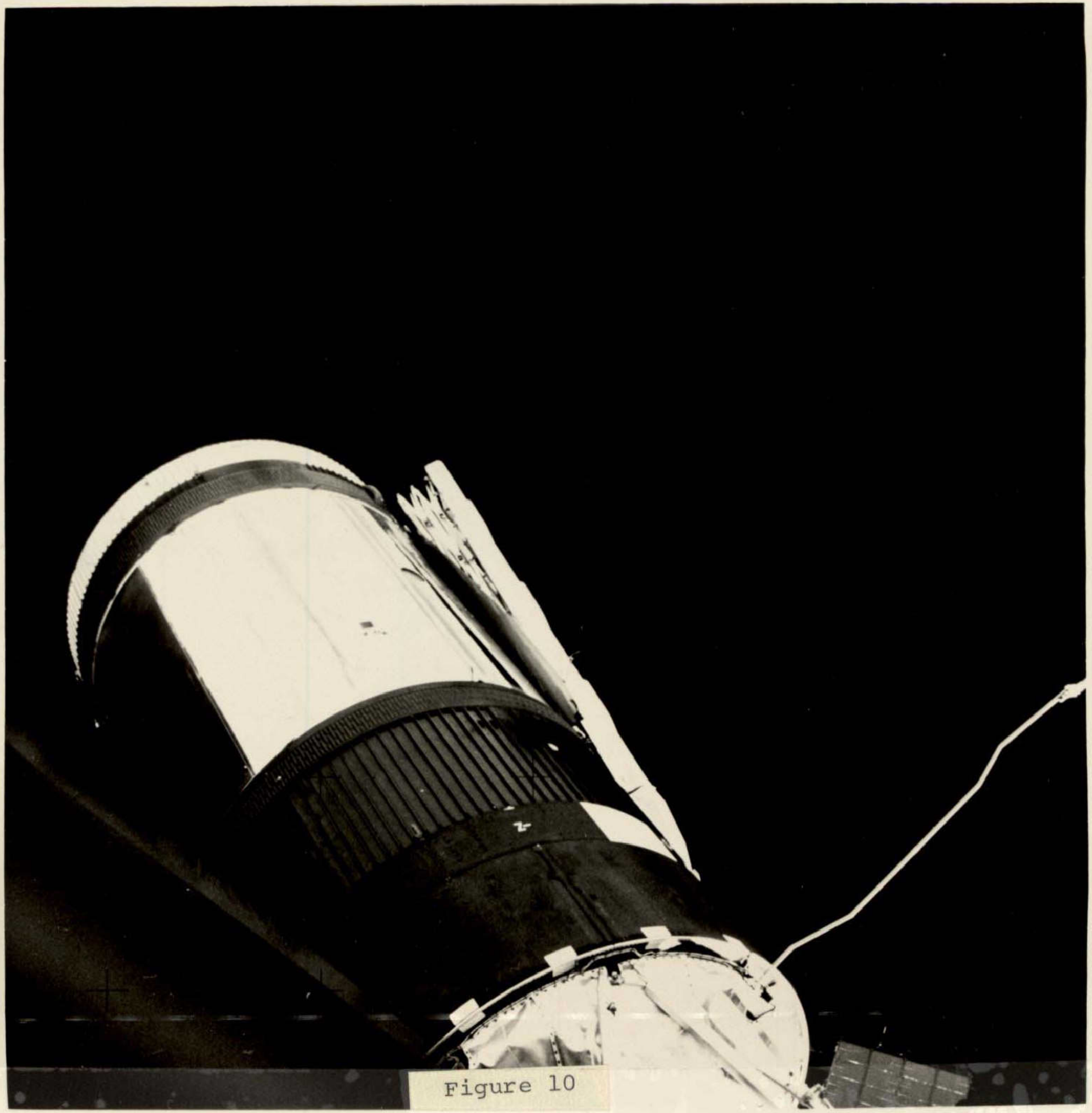


Figure 10

Major development activity was carried on at industrial plants located throughout the United States. Prime contracts were executed at the McDonnell-Douglas Astronautics Company at Huntington Beach, California, for the Orbiting Workshop and at St. Louis, Missouri, for the Airlock Module; the Multiple Docking Adapter was developed by the Martin-Marietta Corporation, Denver Division. The Saturn V launch vehicle was a product of The Boeing Corporation, Michoud, Louisiana (for the first stage SIC), the Rockwell International Corporation, Seal Beach, California (for the SII second stage), and the International Business Machine Corporation, Huntsville, Alabama, (for the Instrument Unit); the Rockwell International Corporation, Downey, California, was responsible for the Command and Service Module. The Chrysler Corporation, Michoud, Louisiana, produced the first stage of the Saturn IB; McDonnell-Douglas, Huntington Beach, California, also produced the S-IVB stage, the second stage of the Saturn IB manned vehicle.

In addition to these prime contractors, other major activity was also conducted at the Ball Brothers Corporation, Boulder, Colorado; General Electric Corporation, Valley Forge, Pennsylvania; the Bendix Corporation, Teterboro, New Jersey; Honeywell Corporation, Lexington, Massachusetts; the Navel Research Laboratory, Washington, DC; the High Altitude Observatory, Boulder, Colorado; Harvard College Observatory, Cambridge, Massachusetts; the Dudley Observatory, Albany, New York; and Westinghouse Electric Corporation, Pittsburg, Pennsylvania. A complete list of all Skylab contracts can be found in Reference 17.

Skylab was designed and operated as an experimental space station and as such, a number of specific scientific, application, and medical experiments were performed (Table II and Appendix II). It is not the intent of this dissertation to report on the results of these investigations in any but a summary manner. The detailed results of the investigations are being reported by the Principal Investigators in a variety of scientific journals and meetings. Summaries of the results have been presented at the Skylab Medical Symposium (Reference 18) held at the Johnson Medical Center, Houston, Texas; the Materials Processing Symposium (Reference 19), Marshall Space Flight Center, Huntsville, Alabama; the Comet Kohoutek Conference (Reference 20), MSFC; the Earth Resources Conference (Reference 21); and the Skylab Science Symposium, MSFC (Reference 22).

Table II - Skylab Experiment Complement

Life sciences*

M071	Mineral balance
M073	Bioassay of body fluids
M074	Specimen mass measurement
M078	Bone mineral measurement
M092	Lower body negative pressure
M093	Vectorcardiogram
M111	Cytogenic studies of the blood
M112	Man's immunity in vitro aspects
M113	Blood volume and red cell life span
M114	Red blood cell metabolism
M115	Special hematologic effect
M131	Human vestibular function
M133	Sleep monitoring
M151	Time and motion study
M171	Metabolic activity
M172	Body mass measurement
S015+	Effects of zero gravity on human cells
S071+	Circadian rhythm, pocket mice
S072+	Circadian rhythm, vinegar gnat

Solar physics

*S020	X-ray and ultraviolet solar photography
S052	White light coronagraph
S054	X-ray spectrograph
S055A	Ultraviolet scanning polychromator spectroheliometer
S056	X-ray telescope
S082A	Extreme ultraviolet spectroheliograph
S082B	Spectrograph and extreme ultraviolet monitor
-	Hydrogen-alpha

Earth observations*

S190A	Multispectral photographic facility
S190B	Earth terrain camera
S191	Infrared spectrometer
S192	Multispectral scanner
S193	Microwave radiometer, scatterometer, & altimeter
S194	L-band microwave radiometer

Astrophysics

S009	Nuclear emulsion
*S019	Ultraviolet stellar astronomy
*S063	Ultraviolet airglow horizon photography
S073	Gegenschein and zodiacal light
*S149	Particle collection
S150	Galactic X-ray mapping
S183	Ultraviolet panorama
S228	Transuranic cosmic rays
S230	Magnetospheric particle composition
S201	Cometary physics
S232	Barium Plasma Observations
S233	Comet Kohoutek Photography

Materials science and manufacturing in space

M512	Materials processing in space
M551	Metals melting
M552	Exothermic brazing
M553	Sphere forming
M518	Multipurpose electric furnace
M556	Vapor growth of II-VI compounds
M557	Immiscible alloy compositions
M558	Radioactive tracer diffusion
M559	Microsegregation in germanium
M560	Growth of spherical crystals
M561	Whisker-reinforced composites
M562	Indium antimonide crystals
M563	Mixed III-V crystal growth
M564	Metal and halide eutectics
M565	Silver grids melted in space
M566	Copper-aluminum eutectic
M479	Zero gravity flammability

*Johnson Space Center development responsibility

+Johnson Space Center integration responsibility

Table II - Skylab Experiment Complement (cont.)

Engineering and technology

*D008+	Radiation in spacecraft
D024	Thermal control coatings
M415	Thermal control coatings (IU)
M487	Habitability of crew quarters
*M509	Astronaut maneuvering equipment
*M516+	Crew activities and maintenance
T002	Manual navigation sightings
T003	Inflight aerosol analysis
T013	Crew vehicle disturbances
T020	Foot-controlled maneuvering unit
*T025	Coronagraph contamination measurements
T027	Contamination measurements
-	Proton spectrometer

Student investigations

ED11	Atmospheric attentuation of energy
ED12	Volcanic study
ED21	Libration clouds
ED22	Objects within Mercury's orbit
ED23	Quasars
ED24	X-ray stellar classes
ED25	X-rays from Jupiter
ED26	Ultraviolet emissions from pulsars
ED31	Bacteria and spores
ED32	In vitro immunology
ED33	Microorganisms in varying gravity
ED41	Motor sensory performance
ED51	Chick embryology
ED52	Web formation
ED61-62	Plant growth and plant phototropism
ED63	Cytoplasmic streaming
ED72	Capillary study
ED74	Mass measurement
ED75	Brownian motion
ED76	Neutron analysis
ED77	Universal gravity
ED78	Liquid motion

Science demonstrations

*SD1		Gravity gradient effects
*SD2		Magnetic torque
*SD4		Momentum effects
*SD5		Energy loss and angular momentum
*SD6		Bead chain
*SD7		Wave transmission reflection
*SD8		Wilberforce pendulum
*SD9		(Part I) Water drop
*SD9	(TV107)	(Part II) Fluid mechanics series
*SD10		Fish otolith
*SD11		Electrostatic effects
*SD12		Magnetic effects
*SD13		Magnetic electrostatic effects
*SD14		Airplane
SD15	(TV115)	Diffusion in liquids
SD16	(TV111)	Ice melting
SD17	(TV112)	Ice formation
SD18	(TV113)	Effervescence
SD19	(TV102)	Immiscible liquids
SD20	(TV101)	Liquid floating zone
SD21	(TV106)	Deposition of silver crystals
SD22	(TV103)	Liquid films
SD23	(TV116)	Lens formation
SD24	(TV114)	Acoustic positioning
SD28	(TV104)	Gyroscope
SD29	(TV118)	Cloud formation
SD30	(TV110)	Orbital mechanics
SD33	(TV105)	Rochelle salt growth
SD34	(TV108)	Neutron environment
SD35	(TV117)	Charged particle mobility

*Johnson Space Center development responsibility

+Johnson Space Center integration responsibility

C. Scope of Paper

The references and bibliography listed provided the documented results of the Skylab Program and form the foundation of this dissertation. However, this analysis is a result of the author's experiences as the Director of the Skylab Program. These experiences cover program conception, proceed through design, development, fabrication, test, and assembly, and continue through launch operations, flight operations, and finally, crew recovery.

(All aspects of the program planning and execution were encountered. Financial, schedule, and resource management problems, as might be expected, were part of the development. However, this paper will not attempt to cover financial and resource management except as is relevant in the area of program management.)

The analysis of the program lessons contained herein is that of the author, and the conclusions reached may or may not coincide with those of other individuals, either who have or have not been associated with Skylab. The conclusions do not necessarily represent those of NASA. This is not to imply that they are consciously different from any official position of NASA, but does mean that no attempt has been made to coordinate, integrate, or assimilate the conclusions and analysis with any other group or individuals. The discussion is, again, that of the author.

An attempt has been made to keep the conclusions general in nature and applicable to large technology programs in general. Certain of the conclusions are in themselves generally applicable to development programs of any scope. However, the conclusions should be applied on a selective basis when all development factors are included. That is to say, the size, cost, and scope of the activity will dictate the degree to which the conclusions should be applied. However, the conclusions expressed here should be directly and completely applicable to the development of a large permanent space station.

THE HISTORY OF SKYLAB

Skylab was an evolutionary program; that is, it did not spring forth as a fully developed concept. The initial concepts were studied under the Apollo Extension Systems Program, which was a systematic examination of uses of potentially excess Apollo hardware. By 1962 a concept of using an S-IV stage as a laboratory in space began to emerge.

Several distinct program steps led to the final configuration in 1969. The evolutionary development naturally resulted in some inefficiencies, compromises, and appendages, and many remained until the completion of the program. (An evolutionary development should be avoided since the resulting system is an inefficient compromise.)

The development program was a complicated one despite the fact there was little high-risk technology involved. Skylab technology was primarily current "state-of-the-art." However, the individual modules were complex, contained a large number of items, such as experiments, and, therefore, had many interfaces. At the same time, the interaction between the modules was relatively complex.

The development and test of space systems and missile systems has evolved over the years and has resulted in a systematic and logical sequence of testing which normally begins with verification and qualification at the lowest component level and proceeds through subelement, subsystem, system, module, and finally integrated testing. In this manner, the final vehicle, as it is on the launch pad, has had many hours of test to verify each element at its lowest level and to predict how it will behave in the presence of a myriad of other components. Off-nominal testing is employed to examine the behavior when the component is subjected to unusual stresses, and finally, qualification testing is designed to prove the system will operate properly in the expected flight environments.

The Skylab development did not completely ignore this evolution, but several innovative steps were adopted. Since many of the components had been used in previous programs (e.g., Gemini, Apollo, and ERTS), the verification cycle could be accomplished by examining the similarity of use and environment and only testing where engineering analysis and judgement indicated a need. Secondly, many components did not represent significant new applications and verification could be accomplished by analysis and calculations. Thirdly, where components were new and unique, but where sufficient design margin could be employed, testing was eliminated or reduced. And finally, where testing was considered essential, systems level qualification was considered in lieu of component qualification.

Because of the physical size of the modules, it was not possible to conduct all of the customary integrated tests in the Skylab development and verification cycle. Also, the various modules did not meet until delivery to the launch site (with the exception of the MDA and Airlock) since their development, fabrication, and checkout were accomplished at a number of locations throughout the Nation and, in some cases, the World. This necessitated a sequence of interface control verification methods and simulator tests to minimize the testing time at KSC. Improperly designed modules would have resulted in excessive delays in correcting physical, electric, and electronic mismatches. A careful examination of these verification sequences will give future developers an insight as to the effectiveness of the Skylab methods as well as an assessment of the potential of improved methods and techniques.

The multidisciplined set of experiments and activities planned and accomplished on the space station had a variety of often conflicting and interacting requirements. For example, the solar instruments required that the vehicle be oriented in a solar inertial attitude while the earth resource experiments needed to be pointed along the earth radial vector (termed Z local vertical). The demands for crew time, electrical power, and attitude peculiarities created an operational challenge which represented a unique step forward in flight planning and execution.

There is no date which can be said to mark the beginning of the Skylab Program. The evolution of the program can be traced back to the early days of the Apollo Program, although the ideas concerning space stations go back many years prior to that. Indeed, the ideas about space stations fill science fiction and were discussed by Dr. Oberth in 1923. However, the specific configurations which led to Skylab began in 1960 with early studies of other uses for Apollo hardware.

The Apollo Program was initiated by President Kennedy in 1960, and a versatile set of hardware was developed. The launch vehicles (Saturn IB and the larger Saturn V) provided the Nation with a heavy lift capability which was unparalleled. The Command and Service Module (CSM) was a highly maneuverable vehicle for manned use in both earth orbit as well as in translunar space. It has proven to be a versatile spacecraft. The Lunar Module was a more specialized craft which, while it was not utilized for other purposes, provided components and techniques which have been applied in a number of programs. Equally important, the resources applied to the lunar landing provided the Nation with a range of facilities which made possible a wide range of future programs. The Kennedy Space Center has provided the buildings and facilities needed to assemble, test, and launch the space ventures of the future. At the Johnson Space Center (initially the Manned Space Craft Center) the data handling and computing facilities of the mission control center, as well as the thermal vacuum chambers, crew trainers, simulators, centrifuges, and other testing devices, permitted the control of a variety of missions. The manufacturing facilities, testing complexes, and laboratories of the Marshall Space Flight Center were available to undertake whatever future tasks were identified. The Goddard Space Flight Center contributed the world-wide network of microwave, cable, land-line, and satellite links which permitted monitoring, control, and access to the space ventures. Equally important, the space and missile development programs of the Nation provided the industrial base, the manpower, tooling, technology, and skills needed for future space activities.

The most important requirement, the know-how, existed in a limited number of people, and it was the availability of those individuals which primarily dictated the timing of the program which began as the Apollo Extension System or AES. Studies were conducted under this early (1961) project which examined a wide variety of uses for the Apollo hardware. Quite early the Command and Service Module (CSM) was identified as being adaptable to a wide variety of earth orbiting missions for scientific purposes. One of the early missions identified was the use of the CSM as a carrier for a variety of solar telescopes which would be placed in orbit. The astronauts were to deploy and operate them in a study of the Sun and its activities. This cluster of solar telescopes was called the Apollo Telescope Mount or ATM. (For the remainder of Skylab, the instruments changed, the ATM configuration changed, the mode of operation changed, but the name remained.)

At the same time, other studies examined the use of the upper stage of the Apollo launch vehicles, the S-IVB, as a workshop. By 1965, the concept of the "spent stage" workshop had been formulated, while at the same time, the Gemini experience with extravehicular activity (EVA) indicated the need for the study of man in weightlessness. Thus, an early version of the workshop consisted of a scheme for permitting an astronaut to open a hatch in a "spent" S-IVB stage in orbit after it had performed its primary mission as a propulsive stage. There, the study of man in space could proceed under relatively controlled and confined conditions.

The problems of easily opening a hatch which would seal the liquid hydrogen tank of the stage while it was a propulsive unit led the Apollo Applications Program Office (formed in August 1965) to solicit the Douglas Aircraft Corporation proposal to develop an S-IVB Orbital Workshop involving an "in-orbit" conversion of the propulsive S-IVB into a shelter suitable for habitation.

Late in 1965 and early in 1966, studies showed that the spent stage concept needed services (i.e., power, consumables, etc.) which might be supplied by the proven Gemini components. Consequently, a fixed price contract was negotiated with the McDonnell Aircraft Corporation to produce an airlock for the S-IVB spent stage workshop. During that same period, the planning for the Apollo Applications Program firmed up, assignments were made, experiments were selected, and some hardware was fabricated.

By December 1965, the cluster concept was officially scheduled. The cluster concept (at that time) envisioned the launch of a "wet workshop" (i.e., the use of the S-IVB as a propulsive stage first) followed by a manned launch with a subsequent rendezvous, docking, and entry into the workshop for experimentation. Six months later, a second crew was to visit the workshop to be followed immediately by the launch of an unmanned modified Lunar Landing Module (LM) which was equipped with an ATM solar observatory.

Thus, the relatively simple concept of using the empty S-IVB stage to study the weightless maneuvering of an astronaut had evolved into a complex set of hardware developments and operational concepts. By this time, habitability requirements had been added (i.e., crews quarters, two floors, walls), environmental systems provided (i.e., a two-gas atmosphere, thermal systems, pressurization systems), as well as mission expendables (i.e., food and water). The operational concepts envisioned a series of timed launches and rendezvous, including two launches a day apart, one of which was to be an unmanned rendezvous. A total of 22 Saturn IB launches, and 15 Saturn V launches were called for by this schedule!

(At the completion of the Gemini Program in January 1967, Charles W. Mathews of the Johnson Space Center, the former manager of the Gemini Program, was named Director of the Apollo Applications Program (AAP), and the author was named Mission Director, having served in this capacity on Gemini.)

For the next 2 years there was a great deal of "activity" within the AAP, but little real progress. Many experiments were assigned and some hardware delivered. Roles and missions were clarified and altered, and contracts were negotiated and modified. However, because of the pressures of the Apollo lunar program, and because of the tragic Apollo fire at KSC which cost the lives of three astronauts, the AAP was continually rescheduled, replanned, and reassessed. A side effect of the AS-204 fire was to delay all follow-on programs in order to concentrate manpower and know-how on the announced national program, Apollo.

(In May 1968, Mr. Harold Luskin was appointed Director of AAP, succeeding Mr. Mathews. (The author had been reassigned as the Apollo Mission Director in the fall of 1967.))

By the end of 1969, the circumlunar mission, Apollo 8, was scheduled, the Saturn V rocket was proven ready for flight, the Apollo Command and Service Module had been tested, and an unmanned Lunar Module had flown. It was appropriate, therefore, to divert some additional effort on the follow-on Apollo Applications Program and full funding was released.

(Unfortunately, in November 1968, Mr. Luskin died suddenly before the program could get fully underway. The author was named to succeed Mr. Luskin at the conclusion of the Apollo 8 circumlunar mission in the first week in January 1969.)

At the same time, the remarkable success of the Saturn V launch vehicle permitted serious consideration of diverting Saturn V vehicles from Apollo to AAP. None of the original plans for Apollo had anticipated the rapid development of the Saturn V. Two unmanned launches, Apollo 5 and Apollo 6, were followed by the manned Apollo 8 circumlunar flight. As confidence rose in the prospect of achieving an early lunar landing, the possibility of an early use of a Saturn V for the Apollo Applications Program became a more attractive option.

Also, as the understanding of the "wet workshop" concept came more into focus, the difficulties involved in converting a spent rocket stage into an orbital workshop were beginning to be faced. It appeared as if a major share of the available crew time would be needed just to outfit the workshop. The enthusiasm for the "wet workshop" began to diminish and ground outfitting of the workshop began to receive serious study. Finally in May 1969, the Directors of the Johnson Space Center (then the Manned Spacecraft Center) and the Marshall Space Flight Center recommended that a Saturn V be used to launch a "dry workshop" into orbit. (A full record of the documentation of the Skylab history can be found in Reference 24.)

The Program Managers from the three affected NASA Centers, JSC, MSFC, and KSC, and the Program Director met in a closed door, weekend session at the Michoud Facility of NASA in New Orleans to develop the plan for implementing this Saturn V option. The agreed upon approach called for the launch of the workshop, fully outfitted and including the ATM, from KSC's Launch Complex 39 using the Saturn V. (This required minor changes to the Saturn to enable the two stages to propel the workshop into orbit.) The following day, three crewmen were to be sent to the workshop, using the smaller Saturn IB rocket, for a 28-day stay. In total, three manned visits were planned, launched on 90-day intervals for stays of 28, 56, and 56 days, respectively. (Fifty-six days was chosen for the last mission because preliminary analysis indicated that consumables, food, water, oxygen and nitrogen, would limit the duration. Also, the early medical opinion was that all physiological effects would have stabilized in that time.) The orbital attitude and inclination were set at about 240 nm and 50°. (The inclination was set at 50° since it would result in coverage of all the United States except Alaska and was within launch safety limits. The altitude was selected to minimize any disturbing effects the atmosphere might have on the attitude stability of the workshop. Higher altitudes were desired also to extend the orbital life of the workshops, but lower altitudes would result in less exposure of photographic film to the effects of radiation. The selected altitude was a good compromise.) In order to meet the scheduled launch date, it was decided to minimize changes from the basic "wet workshop" configuration. (From time to time, deviations were made from this fundamental configuration as the issues became clear. However, these changes were carefully weighed and analyzed for effect before they were adopted. For example, the workshop floor was inverted in order to facilitate manufacture and assembly. Changes of this type were made to increase the efficiency of the development program. Other major changes, such as the addition of the Earth Resources Experiment Package (EREP), were made to improve the capabilities of the program.)

(As these decision were being made, a major national decision was made by the Department of Defense when on June 10 the Manned Orbiting Laboratory (MOL) program was cancelled. This left the NASA program as the only national space station activity.)

The "dry workshop" concept was approved by the NASA Administrator, Dr. Thomas O. Paine, on July 18, 1969, just 2 days after the successful launch of the first lunar landing mission, Apollo 11. The program was finally fully funded, fully supported, and fully underway.

Detailed instructions were issued quickly, and the required contractual changes were negotiated with each of the program contractors. In December, a Cluster Systems Review was held at MSFC to review the various systems. As a typical example of how major changes were made in the program, the development of the configuration of the electrical power system is classic. The initial "no change" decision made when the dry configuration was first described, resulted in two separate electrical power systems: (1) The ATM system which consisted of the ATM solar panels, the ATM power conditioners, chargers, batteries, and distribution system. This power was used to support the ATM and its electrical/electronic components, including the attitude control system; (2) The workshop solar panels provided the energy for the workshop electrical system. The solar panels, power conditioners, charger, battery, and regulator provided the electricity for the workshop, airlock, and docking module. Each system provided approximately the same level of power (3-4 KW) into the independent systems. At the Cluster Systems Review, a formal question was posed challenging this design (the formal vehicle for question was the Review Item Discrepancy (RID), which raised the question, proposed corrective action, and required a written answer disposing of the issue). In this case, the proposed solution was to buss the two systems together to permit load sharing. The disposition of this RID was to request that the contractor propose a system for sharing the load. In due time, the proposal was made and analyzed by the NASA technical team. The agreed to solution was proposed to the Level III (module level) configuration control board, referred to the Level II (project level) board, and finally, referred to the Level I (program level) board. Here, the Program Director weighed the increased cost and complexity against the increased flexibility and probability of success and decided to implement the change. The contractual change implementation was initiated, and the design was incorporated.

In retrospect, this specific decision saved the Skylab Program. Without the ability to share the electrical power, the flight failure experienced on launch of Skylab 1 would have been fatal to the program (see Mission Summary).

Throughout the early days of the Apollo Applications Program, the program name, AAP, was felt to be uninspiring. During the early phases, it was necessary to identify the program with the use of the Apollo hardware and know-how. But, after the program had been accepted, it was desired that the program be uncoupled from the lunar program to give it a purpose and visibility of its own. Consequently, a list of appropriate titles was sent by the program to the NASA Project Designation Committee. They selected Skylab, and, thus, the Skylab Program was named. (The name Skylab had been initially proposed by Col. Donald Steelman, USAF, while on duty with NASA in the Apollo Applications Program Office.)

Early in 1970, the full assessment of the modifications to launch pad 34 became available. Pad 34 was old, required significant refurbishment, and needed contractor support for several years for the sole purpose of maintaining the launch complex. Consequently, a study was undertaken to design the modifications needed to Complex 39 to accommodate the smaller Saturn IB. By keeping the Command Module, Saturn S-IVB stage, and the Instrument Unit at the same level as for a Saturn V launch, modifications were minimized and resulted in the "milkstool" launch platform. Design studies showed a savings of $10 to $12 million by using this approach, and on May 15 it was officially adopted.

In the middle of 1970, a major change was made to the contractor responsibilities in Skylab. Originally, the MSFC role included the in-house development, fabrication, and test of major modules, without contractor support. The solar observatory, the docking module, the medical experiments, and several smaller elements were to be developed by the Center. As the program progressed, more and more equipment was placed in the docking module, and the development effort shifted from being predominantly structural engineering and fabrication to being predominantly system engineering and electrical design and fabrication. After a review of the in-house capability to do all of the jobs, it was properly decided to contract for the docking module. MSFC continued to build and supply the structure, but it was to be shipped to the Martin Marietta Corporation (MMC) in Denver for the cabling plumbing, and systems integration. (This represented a major change in the role of the Martin organization. Previously, MMC had an integration and analysis role with all three Centers and Headquarters. Now, MMC was to be responsible for more than paperwork. Their responsibility now included a key hardware element. In retrospect, the assignment of the tasks of an integration contractor to an organization without an in-line hardware responsibility was not correct. The integration contractor was not really considered, nor treated, as a full partner. With the assignment of the docking module to MMC, gave them an integration role and a key hardware role and put them in an advantageous position to carry out their integration assignment.)

Since the Skylab could remain in orbit for long periods of time and could sustain stranded crewmen, it became possible, for the first time, to consider developing a rescue capability. The Skylab Director of Reliability, Quality Assurance, and Safety, Mr. Haggai Cohen, proposed a study of the rescue potential. As a result, in December 1970 a crew rescue capability was base lined by the Program Director and approved by the NASA Administrator. This limited rescue capability assumed that the workshop was the "storm cellar" to which the crew would retreat in the event of a problem. (In the event of a workshop problem, the crew was expected to retreat to the Command Module and return to Earth. Multiple failures which incapacitated the CSM and the workshop could not be accommodated.) The rescue vehicle was to be the next vehicle in line (i.e., Skylab 3 was the rescue vehicle for the Skylab 2 crew). An additional two seats were to be added to the CSM if needed, and a two-man rescue crew would be launched to bring back the stranded three-man crew. The key requirement was, of course, that the emergency did not require an immediate rescue, since up to 48 days could be required from call-up to launch of the rescue craft.

The development of the NASA portion of the Fiscal Year 1972 budget made it clear that there were not enough funds available for the full Apollo and Skylab programs as planned. As a result, an integrated Apollo/Skylab schedule was developed which slowed down the Apollo schedule and, more importantly, shifted Skylab until after Apollo was completed. The net result was a decrease in the NASA requirements to within the President's budget, although the Skylab portion of the budget increased due to the delay of the launch from November 1972 to April 1973. (Officially, the launch was scheduled for mid-1973, but the internal schedule was April 30, 1973.) This was the last major schedule change for Skylab. Indeed, there was no schedule change until the spring of 1973 when a 2-week delay was announced.

For the next 2 years Skylab proceeded in the traditional manner for development programs. Detailed problems arose from day to day. Solutions were found and the program proceeded. Details of the development program can be found in the Skylab Preliminary Chronology (Reference 23). However, several unique items should be noted herein because of the unusual circumstances or importance.

In the spring of 1971, a review of the proposed medical experiments was held for the Deputy Administrator of NASA, Dr. George M. Low. He expressed concern about the lack of base line data with which to compare the in-orbit medical results. At his request, a 56-day medical test was scheduled in an altitude chamber at the Johnson Space Center. The test was completed on September 20, 1972. Astronauts Crippen, Thornton, and Bobko spent 56 days simulating the Skylab mission. They consumed Skylab-type food and water, breathed the Skylab atmosphere, and to a first approximation, duplicated the 56-day mission (without the effects of zero gravity). The test showed no change in the physiological characteristics of the crew, and left zero gravity as the primary variable for the flight tests.

The medical experiments continued in the next 2 years to be the most contentious element of the program. In June 1971, private medical conversations were base lined by the Program Director after an affirmative decision by the Administrator of NASA. While the ability of a patient to talk privately to his doctor may seem to be fundamental to the doctor/patient relationship, it was not at all accepted by the news media. There was continual friction throughout the program with the assertion by some that private conversations represented a censorship of the program. In truth, the program was conducted in the open, with full disclosure of all events.

Also in the area of medical experiments, the urine collection system design was in serious contention for almost a year. The original design called for urine to be sampled at each urination, the sample to be dried in orbit, returned to Earth, reconstituted, and analyzed. Unfortunately, while this process preserved the chemical constituents of the urine, the hormonal constituents were lost in the process. The original medical experiment objectives were not clear on whether the hormonal balance was a part of the protocol. However, since these hormones seemed to be key in describing many of the physiological (and psychological) responses to weightlessness, it was clear that all reasonable efforts should be made to recover these more complex constituents. After much analysis, discussion, and argument, it was concluded that since the basic system destroyed the hormones, a change in the collection system was needed. In July 1971, a centrifugal separator urine collection system was base lined. The new system required that each crewman's urine be pooled for 24 hours and a sample be taken, frozen, and be returned for analysis. (This problem was very difficult to solve because the desired solution crossed normal jurisdictional lines. The requirement was the responsibility of JSC, and the hardware implementation the responsibility of MSFC. The final solution, the centrifugal collector, was the result of research and development by JSC and was built by MSFC.)

The whole body shower issue in Skylab represents a case where the author, acting on personal feelings, guessed wrong. Early in 1970, it was decided that the crews would desire a whole body shower for morale purposes. As a result, proposals were solicited. The initial propositions were complex and expensive and were rejected. The Program Director challenged the in-house design groups to design a simple, inexpensive shower. Finally, in mid-1971, the MSFC design group proposed a simple pressure-fed whole body shower. A pressurized bottle of water fed a shower head located in a simple collapsible cloth shower area. The water was collected at the base by a version of the Skylab vacuum cleaner. The system was accepted, base lined, and built. It worked in orbit, but, to the surprise of the author, many of the astronauts did not feel it was required nor needed. Because of the time to operate and clean up, few of the crewmen thought it worth the effort. Future systems should be simpler to operate.

In mid-1971, one of the more gratifying experiences in Skylab was initiated--The Skylab Student Project. It began with a request by the MSFC Program Manager that a way be found to encourage the participation of high school students in the Skylab missions. After a brief analysis, a Headquarters contract was let with the National Science Teachers Association (NSTA) in Washington, DC, to conduct a nationwide contest among high school students for the selection of a number of experiments to be flown on Skylab. Over 15,000 proposals were received and evaluated by the NSTA. Finally, by April, the NSTA and NASA agreed upon 25 student experimenters. The enthusiasm of these young people was gratifying and satisfying. The experiments were real, not contrived, and some had remarkably sophisticated scientific content. Each student investigator was linked with a NASA scientist as an advisor. Each advisor was instructed to ensure that the experiment remained the product of the student, and, within the bounds of visibility, these instructions were followed. It should be noted though, that the teenagers selected had a wide variety of interests, some who had a deep and lasting interest in science and some who happened to propose good experiments but whose interests changed between the initial contest and the publication of the final results.

In January 1972, the Skylab flight crews were named after several months of discussion and debate over the proper composition. The elements of NASA associated most closely with the realities of flight operations were most conscious of the fact that Skylab was a new, technical, and operational venture and as such it required flight crews which were operationally and test oriented. Their proposal was for a dominance of the pilot-astronaut, at least until the system was mature, which might be accomplished by the third mission. On the other hand, the elements of NASA associated with the science and experiment ambitions of Skylab argued strongly for active participation and in some cases for dominance by the scientist-astronauts. In the end, the crews for each of the three missions were composed of two from the pilot-astronaut category and one from the scientist-astronaut pool. By cross training (and by inclination in most cases), the flight crews became very versatile; the pilots were reasonable "scientists" and the scientists were capable "pilots." In retrospect, the composition of the first crew was probably correct, but the second and third crew could have substituted a scientist for a pilot. Astronaut Kerwin (medical doctor), for example, helped Astronaut Conrad (pilot) deploy the solar panel, and his performance probably could not have been improved if he had had more pilot training and less medical training. Conversely, without any intent to demean their significant achievements, the third crew may have had an even greater contribution if, for example, an earth scientist had been added to the crew.

The names of the crews were announced on January 18. They were Charles Conrad, Jr. (Commander), Dr. Joseph Kerwin, and Paul Weitz for the first manned mission; Alan Bean (Commander), Dr. Owen Garriott, and Jack Lousma for the second manned mission; and Gerald Carr (Commander), Dr. Edward Gibson, and William Pogue for the third and last mission. The backup crews were also named at the same time.

The development and fabrication and test of the Skylab hardware, experiments, and equipment proceeded. Several times there was internal rescheduling of events, but basically the schedule was maintained, with one important trouble spot. The largest element, the workshop, had the most experiment interfaces and was subjected to the effects of many minor changes. Rather heroic efforts were necessary to come close to maintaining the schedule and the installation of parts, cables, experiments, and equipment required tight scheduling and control. Most importantly, the assembly plan had to be very flexible to accommodate the relatively frantic part of the development. It was very fortunate that the initial planning called for the workshop to be available more than 6 months prior to the KSC need date. In fact, the workshop was delivered to the KSC facility about 2 weeks late--the 6-months schedule reserve was needed.

All hardware was delivered to KSC during the fall and winter of 1972 as was the necessary ground support equipment and test equipment. Unfortunately, it did not always arrive in the precise order as the plan had called for and there was some replanning necessary. As a result, the prelaunch preparations fell about 2 weeks behind schedule. In February 1973, a review of the progress was conducted, and it was concluded that for a variety of reasons, the launch date should be delayed for 2 weeks from April 30 to May 14. There was considerable consideration given to maintaining the April 30 date since it had been held for over 2 years and it would have been a significant management and technical accomplishment to have been able to forecast the effort needed to prepare a project of the complexity of Skylab. However, a careful assessment of the overtime and extreme effort which would be necessary to regain the lost time indicated that while it was possible, the effort would have been too large to accommodate any subsequent problem and would not have permitted the careful attention which seemed needed. As stated, a more cautious scheduling was adopted with the launch date May 14.

Subsequent preparations went as planned with the various tests as planned with no serious anomalies being found.

The Countdown Demonstration Test began on April 25 and lasted until May 2. All final procedures were rehearsed as if the test was a real launch. On May 7, the 7-day countdown sequence was initiated in preparation for the May 14 launch.

MISSION SUMMARY

By NASA definition, the operational phase begins a few weeks before liftoff at the completion of the Countdown Demonstration Test (CDDT) which occurred on May 2. From that time on any and all changes to the flight hardware, ground complex, test procedures, crew check lists, or flight plan required the written approval of the Program Director.

As part of the final approval of the mission operations and hardware preparations, a series of Flight Readiness Reviews were held at JSC, MSFC, and KSC from April 9 through 12. These Center oriented reviews were in preparation for the mission Flight Readiness Review (FRR) held at KSC on April 18-20. The results of preparations and tests to this point were reviewed by the Associate Administrator for Manned Space Flight (Dale Myers), the three MSFC Center Directors (Drs. Kraft, Petrone, and Debus), the Program Director, and other NASA program officials. The readiness of the flight hardware, ground systems, flight crew, ground support crews, procedures, communications network, and recovery crews were reviewed and found to be satisfactory.

One area was found to be deficient. The computer program needed for operation of the mission control center at Houston was not completely operational. Two important subroutines were not completed. The program which was to convert the ultraviolet data from the S-055 spectroheliometer into images of the Sun was not completed. (These images were to be used for real time flight planning and, while usable images were available during the first mission, the principle investigator was not satisfied with the program until January 1974). The other deficient program was to permit the transmission of data from the computers at JSC to the computers at MSFC. Because of transmission line losses and data dropouts, the data could not be sent real time. Instead, the data was recorded on magnetic tapes and flown to Huntsville each day. Also, a remote terminal of the Houston computer was installed at MSFC to permit the designers to see the Houston data. This program was available for use before the end of the first mission.

It is appropriate to observe here that this is an example of what can occur when the ground systems are not afforded the same attention as the flight systems. The software review board, chaired by the Program Director, did not review and examine the ground software progress regularly and systematically.

The final countdown began 1 week prior to launch and proceeded at a relatively leisurely pace. Few problems were encountered, none were of a serious nature. Ordnance devices were installed; the batteries were installed and activated on schedule.

The launch-minus-2-day meeting was held on May 12. The responsible official for each element of the program, workshop, Command and Service Module, recovery, network, flight crew, security and public affairs, summarized the final preparations and the readiness for flight. A detailed weather assessment and forecast was made by NOAA. Based upon these statements and the previous reviews, acceptances, and studies, the Program Director assessed the mission as ready for launch and he so appraised the Associate Administrator for Manned Space Flight. The launch of SL-1 was scheduled for 1330 on May 14, 1973.

The launch countdown proceeded without a hitch. Minor problems were resolved quickly and without impact to the schedule (based upon Gemini and Apollo experience, built-in periods of inactivity, i.e., "holds," were incorporated in the count to provide time to resolve problems. For the most part, these built-in holds were not required for Skylab, but are recommended for any program in the future). Propellant loading for the Saturn V began on schedule at T-5 hours 30 minutes, with range safety checks 90 minutes later. All tests proceeded normally until finally at T-0 hours 8 minutes, Skylab was switched to internal power. After final systems checks, the terminal automatic sequences began (at T-0 hours 3 minutes 7 seconds) and the launch sequence was subsequently controlled by the launch processor computer. Internal power transfer, sequence verification, swing arm retraction, final checkout and launch commit occurred as planned.

At 1730 GMT (1330 EDT) on May 14, 1973, Skylab was launched.

The Saturn V launch vehicle lifted off and, as the tail fins of the S-1C stage cleared the top of the launch tower, control shifted from the launch director at the Kennedy Space Center to the flight director at the Johnson Space Center.

At 63 seconds, as the vehicle passed through Mach 1 and was approaching maximum dynamic pressure, the meteoroid shield which covered the cylindrical portion of the workshop was ripped from the main structure. As it separated, solar array number 2 was unlatched and only air pressure kept it from deploying. Solar array number 1 was fouled by debris from the shield which subsequently prevented that array from deploying.

Failure analysis identified the most probable cause as a "sneak path" for aerodynamic pressure which lifted the auxiliary wire tunnel into the airstream. This tunnel had been assumed sealed at the aft end when the structural load calculation was made. Unfortunately, a poor design (omission of a cap or seal on hollow structural stringers, a poor metal-to-metal seal, and unplanned venting around a boot seal) resulted in unexpected air flow and a resultant burst pressure at the forward lip.

Examination of the telemetry data showed abnormal vibration, a change in telemetry power, a roll rate, and movement in the torsion rods attached to the shield. However, the flight controllers in Houston only received a TM indication that solar array 2 had deployed. This anomaly was reported as it occurred and the reports were monitored at KSC. However, primary attention was focused on the trajectory as the Saturn continued on its flight path.

At the completion of the second stage burn (591.1 secs.) the two retro rockets separated the launch vehicle from the workshop. It is probable that the plume from one in-line rocket impinged upon solar array number 2. Vehicle motions support this theory and the forces were calculated to be sufficient to swing the released array to where the momentum would cause the wing to reach the 90° stop, and tear completed free at the hinge line. All telemetry from array number 2 ceased at about 594 seconds. The workshop experienced yawing motions at this time, which also supports the analysis.

In retrospect, it was fortunate that solar array number 1 was fouled by the meteoroid shield debris.

After 599 seconds of powered flight, Skylab was injected into a near perfect orbit, 435 km above the Earth.

After insertion, the automatic sequencer was designed to cycle through the deployment and activation activities to place the cluster in its orbital configuration. Reports of a possible failure were beginning to be discussed and the deployment was awaited to prove or disprove a malfunction of some sort. The deployment sequence jettisoned the refrigeration system radiator shield, maneuvered the workshop to a gravity gradient orientation, activated the refrigeration system, and then jettisoned the large payload shroud which covered the solar observatory, airlock, and multiple docking module. The sequencer maneuvered the vehicle to a solar inertial attitude and the solar observatory was rotated 90° from along the thrust axis of the vehicle to where it faced the Sun. The solar panels attached to the solar observatory were deployed and electrical power was generated.

The final automatic commands were to have deployed the workshop solar arrays and the meteoroid shield. No signals were received indicating these events occurred and no electrical power was generated by the large panels. As the workshop came into view of the Goldstone tracking station, a backup command was transmitted from Houston and, while the vehicle acknowledged receipt of the command, no action resulted.

Telephone conferences between KSC, JSC, and MSFC confirmed the reports. Some or all of the meteoroid shield was missing and there were indications that one solar array was missing and that the other was released but did not deploy. The meteoroid shield was also part of the passive thermal control system. Confirming its loss, the skin temperature and the internal temperature began to rise at a rapid rate since now the exposed surface was subjected to the full solar radiation and the temperature rose about 200°F higher than the design temperatures.

A teleconference with the technical experts at the three involved NASA Centers was held and it was determined that, without corrective measures, the workshop internal temperatures would be unbearable. There was debate as to the advisability of launching the first crew as soon as possible (on time the next day) to get an on-site report of the damage. However, with each minute the postulated failure was further confirmed by telemetry data and analysis. If the crew was launched without a method for protecting the exposed workshop from the solar heat, it was concluded they could accomplish few of the experiments and certainly could only stay a few days since the food was stored in the workshop. Also, once they were launched, it would take several weeks to prepare the next vehicle for launch. It was certain the vehicle could not survive that long without corrective measures.

The launch of SL-2 scheduled for the next day was postponed for 5 days while corrective measures were planned. (The altitude of the Skylab orbit was chosen such that the ground track repeated each 5 days. Thus, a 5-day delay resulted in almost no alteration of flight dynamics.)

A series of assignments to the NASA Centers were quickly made. MSFC was to analyze the effects of the temperature on insulation, seals, and hardware while JSC was to examine the effects on food and medicine. A failure investigation was started and all were solicited for potential fixes.

Throughout the night of May 14, the flight controllers at JSC and the engineers at MSFC worked to save the workshop from catastrophe. In the solar inertial attitude (the design attitude) the maximum workshop area was exposed to the full solar heat and the temperature soon reached a critical level. The flight team maneuvered the workshop such that the small end of the vehicle (the docking port on the MDA) was pointed toward the Sun and the temperature of the workshop dropped since the exposed surface was now parallel to the Sun's rays. However, so were the remaining solar panels and the battery power began dropping. Equally serious, the coolant fluid in the auxiliary cooling system (which maintained the food at freezing temperatures) approached the freezing level. An iterative process was begun to try to find an attitude which would result in a stable temperature which was not excessive and which would also provide sufficient solar energy for the electrical power system. By the morning of the 15th a reasonably stable attitude was found which resulted in internal temperatures about 130°F and a satisfactory electrical power level. It cannot be stated that a stable "hands-off" attitude was ever reached, but, about 14 hours after liftoff, the vehicle was under control. For the next 10 days, the engineers and flight controllers continually maneuvered the spacecraft to control the attitude. The control was complicated by unfamiliarity with the control moment gyro attitude system which required the dumping of stored momentum at intervals to prevent gyro momentum saturation. The design condition called for a periodic update to the digital computer to correct the reference attitude. An unexpectedly high drift rate on the rate gyros caused the vehicle to drift and the flight controllers occasionally lost reference and the vehicle had to be maneuvered to determine its special reference. By finding a means of monitoring the solar panel output and the CMG momentum, the vehicle attitude was estimated and attitude thrusting was used to keep the vehicle in the proper attitude, inclined about 45° to the Sun.

This constant and successful compromise between electrical, thermal, and attitude requirements continued for the first 10 days and the fact that control was not lost is a tribute to the men analyzing and controlling the flight. There were several "near misses" but no full losses in control. However, the unusual maneuvering caused a high usage of thruster attitude control gas. More than two-thirds of what had been predicted as needed for the entire 8 months of flight was used in those 10 days. Fortunately, the system was overdesigned and margins remained throughout the flight (although subsequent CMG problems in the last mission resulted in a situation where careful management was required.)

While the flight control team worked to keep the workshop operable until a fix could be found, the design teams looked at several potential sunshades to protect the vehicle from the heat of the Sun as well as ways to augment the electrical power.

To coordinate and direct the activities, a daily teleconference was held between the Center program elements, the Center Directors, and the Program Office. These meetings served to keep the rapidly moving solutions coordinated and as a means of exchanging information concerning the fixes. Also, the progress reports formed the information base for the daily press releases which were issued identifying each issue, all progress, and the latest problems. The NASA Administrator had instructed the Program Director to be open and public at each step of the way. The press releases were complete and timely and appeared to demonstrate that the NASA open information policy was being followed.

Many original ideas for shielding the workshop from the Sun were initially looked at by the design teams; windowshade designs, umbrella-like designs, inflatable surfaces, awnings, spray-on materials, paint, and devices which unrolled when pressurized (much like a party favor) were examined in some detail. On the second day of the mission, the development/management team decided to concentrate on two designs.

The Johnson design team concentrated on an awning-like device which was to be attached to the workshop by the crew while they remained in the Command Module. While maneuvering the CSM in close formation with the workshop, and while standing in the open hatch of the CM, the crewman was to attach a pulley and ropes to the "bottom" and "top" of the workshop using a long pole. By careful maneuvering of the CM, the awning was to be draped over the sun side of the workshop.

The Marshall design team was to concentrate on a windowshade-like device which would require the crew to enter the workshop airlock and, while EVA, attach poles the length of the workshop and, by ropes and pulleys, pull the "shade" the length of the workshop, from "top" to "bottom."

Simultaneously, a coordinated activity was initiated to find the proper material for a sunshade. The material had to be lightweight, be capable of being packed into a small volume, have the proper thermal qualities, and maintain its strength and properties after long exposure to ultraviolet, heat, and vacuum.

Meanwhile, other design groups pursued independent paths. At the Langley Research Center, a design and fabrication group began the design of an inflatable flat balloon which was to be deployed through the solar side scientific airlock. (The scientific airlocks were provided as a means of extending experiments outside the workshop without having to depressurize the living quarters. Cannisters containing the experiments were attached to the 8"x8" aperture, and by proper opening of the doors, the experiment could be extended into space). Once deployed, the balloon was to be inflated and it would then provide the needed thermal shield.

A separate Johnson Space Center group took a somewhat similar approach and began the design of a parasol device which was also to be deployed through the scientific airlock. Once the telescoping rods to which the thermal material was attached were fully extended, the rods were to spring open, like an umbrella, and the shielding would be in place.

Each of these later two approaches were constrained to fit in a spare experiment cannister (T027) since there wasn't sufficient time to build a larger container. As a result of this volumetric constraint, extremely thin material was necessary. (For the parasol, for example, a laminate of nylon was bonded to 0.05 mm aluminized mylar).

The JSC parasol design group quickly demonstrated the soundness of the design by the use of commercially purchased fishing rods. Since this design could be deployed from the interior of the workshop without EVA, and since it did not require careful maneuvering of the Command and Service Module, it was selected as the primary JSC development while the "awning" was relegated to backup status. The awning was continued since, while operationally complex, it had simple design concepts and was not faced with the packing problem which faced the parasol.

After 2 days of design effort, it was apparent that more time was needed and the launch date of the manned Skylab 2 was extended until May 25.

Maximum effort was made not to cut corners which could jeopardize crew safety. Full quality control was used with inspection buy-off at every step. Expedited, but complete, documentation was employed. A safety analysis was made and documented and all procedures were written and used for training. The possibility of causing a crew fatality because of an error made as the team worked around the clock caused management to be extremely cautious at every step.

While the thermal design teams wrestled with the problem of producing the sunshield, the electrical power teams attacked the problem of providing adequate electrical power, if the workshop was ever manned. Two separate time-phased approaches were decided upon, one for a near-term solution by the first crew and a second for a far-term solution for use on a later mission.

For the immediate problem, it was decided that no new augmentation device could be made quickly and that the fixes had to be whatever could be accomplished with the hardware on hand. It was decided, therefore, to load all of the hydrogen and oxygen possible in the Command and Service Module (CSM). Since an earlier program decision had made it possible to continue using the CSM fuel cells long after docking, this power would ease the shortages until the cryogenic supply was depleted. Further, it was decided that the Skylab 2 crew would carry a variety of tools to free the apparently stuck solar array panel. A team was established to recommend the necessary tools. A mockup of a stuck solar array was set up at the Marshall Space Flight Center and accurate samples of the materials which could be restraining the panel were made available to test the tools.

For the long term, a variety of approaches was considered; roll-out flexibile solar panels, folded panels, and modifications of the ATM panels were considered the most likely candidates. The JSC design team pursued the ATM approach which used two spare ATM panels fixed to a simple structure. This structure was to be launched with a later CSM (with the arrays folded). It was fitted with a docking collar which would permit it to be docked to the rescue hatch of the Multiple Docking Module. The power would then be bussed with the main power through an existing connector inside the MDA.

MSFC was assigned the task of designing an array to be deployed by the crew while EVA. Both flexible arrays and folded arrays were considered. These arrays were to be bussed to the main power supply through the ATM electrical system.

(Both of these long-term solutions were pursued vigorously until the Skylab crew released the fouled solar array. Since adequate power was then available, all remaining activity was terminated.)

Meanwhile, each of the proposed thermal shield designs solutions was practiced in the Marshall Space Flight Center's Water Immersion Facility (WIF) to insure the crew could properly deploy the mechanisms. (The WIF is a four-story water tank which is used as an analog of zero gravity. All equipment is made "neutrally buoyant" at the proper depth. The crew is similarly ballasted and the rehearsals are conducted on full-scale mockups, in space suits, using flight procedures. The fidelity of the simulation is fair, provided motions are slow enough to avoid the drag forces of water.) Crewmen, including members of the primary crew for Skylab 2, practiced deploying the JSC awning and the MSFC twin pole thermal shield. The crew trained as well on a procedure to use a hook to try to pull the solar array from the restraining debris.

To coordinate and control the many new and unusual equipments being planned for launch in the Command Module, the Johnson Space Center established a special Stowage Team with configuration control maintained by the JSC Program Manager. This team was in charge of safety packing the many large containers in the small volume of the Command Module. The problem was complicated by the requirement that the couch envelope not be violated in the case of a land landing (a normal safety constraint) but was eased somewhat because the Command Module had been designed for a certain degree of stowage flexibility.

Throughout the development of the thermal shields, the material presented a problem. The material had to have the proper thermal qualities (alpha/epsilon (a/e)), be light and flexible, not be permanently set by packing, and, equally important, be available in adequate supply to provide the material needed for flight, backup, and for the development tests. Nylon bonded to aluminized mylar fit all of the requirements and was available in sufficient (although not abundant) supply. Unfortunately, to get the proper alpha/epsilon, the nylon side had to be exposed to the Sun and the available data indicated deterioration of the strength due to the Sun's ultraviolet emissions. Tests were conducted at JSC and MSFC to estimate the lifetime of the material. These tests had to be accelerated (using solar simulators) to get a quick estimate of the useful life and resulted in confused data.

The JSC awning and the MSFC shade were coated with the same thermal paint as had been used on the workshop to achieve the proper alpha/epsilon. The thermal and life questions had, therefore, extensive test data to provide the adequacy. The only serious question was the effect of folded storage: would the paint stick to itself or take on a permanent set? A test program was initiated to settle this question.

The parasol, however, could not be coated with paint since the added thickness would make it impossible to pack the material in the cannister. The initial solution proposed by JSC was to use the material with the mylar side toward the Sun. Tests were undertaken to prove the analysis, but, on the day before the launch, it was revealed that the alpha/epsilon was not adequate.

It was decided that the JSC parasol would be flown as the primary solar shield with the nylon side toward the Sun. This approach was chosen since all test results indicated the material would last at least 30 days and the parasol could be deployed from within the workshop without the necessity of an EVA. Tests on the material were to be continued since once the parasol was deployed and the workshop cooled down, an EVA could be planned before the completion of the manned mission to deploy the twin pole thermal shield. This twin pole shield was designated as backup, to be used if the crew could dock but, for some reason, could not enter the workshop or deploy the parasol. Finally, the JSC awning was stowed onboard the CSM for use in the event the crew could not dock with the workshop. In that event, the awning was to be installed by the crew as they stood in the open CSM hatch. This would solve the thermal problem, at least while the ground personnel tried to figure out what to do next.

The Langley "flat ballon" device was not flown because of the inability to predict how it would deploy in zero gravity, although all of the testing on the ground had been satisfactory

Finally, it was decided to have the crew attempt to free the restrained solar array while standing in the open CSM hatch before they entered the workshop. A set of tools was decided upon as well. The speculation was that restraining debris could consist of metal straps, bolts, and/or sheet metal. Shear type metal cutters and a universal handling tool (a hook-like device) were stowed as were long handles.

The stowage of the Command Module began the evening prior to the liftoff of the Skylab 2 mission as the various parts and equipments were flown to Florida from the development agents. The last item to arrive was the JSC parasol packed in its cannister which arrived after midnight for the 9:00 a.m. liftoff the next day.

(It should be recorded that during this 10-day period, the aerospace industry performance was outstanding. Not only those individuals directly involved in the round-the-clock activities described here, but assistance was offered from all quarters. Offers of ideas, designers, materials, parts, advice, and prayers came from a number of aerospace companies.

Ideas were also sent to NASA from many unexpected quarters. School children sent suggestions, university classes accepted the problem as a design project, and technicians and engineers made suggestions based on their personal experiences. Some ideas were not practical (i.e., the school boy suggestion that Skylab be parked in the shade of the Earth) but many paralleled the solutions adopted.)

At 1300 GMT (0900 EDT) on May 25, the eleventh day since the launch of Skylab 1, the first crew was launched from Launch Complex 39B precisely on time. The launch vehicle, a Saturn 1B, performed properly and insertion of the CSM into an orbit 156 km by 357 km occurred 10 minutes after liftoff. During the next 6 hours, the spacecraft was maneuvered into the final 424 km by 415 km rendezvous orbit. During the fifth revolution, Skylab 2 completed the rendezvous maneuvers and began station keeping with the workshop. The crew's description of the workshop's condition confirmed the hypothesis--the micrometeoroid shield was gone, the number 2 solar panel was torn off and gone, while solar panel number 1 was only slightly deployed (Figure 11) and apparently was restrained by a strap from the shield (Figure 12). The crew conducted a fly-around of the workshop and transmitted 15 minutes of television to the ground. (This TV proved invaluable later on since it allowed the stuck panel to be duplicated on the ground, and for procedures to be developed and practiced which, eventually, freed the panel from the debris.)

Following this inspection, the Command Module was "soft docked" to the Saturn workshop. (A soft dock consisted of inserting the Command Module probe into the workshop docking adapter. Latches on the probe engage the ring but the final retraction of the probe to seal it to the workshop was not executed.) A soft dock was used to permit the crew to prepare themselves for an extravehicular attempt at freeing the solar panel, without having to station keep in formation with the workshop. When all preparations were completed, the crew separated the two craft and maneuvered into position. While Conrad maneuvered the spacecraft, Weitz opened the hatch and attempted to pull the panel loose using the ten-foot pole with the hook on the end.

Astronaut Weitz was unable to pry the debris loose or to break the restraining strap. (It was found later that, in addition to the metal being wrapped around the beam fairing, a nut had been wedged into the honeycomb structure firmly locking the metal). As the astronaut pulled on the pole, the two vehicles were drawn together and the workshop attitude control system expended large amounts of the control gas while the Command Module thrusted away from the workshop. The unsuccessful attempts were finally terminated and the crew tried to redock with the workshop.

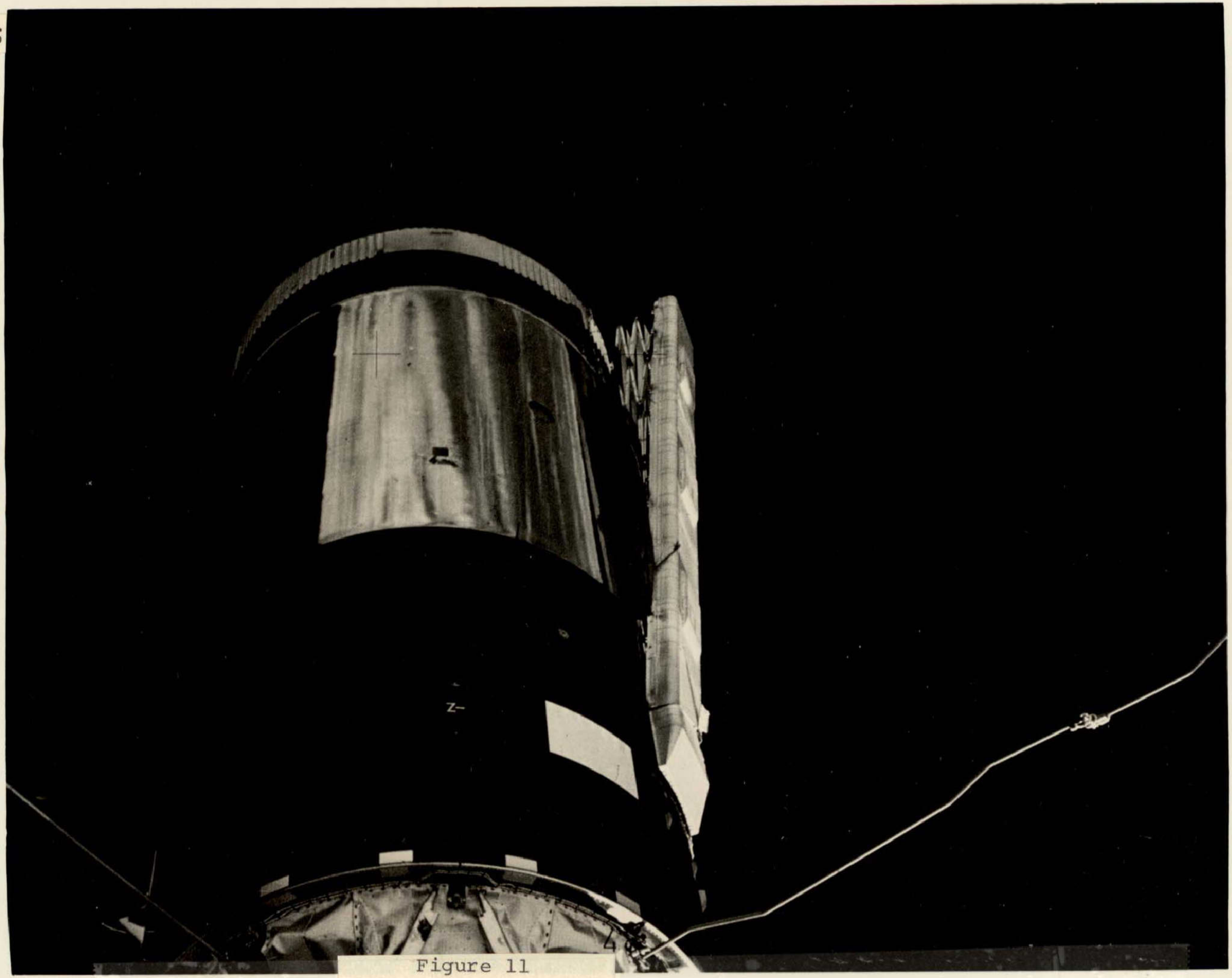


Figure 11

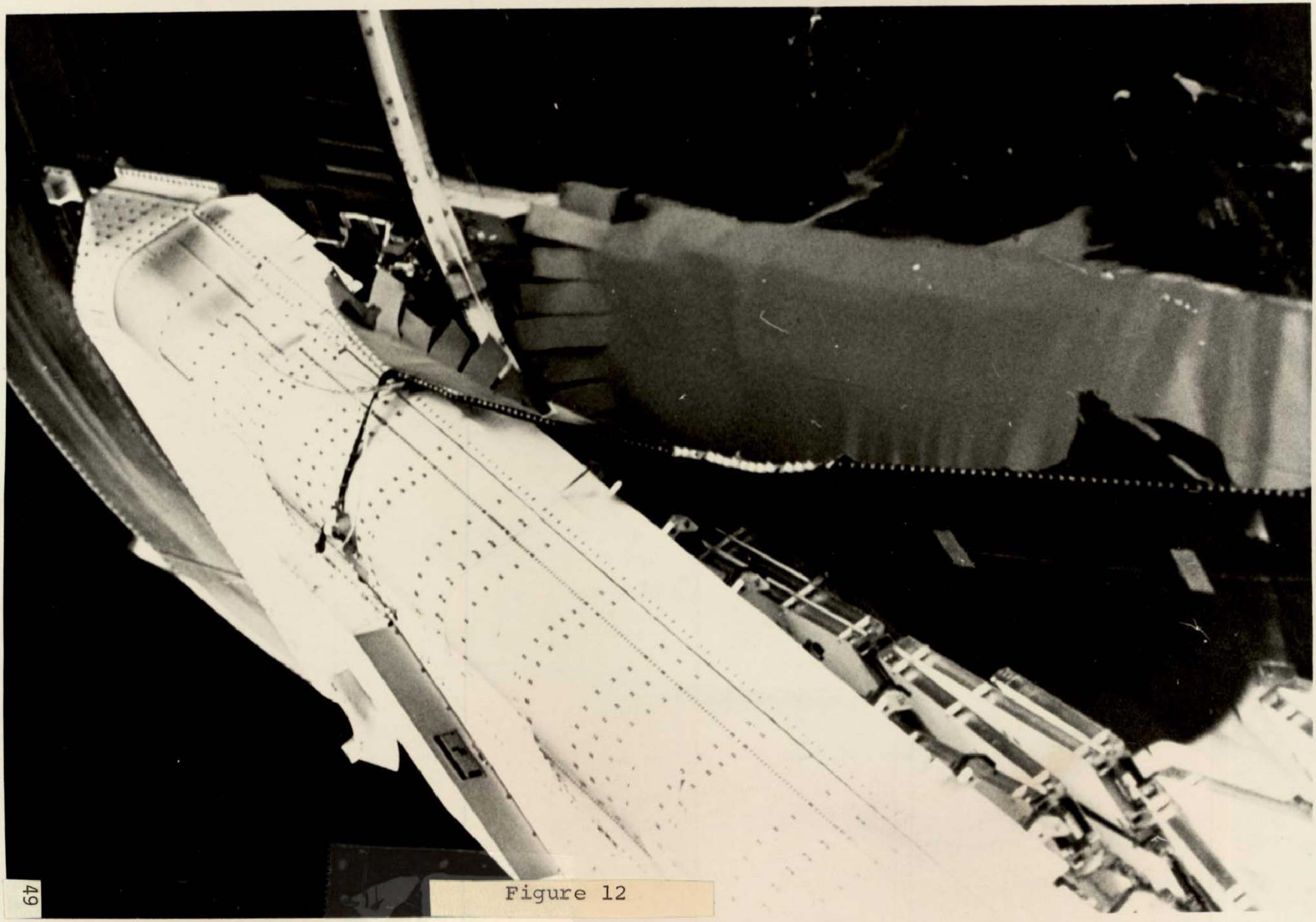


Figure 12

The crew was unable to achieve a docking. Seven attempts were made without success. The probe capture latches failed to engage. Fortunately, during the development program a failure-mode analysis had resulted in the preparation of a procedure to correct this type of failure (no previous failure of this type had been encountered, but the procedure was developed since the failure had been hypothesized). The crew again donned their space suits, depressurized the spacecraft, and removed the Command Module forward hatch. This allowed access to the docking mechanism and the circuits controlling the latches. By disconnecting a cable, the latches could be properly reset and, finally, on the eighth attempt a firm, hard dock was achieved.

The crew slept in the Command Module after a long 22-hour day.

On the next day, the crew prepared to enter the workshop. After donning face masks, the crew entered the docking module tunnel. As the crew entered each successive module, the atmosphere was sampled prior to opening. No toxic gasses were encountered in any module and the crew finally entered the workshop where the temperature was 130°F. The humidity was low so the crew was able to enter and work for short periods without particular discomfort.

At about 5 hours into the workday, the Skylab parasol was deployed through the +Z (solar side) scientific airlock. The thermal shield performed its task despite the fact that one of the telescoping rods did not lock in place and the sunshade was not fully extended (Figure 13). The skin temperatures began falling immediately and within an hour the vehicle was maneuvered to the solar inertial attitude. The internal temperatures dropped as well and stabilized at about 80°F in about a week. This temperature, while high, was tolerable because of the low humidity of the workshop. (The environmental control system removed moisture from the atmosphere and, premission, had been the source of controversy since the resulting atmosphere was dry).

Following the completion of the remaining activation activities, the crew established a work routine. Day-night cycles corresponded to that of the flight control personnel, i.e., Central Daylight Time. The crew workday consisted of about 16 hours of controlled activity and 8 hours of sleep. All crewmen slept at the same time.

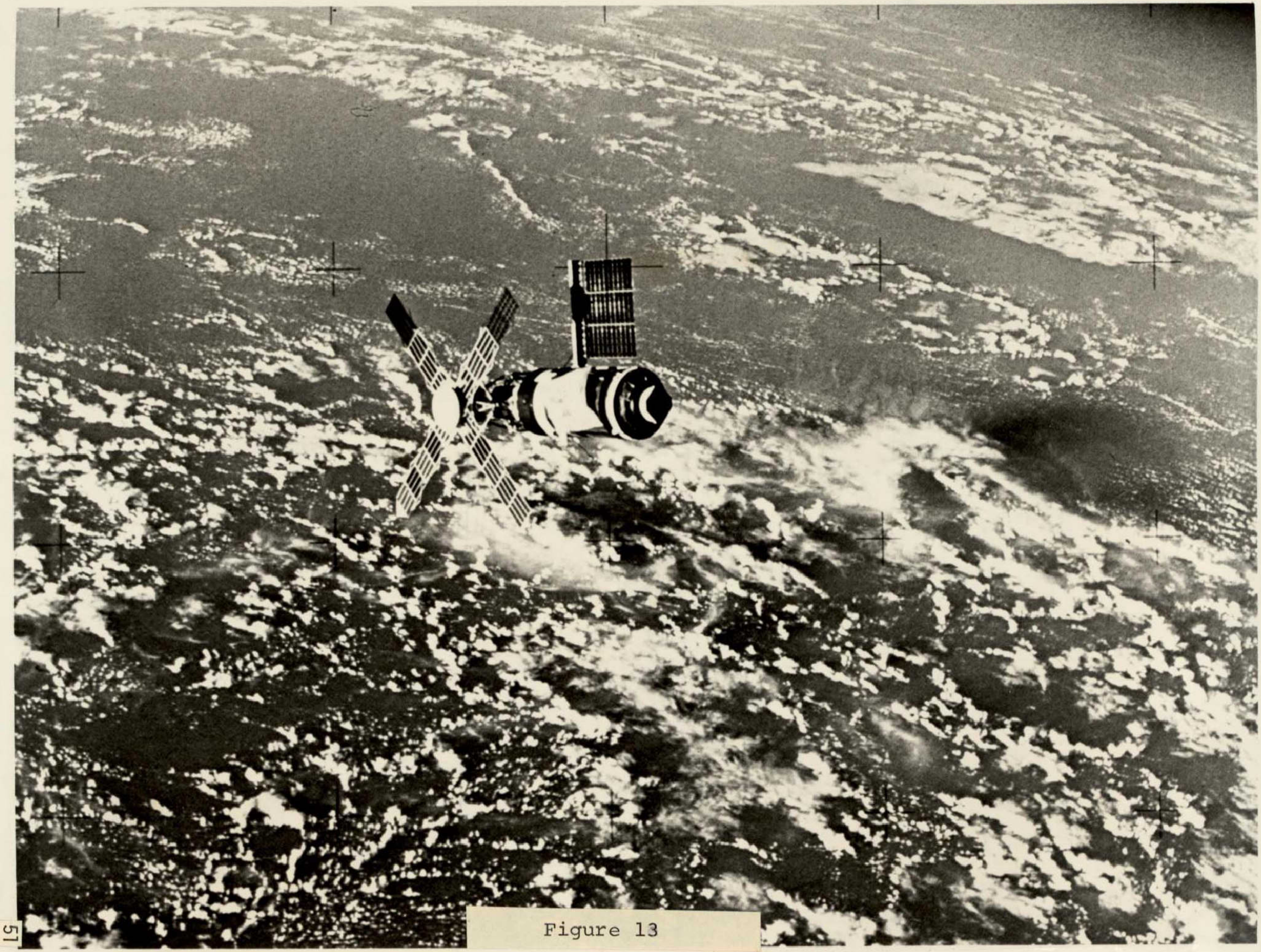


Figure 13

SKYLAB SPACE STATION CLUSTER DEPLOYED IN EARTH ORBIT

(No attempt will be made here to document the scientific and technological investigations. Only the operational activities will be discussed.)

A premission flight plan had been established but it was used only to scope the times available for experimentation. It was recognized that most of the observations desired were transient (earth resources observations depended upon, among other things, on the weather. Solar observations of the dynamic and unpredictable solar processes were desired). A mission planning technique had been developed to take care of the changing requirements for the experiments. Mission planning was complex since the Skylab experiments imposed conflicting requirements on the orbiting vehicle or the timeline. Medical experiments were generally repetitive and, therefore, required daily time blocks. Solar experiments required a solar inertial attitude and were somewhat dictated by forecasts of solar activity. Earth resources required local vertical pointing and were time and position dependent since it was planned to observe specific points on the Earth's surface (the variable cloud cover complicated the planning). Other experiments required night cycles, coordination with rocket firings, operation with ground truth and aircraft, and pointing at stellar points.

The mission planning control was directed by the Mission Management Team, chaired by the Program Director. This group with representation from all involved NASA elements, met daily and established policies and priorities concerning the in-flight activities and resolved the major conflicts between experiment requirements.

Flight planning began when the Program Scientist (who reported to the Program Director) formulated a 7-day schedule of flight plans, in a gross sense. At this level, a flight plan consisted on a one-line bar chart allocating time to classes of experiments. The Program Scientist arrived at the allocation on the basis of the priorities established, the experiment peculiar constraints, discussions with the investigators, and a desire to maintain a balanced program. For most days, more than one option was developed.

Obviously, the Program Scientist had to have operational knowledge in addition to a sensitivity and knowledge of science.

Detailed flight planning was conducted on a 24-hour basis with three groups of flight planners--the summary shift, the execute shift, and the detail shift. On any specific day, the summary shift began work at midnight on the plan for the day after next; i.e., on Monday morning they planned Tuesday's activities. The process began by using the gross plans developed by the Program Scientist and expanding the plan to show the time related activities of each crewman along with instructions on each experiment. It was at this level that the requirements of the experiments, the workshop systems, consumables, "housekeeping" requirements, and network constraints were balanced and compromises established. This summary plan was, in general, completed at 8:00 a.m., in time to raise any issues to the Mission Management Team for resolution. During the day, this summary plan was transmitted to the flight crew so they could read and comment on it during their presleep period. From about 7-8:00 a.m. until 10-11:00 p.m., the execute team provided the ground support as the flight crew performed the activities planned the day before. The evening shift, which worked from about 6:00 p.m. until 2-4:00 a.m., then developed detailed instructions for the crew for the execution of the summary plan. These instructions included details such as camera settings, film requirements, detailed and timed procedures for conducting an experiment, location of equipment, and other pertinent details.

The flight planning for the first manned mission was complicated by the shortage of electrical power. The solar observatory solar panels provided about 4,000 watts of power (the CSM fuel cells provided sufficient power to keep the CSM systems active) and the systems required slightly less than 3,000 watts. Thus, only 1kw was available for experiments. The competition for the power was quite intense. The problem was further compounded by the experimenters lack of faith in the continuation of the mission and their understandable desire to complete as many of their experiment objectives as possible.

As stated, the Command Module fuel cells were operated to provide the power necessary to keep the spacecraft active so it could be used for return to Earth. It was placed in a "quiescent mode" with all unneeded systems turned off. About 1,000-1,200 watts of power was needed for this mode, and obviously when the cryogenic fuels were depleted, the solar arrays would have to supply the power or the spacecraft would have to supply the power or the spacecraft would have to return to Earth. Levying that requirement on the solar arrays would have left virtually no power for experiments. Also, since a local vertical attitude reduced the power generation, the earth resources passes were severely limited. Cryogenics for the fuel cells were predicted to be depleted on June 13.

Great premium was, therefore, placed upon freeing the workshop solar panel from the restraining debris. The problem was further complicated by the fact that the hydraulic fluid in the actuator, which normally would deploy the solar panel beam, was frozen.

Using the television pictures and the verbal description provided by the crew, the Skylab ground teams developed a method of cutting the restraining debris and for breaking a clevis on the actuator to free the frozen hydraulic unit. The method was practiced in the Marshall Center's Water Immersion Facility and the detailed procedures were developed. The procedures were transmitted to the flight crew, and on the 15th day of the mission, Astronauts Conrad and Kerwin, in an extravehicular exercise, freed the wing and deployed it to the full operational position.

Six hours later a full 7,000 watts of power was available and the experiment plans could be renewed at the pre-liftoff planned level.

The mission was continued in a relatively nominal manner and by the completion of the 28-day mission, all primary objectives were successfully accomplished and, considering the problems encountered, a remarkably large number of the experiments were performed. The earth resources experiments were reduced a larger percentage than the other experiment categories because of their peculiar power requirements.

On June 22, 1973, at 09:49:48 EDT after 28 days in orbit the crew returned to Earth where they participated in the required post-flight medical tests. No serious medical effects were observed and all effects disappeared in a matter of days. There was some concern immediately upon recovery when Astronaut Kerwin exhibited some cardiovascular deconditioning as evidenced by his behavior in the Lower Body Negative Pressure (LBNP) test. Such deconditioning was not unexpected and the symptoms disappeared in 7 days.

The original mission plan called for the launch of the second crew on mission day 96 (August 17). However, because of an uncertainty in the condition of the parasol thermal shield material and because of excessive drift in the attitude control system rate gyros, it was decided to accelerate the launch to mission day 76 (July 28).

The second manned launch occurred on July 28, 1973, at 11:10:50.5 GMT (7:10:50.5 EDT). The crew, Astronauts Alan Bean, Dr. Owen Garriott, and Jack Lousma, was scheduled to remain in orbit for 59 days (the original 56-day mission was extended 3 days to obtain a more favorable recovery location. Since Skylab had a ground track which repeated every 5 days, the same location was possible on day 54 or day 59. The good physical condition of the Skylab 1 crew was used by the Program Director to extend the mission to 59 days rather than shortening the mission. (It was proposed that the mission be further extended to recover the time lost at the beginning of Skylab 2. This request was turned down by the NASA management because of medical uncertainties if the crew were left in zero gravity for a longer period.)

The Command and Service Module was inserted in a 154.7 km by 231.3 km orbit by the Saturn 1B. The required rendezvous maneuvers were performed and at about 8 hours after liftoff the station keeping with the workshop began, with docking occurring about 30 minutes later. This time docking went smoothly. However, during the rendezvous maneuvers, a leak in one of the service module reaction control system thruster valves (oxidizer) was noted. The leak was noted in a forward firing thruster and, as a result, the entire quad (B) was isolated and deactivated. (A "quad" consisted of four thrusters, orthogonally around the service module (Figure 14). By the proper selection of thruster pairs, the vehicle could be accelerated in any direction or rotated in any manner.)

Soon after orbital insertion, Astronaut Lousma experienced motion sickness. Consequently, the activation activities were slowed considerably. The motion sickness came as a surprise since the previous crew had experienced no discomfort. Previously, Mercury, Gemini, and Apollo

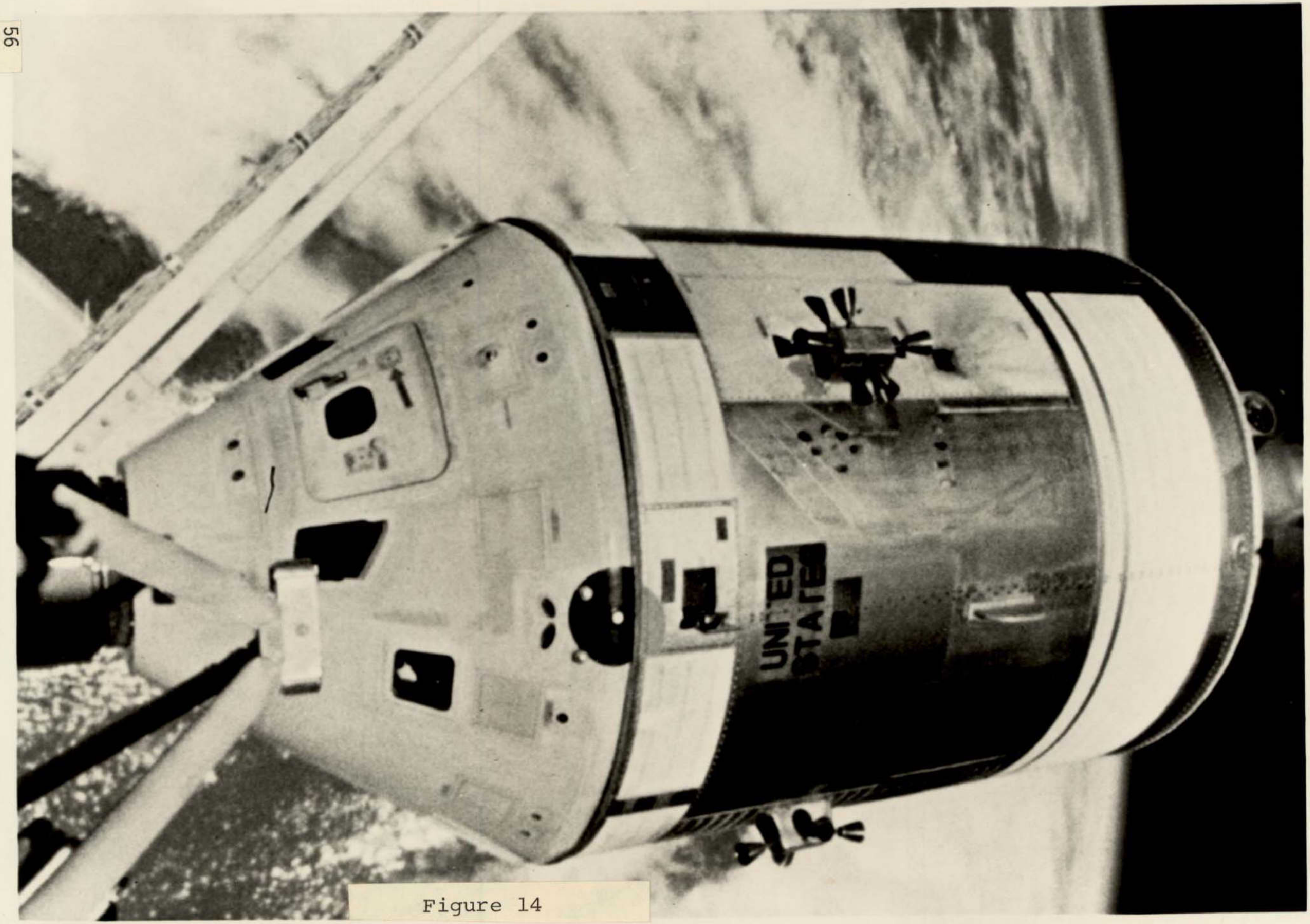


Figure 14

astronauts had not, in general, had any problem. Minor discomfort at most, had been experienced in all but one previous flight. (The Soviets have reported cases of motion sickness during their flights and the different experiences had been a source of mystery for years.) Fortunately, motion sickness had been recognized as a possibility and appropriate medication was available for treatment.

On the sixth day of the mission, a leak was discovered in a second reaction control system oxidizer line. This leak was in quad D. The propulsion system was isolated and inhibited. Since two of the four quads were now inoperative, it became necessary to redefine control modes, entry techniques, and deorbit procedures. Modifications to the procedures were quickly developed in the mission simulator.

However, of more serious concern than the procedural changes was the question of the cause of the two leaks, almost simultaneously in two units. The probability of two unrelated failures seemed remote and the possibility of some type of contamination in the oxidizer supply was postulated. If such was the case, serious concern was expressed if the remaining thrusters were used for attitude control during reentry. Attitude control was, of course, mandatory.

The Program Director elected to activate the Skylab Rescue Vehicle. This called for the personnel at the launch site to begin around-the-clock activities in the preparations for the next launch.

(The preplanned rescue mode required the next in line mission to be launched with only two crewmen and with a specially designed rescue kit which permitted five crewmen to return to Earth. After launch, a normal rendezvous was to be followed by a docking at the rescue docking hatch located in the multiple docking adapter. After docking, the five crewmen were expected to enter the Command Module, separate from the workshop, and perform a normal reentry.)

Simultaneously, the documentation on the failed systems was examined meticulously to see if there was a clue which would explain the leaks. The supply of oxidizer was analyzed as well, and finally, the design engineering team examined all telemetered data for more information. It took several weeks to complete the failure analysis. Incredibly, the two failures were found to be unrelated. The failure in quad B, the first leak, was determined to have been caused by a particle on the seat of the oxidizer valve of the positive yaw thruster in quad B. The second leak in quad D was more difficult to analyze but the conclusion was reached by inductive and deductive reasoning. A careful analysis of temperature data led to the conclusion that the leak was in the plumbing and not in the thrusters. (A complete description of the failures and the analysis can be found in Reference 3.)

The activation of the rescue vehicle was continued up to the point of loading the Command and Service Module with propellants for the Reaction Control System (RCS). At that time the mission was placed in a "hold" posture. The mission could then be called up on short notice, if upon activation of the in-orbit Command Module an additional problem was found. However, based upon the failure analyses, it was concluded that there was no unusual problem in reentering with the leaks in the RCS system and a normal reentry was planned for the end of the missions.

It should be noted that the in-orbit activities of the Skylab 3 crew proceeded without interruption while the ground analyzed the RCS leak and prepared for the potential rescue. It is almost not worthy of stating that the crew was interested in the findings since no one desired to use the rescue mode.

On the ninth day of the mission, a leak was detected in the primary coolant loop. The leak continued (the point of the leak was never found, although both the outside and the inside of the workshop was searched) until on day 27 the pump was turned off and the secondary loop was activated. Later data showed that the back-up loop was leaking as well, although the leak appeared to be small. (Immediate action was started on the ground to provide a reservicing kit for use on the next mission. Both JSC and MSFC began independent designs of servicing kits. After a brief period, a design review of both approaches was held and the best of each were combined into one solution which MSFC built for launch on the last Skylab mission. This was an example of the technique of permitting competing solutions to be pursued up to the point of selection and then combining forces to produce the best combination. The focus of leadership was vested in the combined configuration control board with the Program Director and the JSC and MSFC Project Managers as the directing force.)

(This coolant leak was troublesome for a number of reasons, in addition to its potential effect on the cooled equipments, such as batteries. The coolant system had as its working fluid a low viscosity silicone ester, Coolanol 15. During the development phase, the design of the system was the subject of high level debate because the tubing contained a number of "B" nuts in contrast to the preferred policy of welding or brazing all joints. The laboratory cooling system, located primarily in the Airlock Module, was a derivative of the earlier Gemini technology, whereas the remainder of the workshop was a product of Apollo technology. Coolanol, because of the toxicity in a closed environment and potential flammability questions, was considered to be a dangerous working fluid if a leak occurred. A very comprehensive review was held and special test procedures derived to assure a leak proof system. The system was "locked up" at the factory and the pressure carefully checked. Unfortunately, with the temperature not being constant or uniform or controlled, it was nearly impossible to determine what pressure fluctuations were indicating. It should be noted that the "B" nuts were not eliminated when they became an issue because of the high costs and large schedule impact associated with a new configuration and the assessed low probability of a leak occurring in flight. The leakage in both the primary and secondary systems was, therefore, not only a technical and operational concern, it was the result of a bad program decision.)

On the tenth day of the second manned mission, the first of many extravehicular activities was performed to deploy the MSFC twin pole thermal shield over the parasol. As previously explained, the high-packing density needed for the parasol precluded the addition of coatings to prevent deterioration by ultraviolet radiation. Accelerated tests were conducted to determine the extent of the degradation, but the tests were inconclusive. After considerable debate, (the developers of the parasol were convinced it would last throughout the mission) the Program Director elected to follow the conservative course of action and cover the parasol with the new shield which had an adequate coating (Figure 15). (The converse argument was that planning a long and arduous EVA was not conservative. In retrospect, the EVA sessions of Skylab proved to be relatively easy, showing the benefit of proper preparation and training.)

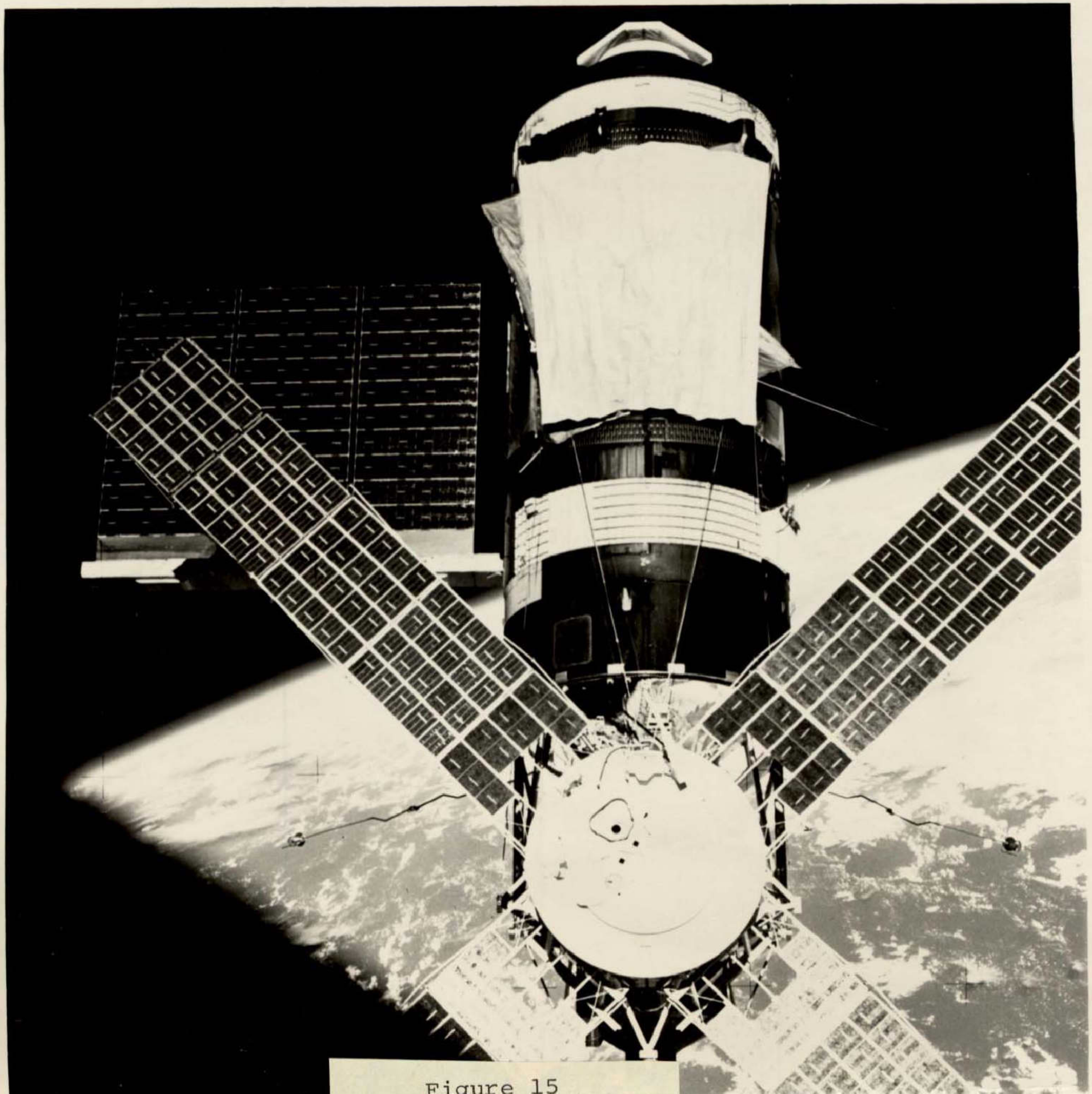


Figure 15

The second mission proved, again, the versatility of man in that considerable unplanned and planned maintenance activities were conducted. The tape recorder, for example, was disassembled and repaired, circuit boards were replaced in the video tape recorder, and finally, during a second EVA, the drifting rate gyro package on the solar observatory was bypassed and replaced by a new package inside the docking adapter.

The crew performance in the second manned mission was particularly energetic, and they worked long and hard to recover the time lost at the beginning of the mission when they experienced the motion sickness. As a result, the experiment operations soon exceeded the planned activities. Thirty-nine earth resources passes were executed and over 305 hours of solar viewing were accomplished. Almost all experiments were performed more than the preplanned allocation of mission time. The student experiments were conducted as planned, including the web-formation experiment. (The crew asked for and received permission to return the two spiders to Earth at the end of the mission. Unfortunately, no provision had been made to feed them in orbit, and they died before they could be recovered.)

During the premission period, a number of simple science demonstrations had been developed to illustrate some basic principles of physics or mechanics. For example, a series of easily accomplished tasks showed the effects of surface tension as a drop of water was manipulated in zero gravity. Six of these activities were accomplished during this mission. One intriguing demonstration was the behavior of fish in zero gravity. Fish which had been hatched on Earth swam in tight circles in zero gravity, while those hatched in flight oriented themselves to the surface they were held against. The fish were returned and it was found that the second set had poorly developed otolith functions. (This has led to formal experiments which were carried on the Apollo/Soyuz Test Program (ASTP) to further investigate the phenomena.)

At the completion of the mission, the workshop was again deactivated and the crew reentered the Command Module for the trip back to Earth. Landing occurred in the Pacific Ocean at 22:19:54 GMT on September 25, 1973.

The recovery activities on this mission were unique in that a constantly changing recovery zone was planned for each day during the second half of the mission. At the completion of the first mission, Astronaut Kerwin experienced some evidence of cardiovascular deconditioning, as evidenced by his reaction to Lower Body Negative Pressure runs. (He quickly returned to normal, and the reactions of each crewman showed wide individual variation. A general trend was noted in that deconditioning to some degree seemed to progress for about a month, at which time no further reactions followed. All effects disappeared after return to a normal gravity field.) As a result of this reaction, senior management permitted the second mission to progress only on a week-to-week basis after the first 28 days. A formal medical review was held by the Administrator to assure there was no progression of deconditioning to a medically unacceptable degree. (Cardiac deconditioning in zero gravity can be likened to that which occurs during bed rest. Bed rest studies are frequently used as an analog to zero gravity exposure.) The on-board medical experiments provided the data upon which the decisions were based.

To support the possibility of an early recovery, the primary recovery ship (U.S.S. New Orleans) was standing by from mission day 29 until mission day 49 in Hawaii. On mission day 49 the recovery ship sailed to support a daily target point. Finally, on day 59 the ship supported the recovery, located just west of San Diego, California.

It is appropriate at this point to touch on the subject of mission duration. Skylab had been planned originally for missions of 28, 56, and 56 days for each of the three manned periods, respectively. Twenty-eight days had been selected because the Gemini Program had progressed through 4-, 8-, and 14-day missions. Medical personnel were confident that the experiences could be extrapolated from 14 to 28 days and then doubled again to 56 days.

During the premission planning period, more and more experiment requirements were added and on-orbit time was quickly exceeded. As a result, the Program Director asked that the mission duration be extended. However; quite properly, NASA management refused all requests until the medical experiment results were available. The 28-day experiences of the first mission were extrapolated to 59 days (from the 56 planned) only because of the peculiarities of orbit mechanics which caused the primary recovery zone to occur on day 54, day 59, and day 64 on a repeating 5-day cycle.

At the end of the second mission, 59 days, the stage was set to extend the last mission as long as possible. Eighty-four days were finally settled upon. In this case, mission duration was not dictated by medical requirements. The determining factor was the amount of food and consumables which could be stowed in the Command Module.

On March 7, 1973, Dr. Lubos Kohoutek of the Munich Observatory discovered the comet 1973f, commonly named Comet Kohoutek. The trajectory was calculated and the perihelion was predicted to occur around the Christmas season. From a science standpoint, the discovery of this comet was interesting since it was discovered so early in its life. It was predicted to be a very bright and visible stellar phenomena. The early discovery also allowed the scientific community to prepare adequately for its observation. The apparent brightness of the comet, combined with the timing, also created a popular interest.

In cooperation with other observers, the National Aeronautics and Space Administration established a project office (at the Goddard Space Flight Center, Greenbelt, Maryland) to coordinate the NASA efforts to collect scientific data on this coment. NASA sponsored observation programs using ground, aircraft, balloon, and spacecraft based instruments. A world-wide effort was planned.

It was inevitable that the instruments aboard Skylab would be considered for this use since the mission was still to be active during the observing period and since the Skylab instruments provided a unique capability. Informal working level discussions established the feasibility of the program and early in the second manned mission, the proposition was officially placed before the configuration control board. The request covered a wide scope; the mission was to be delayed to insure Skylab was manned during perihelion, extra EVA's were to be conducted, experiment film and consumables were to be diverted from the approved program to the new comet observation, priority was to be given the comet observation, new experiment hardware was to be designed and built and flown, and lastly (but perhaps most importantly) the crew was to be specially trained to carry out the observations.

At the time, the Program Director was struggling with the problems of a CSM reaction control system leak (and the probability of a rescue being required) a probable leak in the workshop primary coolant system, rate gyro eccentricities, and a delayed time line because of crew motion sickness. The last thing needed was a major disruption to the orderly program activities. However, due to the scientific merits of the request, a study was initiated to develop a Skylab viewing program for the comet.

At this and subsequent meetings, the Johnson Space Center and the Marshall Space Flight Center conducted feasibility studies and developed detailed experiments which used the on-board instruments to the maximum extent possible. The principal investigators were made a part of the observation team and they allocated their consumables to the comet observations. The JSC team also planned the Command Module Stowage such that consumables, such as film, could be added. (Film for the S019, S052, S054, S056, S063, S082A, S183, S232, T025 experiments was added, as well as appropriate filters and adaptors). A plan for adding food was also developed to extend the mission as many days as possible (an 84-day supply plus 10-days reserve for a rescue potential was made available for the last crew). Water, oxygen, and nitrogen supplies were adequate, although concern was beginning to be expressed about workshop attitude control thruster propellant, particularly after a control moment gyro became momentum saturated as a result of two back-to-back earth observation passes. Loss of control during a momentum dump maneuver caused an automatic switchover to thruster control which used 2584 lb-sec of propellant.

Simultaneously, the scientists of NASA searched for equipment and experiments which could be added. Two experiments, S201 and S233, were approved. S201 used the back-up hardware from an Apollo experiment and was an electronographic camera for observations in the far ultraviolet wave lengths. S233 called for use of an operational Nikon camera (which was already on board Skylab) to take calibrated photometric data of the comet's coma. Considerable doubt existed whether the Naval Research Laboratory (NRL) in Washington, DC could accomplish all of the modifications needed to convert S201 from a lunar instrument to a Skylab scientific airlock experiment. NRL did a fine job and delivered S201 on time.

It is remarkable that the Skylab team undertook such an ambitious program with such enthusiasm at that time since the workshop was plagued with so many problems. Each day brought its own problem (some actual, some imagined, some exaggerated) and the management team had to transform itself fróm the pragmatic tactical problems of the day in the morning Flight Management Team meetings, to the long-range, optimistic planning in the afternoon Configuration Control Board, to the strategic requirements of the priority-setting flight planning sessions in the evenings. Nonetheless, preparations for the observation of comet proceeded. During the unmanned period between the second and third manned missions, the leak in the primary and secondary cooling loops was of overriding technical concern. A reservicing kit had been authorized, built, and tested and was ready for flight. It had to be flown to the Skylab, and the crew had to install it. The loss of the coolant loops would have been catastrophic since the batteries and electronics in the workshop/airlock would have overheated and failed. This unit also provided the cooling needed by the pressure suits for extravehicular activities. The planned EVA's for the third manned mission would have been severely curtailed, if they could have been performed at all.

The pressure from the technical community was to launch as soon as possible

Launch of SL-4 was possible immediately upon recovery of the SL-3 crew. In fact, the possibility of launch prior to separation of the SL-3 crew was seriously considered and studied by the flight management team. A launch in late September, however, would have missed the passage of the comet with a nominal 56/60-day mission. No medical approval could be secured for a longer mission until the medical team could examine the crew, the medical experiment results, and the time history of their return to preflight base line physiological condition.

A complete analysis of the condition of the loops was very difficult since only temperature and pressure measurements were available. All calculations had to make assumptions in order to arrive at a leak rate. The primary system pump inlet pressure had, during the second mission, become dangerously low and the pump had been turned off to prevent damage due to cavitation. All indications were that the secondary system was leaking as well, but there was a reasonable chance that cooling would remain active through November. (The secondary loop was leaking and reached the cutoff point on the last day of the last mission!)

A compromise launch date was finally reached and recommended by the Program Director. By delaying the launch until November 6, the comet could be observed during perihelion during a nominal 56/60-day mission while at the same time, some reasonable assurance existed that the coolant loop would remain serviceable. At the same time, a conditional 85-day mission was planned, subject to a periodic medical review of the crew physiological condition after the initial 56-day period.

Eight days before the scheduled launch of SL-4 (13 days before the actual launch, see below), a most serious anomaly was detected by the ground controllers as they monitored the telemetry from the workshop. The Control Moment Gyro (CMG) number 1 wheel speed indicated a drop in speed from 9,123 to 9,060 rpm. Simultaneously, the current in the motor winding increased as did the bearing temperature. After about 60 minutes, the wheel returned to normal speed as did the current and the temperature. A wheel slowdown, combined with the increase in energy, indicated some bearing distress. The CMG's were, of course, fundamental to the control and orientation of Skylab. Without momentum control, the cold gas attitude control system would soon be depleted.

(The sudden onset of a CMG bearing problem came as a surprise to the design engineers since ground tests of the CMG's had been conducted for years without failure and it was assumed that the zero gravity environment would be more benign. Also, in the unmanned periods, the bearings were not being severely stressed since no maneuvers were being performed. It was difficult to envision a bearing problem which would appear and disappear so suddenly.)

The combination of the wheel speed problem and the coolant loop leakage made it imperative that SL-4 be launched as soon as practical. However, that event was delayed at about the same time.

The Saturn IB launch vehicles had been designed in the early 1960's and extensive use was made of aluminum alloys which were subsequently found to be subjected to stress corrosion. (Stress corrosion is a phenomena which produces rapidly developing cracks when the material is subjected to a corrosive environment and the surface is in tension. It is a time dependent failure which can appear after long periods of satisfactory behavior.) All of the structural components were analyzed (see Lessons Learned) and all elements which were easily replaced were redesigned and fabricated of a different alloy; all elements which could not be inspected were redesigned and replaced regardless of the difficulty involved; and finally, all others were subjected to a rigid and controlled inspection procedure. During the final preparations for shipment of the final S-IB stage from the Michoud, Louisiana, factory to the launch site in Florida, inspection of the tail fins revealed cracks in a web section. The cracks were removed and reenforcing gusset plates were installed and the fins were judged satisfactory for launch. However, the incident sensitized the launch team and special attention was given to the regular inspections.

After the vehicle had been loaded with propellants during the countdown demonstration test, a routine inspection of the tail fins revealed instances of stress corrosion at the mounting bolt holes where the fins joined the stage. The cracks were obviously unacceptable. Action began immediately to replace all fins which had cracks with spare fins. The replacement took place on the pad with the vehicle on the launch platform. All bolts were removed (one fin at a time), the holes inspected by dye penetrant means, all suspected cracks were etched, and the failed fins replaced.

At the same time, a complete analysis was again instituted on all stages and all components were restudied to see if any suspect material was not being examined. Also, all known material was reinspected.

(The structural and material engineers at MSFC were surprised by this failure since they had previously reexamined the stress corrosion potential twice and had certified to the program that all suspect material was routinely inspected. The fin cracks were found during a routine inspection but the crack had formed under a bolt head where inspection would not reveal the presence of a crack until it had progressed beyond the head.)

Since the vehicle could not be reinspected after the flight fuel load had been made, the possibility of cracks forming at the fin mounting holes just prior to launch had to be recognized. Structural analysis showed that a rather large crack was tolerable, but, as assurance, a heavy bracket was added to further distribute the flight loads.

The analysis revealed still another area which was not on the inspection list. The S-IB was supported on the launch stand hold-down arms by a ball fitting on each fin. Each ball was designed to fit in a cup on the hold-down and the earlier analysis had assumed they would be in compression and, thus, not subject to stress corrosion. The later analysis showed the tolerances on the ball and socket to be such that local areas of tension could exist. The ball fittings were inspected and, predictably, stress corrosion cracks were found. (It should be noted that there is a strong probability that previous vehicles had been launched with this type of crack in the ball.) All cracked balls were replaced, and a soft shim was installed to evenly distribute the stresses.

The reinspection of known points of potential cracks also revealed a series of cracks in the main longerons of the aft skirt structure of the S-IVB stage. These main structural members carried the full vehicle thrusts loads from the S-IB stage to the S-IVB tanks. (The cracks were located in such a position that they may have been a result of the forging operations used to form the piece.) These cracks were burnished and removed. Since the structure was normally in compression and any residual manufacturing or assembly stress was relieved, the fix was satisfactory.

Skylab was ready to begin the last manned mission. On November 16, 1973, at 14:01 GMT, Astronauts Gerald Carr, Dr. Edward Gibson, and William Pogue were launched to rendezvous with the workshop. All plans were made for an 84-day mission, but care was taken to clearly state that only 56 days was authorized and that extensions to 84 days would be granted only if the crew and hardware condition warranted continuation of the mission. Rendezvous and docking proceeded normally and the activation period was initiated. Activation was slowed somewhat by a "stomach awareness" which was experienced by some crew members. Also, much new equipment was launched to repair the workshop, observe the comet, extend the mission and augment the experiments. Properly stowing these items took longer than planned.

Three days after the launch, the crew reserviced the coolant loop, removing that concern for the remainder of the mission.

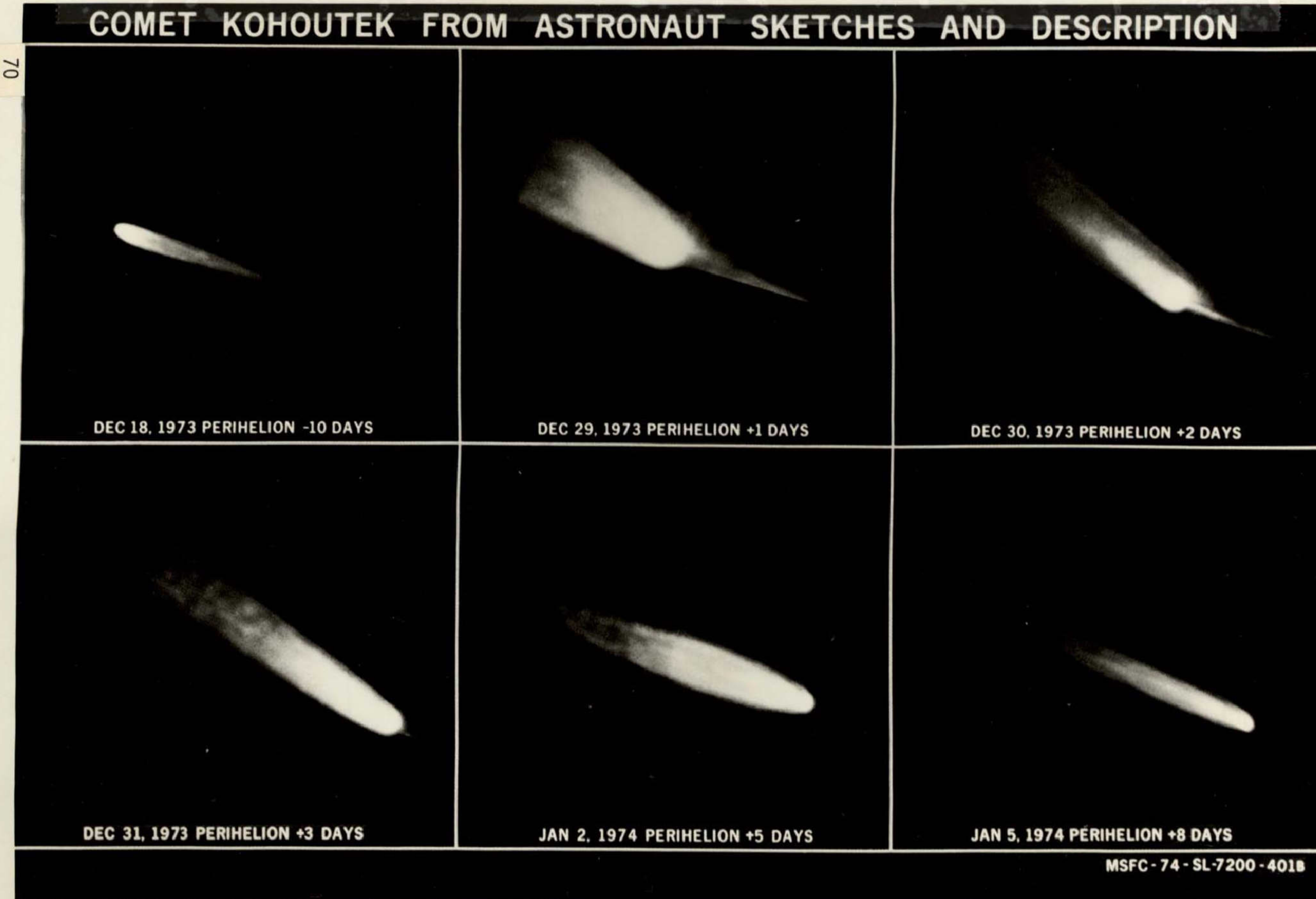
The servicing of the coolant loop is worthy of some additional discussion since it illustrates the interrelationship and interdependency of the many elements of Skylab and how diverse organizations can be organized into a common team.

The leak in the coolant system was detected by the MSFC ground team, examining the telemetry data. The JSC flight control team, in concert with the MSFC engineers analyzed the situation. The SL-3 crew searched (in vain) for a leak. The JSC engineering team and the MSFC engineering team designed fixes and the Skylab management team selected the best components of each. The high-fidelity engineering mock-up was used to perfect the design and the Water Immersion Facility and one-g trainer were used to develop the installation procedures. Finally, the SL-4 crew was able to make the necessary on-site modifications to install the equipment and service the unit.

The SL-4 flight crew performed all of their assigned experiments as planned. Several activities are worthy of note.

The observation of the Comet Kohoutek was one of the foremost objectives of the last Skylab crew. When viewed from the ground, the comet was disappointing to the average viewer. However, to the scientific observers, the comet represented an unusual opportunity for observations from space. The SL-4 crew had been specially prepared for the event and their first observations were made with out-the-window photography 6 days after they arrived and scientific airlock experiments were begun 3 days later. The ATM instruments were not used until near perihelion since they had been designed for solar observations and the comet emission levels were considerably less than those of the Sun. In addition, two EVA's were performed, one just prior to perihelion and one just after, December 25 and 29 respectively. Two experiments, T025 and S201 were performed by the crew while EVA. The crew also spent considerable time observing the comet and recording what they saw. Their verbal descriptions and color sketches were invaluable in the analysis (Figure 16).

As mentioned earlier, the Control Moment Gyro number 1 began exhibiting signs of distress just before the launch of SL-4. As the mission progressed, the same wheel showed more indications of the problem as the wheel speed and temperature exhibited more frequent excursions from normal. Finally at 0815 GMT on the seventh day of the mission



HOW COMET KOHOUTEK LOOKED TO SKYLAB 4 CREW

FIGURE 16

(November 23) a rapid rise in motor current and an accompanying increase of bearing temperature from 21°C to just under 90°C occurred. Simultaneously, the wheel speed pick-off failed. (From the current, wheel speed was estimated to be about 3,800 rpm, down from a normal 9,060 rpm.) The failure occurred while the crew was asleep and while the workshop was out of contact with the ground. Ground controllers removed the current from the wheel when contact was made and the computer automatically switched to two-gyro control. (The possibility of losing one gyro had been considered to be extremely remote but a preplanned computer program had been written and stored in the memory. When the CMG failed, effort was started to write a single gyro control law and to program it in the event that a second gyro failed. It quickly developed that such an undertaking was fruitless since the problem was so complex it could not be completed before the end of the mission.)

The loss of the CMG was a shock and a surprise to the Skylab personnel, but there was reasonable confidence the mission could be completed satisfactorily. The open question was the demands which would be put on the cold gas thrusters during maneuvers since the gas supply was limited. The extravehicular activites scheduled for the day of the failure were conducted and went off as planned.

Still another surprise was in store for the Skylab personnel. On the 19th day of the mission, Control Moment Gyro number 2 began showing signs of irregular operation similar to those of number 1. Ground analyses of the situation led to a hypothesis that the bearing distress was due to a lack of uniformity in the in-flight lubrication system. An automatic "slinger" system was used to provide oil to the CMG bearings automatically. In zero gravity, the oil did not flow in the same way it did on Earth.

The lack of lubrication, combined with the stress of maneuvers, seemed to be the cause of the bearing failure. The bearing temperature was automatically controlled by a sensor and a heater located in the wheel. The heater elements could be controlled by ground command and the designers theorized that a tighter control of the temperature would be beneficial. The bearing temperatures were controlled from the ground for the remainder of the mission.

The control of the workshop with only two gyros operating proved to be quite tricky. Earth resource passes resulted in more usage of thruster gas than had been planned and the Program Director cancelled several passes until a new maneuver scheme could be devised. Earth resource passes had been conducted from sunrise to sunset on an orbit path. Thus, the maneuvers from the solar inertial attitude to the local vertical attitude required maneuvers in all three planes. A new plan, having the earth resource pass conducted from orbit-noon to orbit-noon required a single plane maneuver and, thus, used less propellant. At the same time, each maneuver was optimized in the ground simulators to further reduce the demands. As a result, the earth observations were initiated again. (The value of excess consumables was once again demonstrated. The premission predicted normal usage of the nitrogen gas used for attitude maneuvers was 162,000 N-Sec. Of the 374,000 N-Sec. of impulse loaded on board, 338,000 N-Sec. were used.)

The constraints imposed and the concerns over the bearing distress were reflected in the activities of the flight management team. Each sponsoring office requested priority for their experiment and most experimenters found new objectives as a result of studying the data acquired during the first two missions. Also, the second crew, after getting a slow start because of motion sickness, concluded the mission by working at a pace which could not be maintained for long periods. The SL-4 crew had determined before liftoff that the proper mode of work for an 84-day mission was to establish a more conservative work/rest pattern and to stick with it. The paced work pattern was not understood by all the investigators and they expected the crew to work for the full mission duration at the level the previous crew had finished their mission. The flight planning team initially tried to push the flight crew and there were several verbal exchanges over the communciations links before the flight scheduling became routine.

The last major decision which the flight management team and the Program Director faced was the question of what condition the workshop should be placed at the end of the mission. There was considerable interest in allowing the workshop to continue in an active mode to see how long the various systems, such as the Control Moment Gyros would last. The decision was made to deactivate the workshop and to leave it in a condition that future space vehicles could revisit but to turn off the systems in a controlled manner. Two days of engineering tests in the unmanned mode were permitted.

On February 8, 1973, the crew entered the Command Module, separated from the workshop, and returned to Earth. At 11:17 a.m. EDT, after 84 days, 1 hour, and 15 minutes of space flight, the manned operational phase of Skylab was over.

SKYLAB LESSONS LEARNED

A. Introduction

At the completion of the Skylab Program the major Program Offices involved in the development and operations phases were directed to document their important experiences in a series of reports called "Skylab Lessons Learned." Five reports were prepared, one each by the Skylab Project Offices at JSC, KSC, and MSFC; one by the Saturn Project Office at MSFC; and one by the Headquarters Skylab Program Office.

Mission reports were published as they had been in all previous programs (References 1, 2, 3, 4, 5, 6, 7). These reports are complete and include very detailed descriptions of the hardware, the program, and the operations. Such mission reports are complete documents which are useful records of the missions, but experience and lessons learned ususally remain in the minds of the individual concerned. For Skylab, the "Lessons Learned" documents were directed to be brief summaries of the important experiences which the various individuals involved considered to be worthy of passing on to successive programs. The format was prescribed to be a brief state of the lesson with an amplifying comment on the background. Statements were solicited from all working levels and no "management screening" was done other than to assure the statement was clear and that the lesson was germane. The intent was to document the lesson with enough detail to permit the reader to understand the lesson and the experience which led to the lesson. The reader was expected to use the other written records (i.e., mission reports, mission summaries, review reports, etc.) if additional background was required. In retrospect, the reports would be of more use to readers if an individual had been associated with each lesson such that if further explanation was required, it could be obtained. To correct this deficiency in this report, it should be noted that the lessons documented herein are the personal experiences of the author. This section of this paper is not a summary of the other papers, but is, in fact, a complementary document to the other lessons learned. Experiences which the author shared may appear in other papers and there has been no attempt to remove any duplication.

The lessons documented here predominantly reflect experiences gained in Skylab, but in recognition of the fact that the potential readers may not have the same body of experience as was expected for the original documents, some of the lessons described were not discovered originally in Skylab but they were successfully used, either in the same form as in previous programs or used with minor modification.

Many of the lessons can be classified as the application of common sense and, as such, should need no highlighting. However, experience has shown that as the size of a project increases, the more difficult it is to apply and control the sensible processes. Also, it is most desirable that the manager of large projects have a few simple, easily understood operating principles.

B. Lessons Learned

1. Lesson: The Cost of Change

Nothing is free. The only issue to be addressed is the value against the cost.

Background:

Every document, change, report, study, test, analysis, conference, telephone call, etc., has a cost in manpower and material. All too frequently managers will delude themselves into thinking an action has "no cost" or "no impact" when the true assessment would be that the action can be undertaken with a relatively small effort. Also, decisions to change an item are frequently made without a thought-out assessment of all aspects of the task and with only an assessment of the visible work involved.

For example, when the workshop was in the final stages of preparation, a number of decals (containing operating instructions) were judged to be less clear than was possible. When the final bill was known, each decal change cost tens of thousands of dollars, all accountable. The visible task, removal of the old decal, the preparation and installation of the new, was only a few dollars, as you would suspect. However, good aerospace procedures were used and work orders had to be prepared and processed, the work had to be reviewed and inspected, the drawings had to be changed, the change had to be processed, drawing lists had to be modified, test procedures modified and reviewed, crew checklists had to be changed, and to all this, overhead costs had to be added.

Change options, it should be remembered, may reduce cost, but a price must be paid for everything.

2. <u>Lesson: Plan Conservatively and Execute Boldly</u>

The initial development program plan becomes the measure of progress. Since research and development programs are, by definition, not completely understood, good management will provide adequate reserves in time, resources, schedule, and performance. Once the program is underway, indecision costs time and money.

<u>Background</u>:

In the Skylab development effort, specific management attention was given to providing sufficient funding and schedule flexibility. There was no universal formula or criteria which was applied across-the-board, but the amount of cushion was determined by an assessment of the complexity of the task, the criticality of the function, how the development depended upon outside elements, the experience of the manager, and the degree of optimism/ conservatism the manager had showed in the past. For critical, high-risk items with a normally optimistic manager, cost estimates were as much as doubled.

3. <u>Lesson: Program Variables</u>

Three items can be varied in a development program - cost, schedule, and program content. Establish the most important factors. Ensure that your priority matches that of your management.

<u>Background</u>:

Only two of the variables can be controlled in a development program. The worst examples of program management are those where cost and schedule are tightly controlled and no relief is given in performance. The important variable may change through a program and may be different for different elements.

In Skylab for example, the S-192 Multispectral Scanner (an earth resource experiment) had sensor performance as the highest priority requirement, since it represented a desirable experiment only if it operated with extremely sensitive sensors. Later in the development cycle when the sensor performance was established, schedule was primary since it was required to complete the MDA and a delay would have resulted in a very costly delay in the major module.

On the other hand, when cost rates indicated a potential overrun in the workshop, premium (overtime) work was reduced and a schedule adjustment was more acceptable. Adequate schedule reserve was available in this case.

4. Lesson: Program Reserve

Plan adequate reserve in resources, schedule, and performance.

Background:

Since these three variables can be traded off, initial plans should recognize the possibility of needing all three. For example, in Skylab, the contingency launch vehicle and CSM were added to the program (four sets of hardware were provided for three manned missions) to ensure that three missions could be accomplished even if a launch failure had occurred on one of the three planned missions. It was recognized, however, that in the event the program costs escalated, that hardware could be terminated with a resultant cost reduction. The reduction in program content would not have been large.

A similar approach was successfully used in the Gemini Program where 15 launch vehicles were planned for 12 missions. As a cost avoidance measure, the three back-up vehicles were cancelled.

5. Lesson: Program Initiation

Large development programs should not be started until a full estimate of the resources needed is available, with adequate reserves identified. The resources must include manpower and time requirements as well as funds. These resources must be fully committed and planned by all levels of decision prior to any large scale beginning of a project.

Background:

Skylab was begun prior to the completion of the Apollo Program and funds were requested from Congress. Unfortunately, until the lunar landing was accomplished, a full commitment of the resources needed to support the development could not be made. The result was an evolutionary development program in the early phases. For example, the Airlock Module, in its original configuration, was built for a June 1968 launch. The contract was let in September 1966 and the 22-month development period dictated the selection of Gemini hardware. The Airlock was built and assembled in that configuration. The final Skylab Airlock was somewhat modified from that configuration, but the basic design remained. Much effort could have been saved if the hardware had not been built until the program was ready for full-fledged development.

6. Lesson: Provide Flexibility in Planning

The late additions to program objectives can be extremely productive and may be more important than the initial detailed objectives. Prepare the program plan to be able to accommodate good ideas which are surfaced late in the development cycle. Be prepared to accept new ideas. Have a sufficient financial reserve in the late years.

Background:

Many of the detailed program objectives of Skylab could only be thought of after considerable design had been accomplished. For example, the addition of the solar sounding rocket program permitted the solar data to be calibrated directly and, thus, greatly enhanced its usefulness. The ground based observation program (the Skylab project funded the enhancement and use of ground based solar observatories around the World) gave the solar physicist the base of data needed to observe the solar events as they occurred. Neither of these ideas were conceived at the inception of the program, but as the planning progressed, it became obvious they were required.

Numerous examples can be cited, but the general tendency when program costs increase in the early years is to reduce the fiscal forecast in later years since "all the engineering will be complete" and "the test hardware will be built early." Don't believe it. The engineering will be needed until the end, and new test requirements will be surfaced late as you become smarter.

7. Lesson: Organization

It is important that the roles and responsibilities of the program elements be understood by all participants in the development. For a large program with many dispersed participants, that understanding should be written and recorded.

Background:

As the Skylab Program evolved, the many organizational interfaces led to some areas of overlapping responsibilities. For example, the conduct of subsystem tests at a site other than at the development organization led to confusion as to who developed the test requirements, who formulated the test procedures, who was responsible for the test, who conducted the test, and who evaluated the test results. The Skylab Program used Program Directives to resolve and control such areas of uncertainty. This specific issue was addressed in Directive 26, "Intercenter Responsibilities for Support and Preparation of KSC Test and Checkout Plans and Procedures."

8. Lesson: Use a Phase Approach to Development

A phased approach to hardware development (i.e., Preliminary Requirements Review, Systems Requirements Review, Preliminary Design Review, Critical Design Review, Customer Acceptance Review, Design Certification Review, and Flight Readiness Review) is a good disciplined approach to hardware development and should always be followed. The requirements reviews formalize the task to be done by the subsystem, prior to design. The preliminary design review carefully determines that the requirements can be met and allows the design to be "base lined." The critical design review permits a detailed examination of the design and should only be conducted when virtually all drawings have been released. This permits the design to be placed under configuration control. The CAR formally reviews the test results to ensure the design meets the requirements and should immediately precede shipment. Finally, the FRR ensures that all open items (i.e., test failures, anomalies, reviews, etc.) have been closed prior to flight. Normally, the FRR is conducted just prior to the final full-scale test just preceding launch, the Countdown Demonstration Test, or the CDDT.

The documentation and support needed to conduct such reviews should be delineated at the outset of the program (i.e., a reliability plan should be available at PRR, a hard mockup at CDR), and the paperwork should be distributed to the review team at least 2 weeks prior to the review. Discrepancies, questions, or changes should be submitted in writing and should be closed out in writing. The Review Item Discrepancy (RID) system worked well.

Background:

In the interest of maintaining schedule, the documentation describing some experiments was not complete at the time of some reviews. This generally resulted in unsatisfactory reviews and occasioned subsequent reviews, or "delta reviews." In general, incomplete preparation for the reviews should be avoided except when there are clear gains to the program.

The use of RID's permits the discrepancies to be identified, codified, tracked, and closed out. Thus, at each subsequent review it is possible to see how previous criticisms were dispositioned.

9. Lesson: Configuration Control Procedures

The phased approach to development should be complemented by a progressively mature control of hardware design. Initially, the hardware design is merely conceptual in nature and may be described parametrically, by equations or design parameters, for example. At this stage, the subsystem designer should have control of his design and should have little controls placed upon the details. The designer should be engaged in trade studies, sensitivity analyses, and design variations which will lead to the next phase of hardware control, "base lining the system." This base line permits concentration on a specific design and allows detail design to begin. After a system is base lined, the designer can only change the concept when there is due cause and only after notifying other program elements to assure that each subsystem designer is aware of the design of interfacing subsystems. At CDR (drawing release) the detail design is complete and then formal Configuration Control should be initiated. At this time a rigid process should be established which will ensure that a design modification is only undertaken for understood cause and the full cost, schedule, and interface impact is analyzed prior to initiating the change.

Background:

Controlling the configuration too late in the development cycle results in design instability, particularly when systems interact. A seemingly minor change in, say, a reaction control valve could be reflected as a major change in computer software. Conversely, the application of controls before the design has been completed, or before trade studies have been made, result in costly modifications.

It can easily be seen that subsystem maturity should be timed so each subsystem is in the same state of development at CDR. When one system is based upon known technology and another interrelated system is advancing the state-of-the-art, initiation of design effort and the level of effort should be adjusted accordingly.

At the time of the failure, project personnel mentioned that the shield "probably was not needed anyway." The Program Director did not ask the next question, namely: why test it then? The proper pursuit of the requirement would have saved the cost of repeating the test and probably would have saved the agony of the Skylab 1 launch failure.

Caution: While a review is beneficial to ensure that program resources are not being expended to fulfull superceded requirments, no requirement should be changed without fully understanding the design implications.

10. Lesson: Update Design Requirements

Review design requirements periodically to ensure the hardware continues to reflect the real program needs. Requirement maturity can affect not only the design, but also the test verification of design as well.

Background:

Design requirements are stated early in the development cycle and tend to be more rigid than they deserve. Design requirements are frequently formulated on the basis of the best information available at the time. These requirements should be examined at intervals to ensure that they are proper.

Early in the Skylab Program (1967-68) a design goal of 0.99+ probability of no penetration by micrometeoroids was established and, based upon the environmental model available at the time and with the existent puncture mode analysis, the micrometeoroid shield design was established (the shield was, of course, the one which failed at the launch of Skylab 1). Later data (Pegasus, et al) demonstrated that the model was conservative and refinements to the analysis technique showed the problem to be greatly reduced.

No design change was made since the design was essentially complete and to change the design would have been costly. However, the first systems tests resulted in a failure to deploy. The tests had to be modified and repeated to prove the soundness of the design (the original test failure resulted because the "zero gravity" design of the micrometeoroid shield resulted in deformation during the one-g test. Zero gravity simulation during test is tricky and costly.)

11. Lesson: Paper Review of Designs

Specific design reviews which are based upon an analysis of drawings can inadvertently overlook important features such as operational incompatibilities.

Background:

During the early development phase of the Saturn S-IB stage, data became available showing that 7079-T-652 and 7178-T-6 aluminum alloys were susceptible to stress corrosion cracking. These materials were used extensively in the stage and an intensive effort was undertaken to eliminate the problem.

A drawing analysis was made to identify all components which were made with the suspect material and which were subjected to residual tensile stress. (Stress corrosion is, of course, a long-term material cracking which occurs when the aluminum is exposed to a corrosive environment while under tensile stress.) All parts which could be replaced without a large cost were made of a less susceptible material. Those items which were difficult to replace were replaced only if they could not be inspected on a periodic basis. The remaining items were required to be inspected on a regular schedule.

The Skylab launch vehicles were built in the 1966-68 time frame, and special reviews were undertaken to assure that all time-dependent problems were eliminated. One of the reviews covered the stress corrosion of the S-IB. Another drawing review was held to assure that all susceptible parts were identified.

Skylab 4 completed the last propellant loading test prior to launch when a routine inspection uncovered a crack. Stress corrosion had caused a crack at a mounting bolt hole. All required factors were present: time, tensile stress, and a corrosive atmosphere. The unnerving factor was that the crack appeared from under the head of a bolt and the design inspection had not identified that this point of susceptibility was not capable of "routine inspection." Indeed, there was no way of inspecting for a failure after the flight load of fuel was put in the tanks. As a result, another design review was held. All of the mounting bolts were removed and special brackets were installed which carried the load over the suspect part.

It is quite possible that previous Saturn IB vehicles were launched with cracked bolt holes.

12. <u>Lesson: Detailed Scheduling of Work</u>

All fabrication, assembly, and checkout activities should be scheduled in detail, but rescheduled activities (sometimes called unscheduled work) should be even more carefully controlled and scheduled.

Background:

In a development program involving many elements being supplied from a variety of sources, it is inevitable that some components are not available when scheduled. More than likely, these late components will be rescheduled for weekend, third shift, or slack time installation. Such off-time activities can become uncontrolled since the normal flow of work is interrupted and the configuration is not that originally postulated by the planning staff. The situation, schedule pressure, incomplete planning, and unknown configuration lends itself very well to errors and mistakes. This is precisely the time not to take shortcuts in planning or in documentation.

The workshop was particularly susceptible since it had been most affected by the change from the wet workshop to the dry workshop configuration and was, therefore, the last module to be completely defined. Items were quite late in fabrication and there were many instances of off-line installation. The original installation procedure was developed assuming properly phased activities. When the part was actually installed, frequently, the original procedure could not be used and additional time was lost while a new procedure was developed.

Caution: Never permit off-line installation to be accomplished without a written procedure. The same controls must exist for off-line work as for in-line work.

13. Lesson: Use of Common Test Procedures

When a component is to be tested at a number of locations (e.g., the development contractor's plant, the integration contractor's plant, and the launch site), decide upon a single format and approach for the conduct of the test, for control and approval of waivers or fixes, for configuration control, and for documentation in general. Use the same basic test processes at all of the best sites.

Background:

Each organizational element (contractor or government) has, in general, developed a "standard" method of handling the routine of conducting development tests. Without early management attention and control, test procedures from one test site will not be transportable to the next level of test integration, and much effort (dollars) will be needed to rewrite the documentation.

For example, the MDA test procedures used to prepare the module at the Martin-Denver plant were rewritten when it was tested with the Airlock at the MDAC St. Louis plant, and further modified when the module was shipped to KSC for testing.

Caution: Do not minimize the seriousness of this problem which cannot be simply solved by a decree. Transferring test procedures between test organizations is not without problems as well. The "Angry Alligator" of Gemini IX (a payload shroud on the docking target did not completely separate, and the resultant partially deployed configuration prevented docking) was the result of the use of a procedure by technicians who were not familiar with the practices and terminology of another organization. The optimum method is to use a common test team as well as procedures. The ATM test team followed the hardware from MSFC to JSC to KSC, but even then, careful planning was needed since inspection and safety and documentation requirements are not the same, and common practices must be adapted.

14. Lesson: Lack of Spares

It is not always economical to provide only one flight aritcle without a ready spare.

Background:

As a cost avoidance measure, back-up flight units were eliminated from the experiment development programs in most instances. Since many of the experiments interfaced directly with the major flight modules, when an experiment malfunctioned during preflight test, a backup unit could not be immediately substituted, thereby permitting the readiness work to flow uninterrupted. Instead, the failed experiment had to be removed, analyzed, repaired, reverified, and reinstalled. In the meantime, the main hardware test sequences were stopped or work-around procedures developed. The former course was, of course, unacceptable while the latter course necessitated multiple planning sequences and was, therefore, costly.

A minor variant of the hardware minimization was used on many of the Skylab experiments. Frequently, two articles were built, a flight article and a test article, which were planned to be the backup article after undergoing refurbishment. Again, failures during the testing of the flight article frequently occurred prior to the availability of the reworked test article, necessitating costly work-arounds and delays. Minimizing the buy of subsystem hardware is an effective cost avoidance measure providing that careful analysis is given to the probability of availability, or, if a work-around plan is acceptable in the event the subsystem does not maintain schedule.

15. Lesson: Indicators of Schedule Status

Simple indicators of program progress should be devised for a gross technique for judging the schedule status. The progress toward major milestones is needed to prevent surprise schedule slips in a major element. Such slips in one element unbalance a program and require costly readjustment of the detailed schedule.

Background:

Early indication of a potential slip in a major milestone will permit management to use overtime or work adjustment to keep all elements in balance. Program management used the status of specification test documentation, drawing release status, ICD release status, qualification test status, and other detailed reports to provide an early indication of progress.

A gross indicator of progress can be made by examining the cost/schedule plan against progress. By simply adding up the number of milestones planned for the month and dividing that number by the planned cost and comparing it to the ratio of the milestones actually accomplished and the actual cost, a simple indicator is available. When the planned milestone/dollar ratio is equal to the actual ratio, the program is progressing as planned. If the planned ratio is greater than the actual, the program is falling behind schedule or is heading toward an overrun. However, the indicator is gross and must be looked at monthly and cumulatively. It cannot be believed implicitly, but can only be used as a warning signal.

16. <u>Lesson: Criticality Assessment</u>

Documentation levels, controls, and redundancies can be determined by assigning a criticality to each subsystem, experiment, or component. A component determined to be vital for crew safety (Criticality 1) requires a complete set of documentation and controls. Systems with this criticality are extremely costly to develop and to control since the data package generally begins with the pedigree of the raw material and carefully documents and controls each step of the development, fabrication, and test process.

Components which are required for primary mission success (Category 2) can receive somewhat less rigid treatment although in actual practice the controls on Criticality 2 hardware are almost identical with Criticality 1 components. Items which affect secondary objectives should be placed in Category 3. Considerable relaxation of documentation and control is possible for components such as these. For example, qualification testing can be reduced and verification by analysis is acceptable. Verification by similarity (i.e., use in a comparable but not identical manner) can be utilized.

Peripheral items, such as cameras, small experiments, and crew equipment of a noncritical nature should be categorized as Criticality 4. These items require only enough documentation and controls to ensure they are safe and represent no hazard.

<u>Background</u>:

The Skylab Program made use of failure analyses to categorize systems and assign criticality numbers. Standard documentation and controls were determined for each category. The experience, however, fell somewhat short of expectation since it was difficult for a subsystem engineer to accept that his component "wasn't important." The tendency was to over categorize and, thus, over control the development. It required management pressure to ensure the proper level is assigned.

17. Lesson: Reduced Requirements for Experiments

The tight, detailed, and documented procedures of Skylab and Apollo do not have to be followed for space experiments. Requirements can be relaxed as the flight criticality decreases. Documentation levels can be related to the price of failure.

Background:

The Skylab Program tried to establish levels of control by criticality number. Criticality 4 was a secondary mission objective item. The levels of documentation and control placed upon Criticality 4 was significantly less than on other items. Unfortunately, the individual experiments were classified as Criticality 3 early in the program, and no investigator wanted to be reclassified as "secondary." The Program Director had minimal success in reclassifying the already assigned experiments, but the Student Investigations and Science Demonstrations were all classified in that manner, and the Criticality 4 controls were exericed.

Calling the experiments "secondary" was a psychological mistake and should be avoided. Each scientist desires to feel that his experiment is vital and important.

Caution: Requirements can easily be reduced to a level where the task cannot be accomplished.

18. Lesson: Subsystem Managers

Examine each system to ensure that the responsibility for dynamic systems is not vested in organizations normally responsible for static systems. Where systems cross normal engineering lines (i.e., structural, machanical, electrical), ensure that a subsystem manager is identified who understands he is responsible for all aspects of the item.

Background:

The engineering responsibility for the OWS micrometeoroid shield was vested in the structural group and was, therefore, pursued as a structural/mechanical problem. The structural/ mechanical design was pursued in a normal manner, and a "sneak circuit" aerodynamic load problem was overlooked. (A "sneak circuit" is defined as a path for energy to travel which cannot be found unless the entire system is examined.) A "subsystem engineer" might have asked the interface question which would have uncovered the loads discrepancy brought about by the sneak pressure path. It is clear that the normal assignment, structural design, mechanical design, and loads design, did not uncover the problem.

19. Lesson: Use of Committees

Do not use committees for decisions. Committees are advisors and consultants.

Background:

Committees are useful agents to compile information and to discuss and explore issues. Committees which are addressing subjects which are controversial and upon which there are diverse views, tend to arrive at compromise decisions or the position of the dominant personality. Committees which have simple subjects or a unanimity of opinion were not necessary. A clear cut responsibility for the consequences of a specific decision is frequently lacking, and, indeed, a committee cannot execute an action resulting from a decision.

Decision makers should make maximum use of all information channels prior to passing judgment. Committees are useful to bring together for discussing all sides of the issues and are quite useful tools to ensure that all nuances of a particular path are uncovered. To ensure that this occurs, committee membership should include individuals who represent all aspects of the issue.

Responsibility for a decision must accompany the authority for a decision.

20. Lesson: Incentive Contracts

Incentive contracts are an effective management tool to ensure a successful development. Award fee contracts should be considered for R&D contracts.

Background:

Cost-plus-award-fee contracts were successfully used in Skylab as an effective means of communicating with and controlling major development contractors. This type of contract reimburses a development contractor the legitimate costs incurred for the described work plus a small fixed percentage as a fixed fee from which the contractor receives his profit. Over and above this stipulated percentage, the government provides an additional incentive fee to reward contractors for exceptional performance. The amount of award fee earned during a specified period is determined by a government award fee board which grades the performance and selects the appropriate financial reward. The amount of this fee element (the maximum percentage is fixed in the contract) is arbitrarily determined and is not subject to appeal or negotiation.

Award fee contracts are more flexible than normal incentive contracts which prespecify, in the contract, the incentive elements. They are easy to administer and can be adapted to new circumstances as they arise. Award fee contracts are written with the specific performance requirments established periodically. For example, for one period, the government may consider schedule maintenance as the most desirable performance. The contractor is notified of the goals and his management effectiveness is evaluated and, at the end of the period, a portion of the award fee is granted, as appropriate. For the next period, perhaps cost reductions will be considered the most beneficial to the government and the contractor's performance will be assessed with those predescribed goals in mind.

In this manner, the customer and the contractor both know the expected performance goals, and the successful achievement of those goals is beneficial to both sides.

21. Lesson: Overruns

A tightly-negotiated contract will result in an equal probability of overrun or underrun.

Background:

The total cost of an R&D contract at the end of a program will include:

a. the negotiated price of the original work,

b. the incremental price of added work,

c. the negotiated fee on (a) and (b),

d. any incremental unplanned manpower needed to accomplish the work in (a) and (b), and

e. the incremental cost of the manpower over and above that negotiated in (a) and (b).

Item (a), of course, represents the work known to exist at the time the original contract was let. Item (b) represents work which was not known at the time the contract was let. (The more experimental the program, the larger (b) will be as a percent of (a).) Item (c) represents the fair return (profit) negotiated between the customer and the contractor. Item (d) represents the underestimation (overestimation) by the contractor of the amount of labor needed to do the work described in (a) and (b). Item (e) represents any escalation of labor costs. No fee is paid for (d) and fee on (e) is only paid if the inflation was the result of factors not under the contractor's control. The total cost to the government is less if the negotiator is successful in minimizing the manhours and labor costs negotiated to accomplish the job. Therefore, the probability of an overrun is increased.

This is not to be interpreted as a desire for larger overruns in contracts, but it is a notice that small (a few percent) overruns are not necessarily a sign of bad management. Negotiations for contracts should always err on the lean side.

Program management should assure that an adequate government estimate is budgeted as contrasted with the contract price.

22. Lesson: Safety Concerns

A list of safety concerns should be maintained throughout the program. The list should be controlled and reviewed periodically on a regularly scheduled basis.

Background:

Just prior to launch the Skylab Program developed and published a listing of each accepted risk which had been accumulated during the development program. Each item was discussed and a rationale for acceptance was recorded. This list was reviewed by the Administrator of NASA during the week prior to launch of SL-1.

In order to accumulate the items, it was necessary to rely on the memory of the various individuals involved and to search the records accumulated. Typical of the items recorded was the fact that the guidance computer for the S-IB vehicle was not redundant. A proposed change to add a redundant unit was rejected by the Program Director because the unit was internally redundant, had an excellent flight record, and the extensive modification would have resulted in a new, untried configuration.

It would be better to document such decisions as they were made to ensure that none was overlooked. A periodic review is needed because it is possible that the sum effect of risks may exceed the tolerable level. It should also be reviewed at intervals by upper management while there is still time to take action if it is needed.

23. Lesson: Decision Levels

It is very easy for decision making to gravitate to the top level of management. This practice will result in a slow moving program and also could lead to bad decisions since one man cannot be an expert in all fields. Force decisions to be made at the lowest level that has access to all of the factors which bear on the decision. Identify for each level of management those items which must be elevated for decision and those which should be left at lower levels.

Background:

Skylab used the basic NASA management procedures to establish controlled items. The Program Authorization Document (PAD) established those items which the Program Director was not free to change without higher authorization. Typical items were the launch dates, total program costs, program objective, and development center roles. The program specification expanded on these and contained requirements which were levied on the projects and which could not be changed. Typical of this level of control was the weight of a project, experiments and objectives, project costs, and delivery dates. Project specifications then further detailed the instructions to the prime contractors and contained end item specifications, contractual costs and cost rates, internal schedule milestones, and system performance requirements.

This, of course, is not intended to detail all items controlled but to illustrate the tiered approach to control which was successful. It should be initiated early.

24. Lesson: Disposition of Discrepancies

Comments on the design, hardware, or tests of hardware as made in the formal program reviews should be disposed of in a formal and controlled manner. The originator of the comment should be advised of the disposition and should have an opportunity to comment on the resultant action.

Background:

Skylab used the formal review process of successive detailed studies of each project. The process started with the Preliminary Requirements Reviews (PRR), Systems Requirements Reviews (SRR), Preliminary Design Reviews (PDR), Critical Design Reviews (CDR), Design Certification Reviews (DCR), Customer Acceptance Reviews (CARR), and Flight Readiness Reviews (FRR). At all but the FRR, a procedure was followed wherein members of the review team submitted comments by way of the Review Item Discrepancy (RID) process. Each RID was approved, accepted for further study, withdrawn, or disapproved. Unless care is taken with the study items, the initiator of the RID may not be aware of the final disposition (for example, study may result in ultimate disapproval) and the same item will be raised at the next review. Similarly, items which are disapproved most often result in the initiation of some action which will accomplish the intent of the RID. A rejection of the RID without management action could result in the item not being followed up and/or the initiator feeling his ideas were rejected. A category, "disapproved with action," should be established and then the resultant action should be tracked and treated as an open RID until the action is complete.

All RID's should be treated as open items and should be identified and controlled until the action is completed.

25. Lesson: Provide Operational Flexibility in Design

A primary design criteria for all subsystems should be one of providing a maximum of operational flexibility. That is, subsystems and systems should not be designed to operate in one primary mode but should, where possible, be designed for a variety of operating modes, even if efficiency must be sacrificed.

Background:

Lack of operational flexibility was designed into the video tape recorder as a coat avoidance and schedule maintenance decisions. The video tape recorder was a "late add on" and was a minor design modification of the Earth Resources Technology Satellite (ERTS) recorder. It was controlled by the crew and playback was commanded from the ground. Thus, use of the recorder required a crew member to traverse to the recorder to both turn on or turn off the system, necessitating coordination which should not have been required.

Conversely, the original workshop electrical design had three independent systems: the Workshop Solar Array System (SAS), the ATM Solar Array System, and the Command and Service Module Fuel Cell System. Each system was sized to operate the OWS, ATM, and CSM, respectively. An early decision was made to bus the OWS and ATM systems and later, a further decision allowed the use of the CSM power to operate after docking with the workshop to provide the power needed by the CSM. Because of the failure of the micrometeoroid shield which caused one SAS panel to be torn loose, those two decisions saved Skylab. The CSM powered itself and the ATM solar arrays powered the workshop until the first Skylab crew released the remaining SAS panel during EVA (extravehicular activity) on mission day 13. Six hours later the electrical power available rose from 4,000 watts to 7,000 watts.

26. Lesson: Provide Excess Consumables

Design the systems on any spacecraft for a maximum of expendables and consumables. Assure that the quantities of these expendable items exceed those necessary for the design mission by a wide margin.

Background:

The electrical power and attitude control gas of Skylab exceeded the normal mission requirements. Without this excess, it would have been impossible to save the program since it was the excess which permitted the unmanned activities to be conducted which saved the mission.

As an example of the benefits which can be derived from excess consumables, the question of how much hydrogen and oxygen should be loaded on the CSM for the fuel cells was raised in 1972. A Level 1 decision was made that the CSM would be fully loaded with cryogenics and a water storage tank would be provided to permit the fuel cells to provide power for 10-14 days. (The water tanks stored the water generated and prevented contamination of the instruments.) With the failure of the workshop solar array at launch, that power became mandatory until Astronauts Conrad and Kerwin released the jammed array.

27. Lesson: Stowage Flexibility

The mission peculiar stowage areas should be designed with a maximum of flexibility such that a wide variety of sizes and shapes can be accommodated on short notice.

Background:

The items which had been planned to be launched in the CSM stowage areas were changed radically at the last moment. For example, the first manned mission, Skylab 2, was changed completely in the 10 days between

C.2

Skylab 1 and 2. All of the thermal shield equipments, as well as the tools for releasing the restrained solar wing, were stowed at the last minute. Skylab 3 and 4 lifted off with new experiments, augmented film supplies, additional food, gyro packs, and other hardware supplies which had not been planned.

Stowage containers should be designed to tie down and restrain stowage items without major modifications.

28. Lesson: Trained Observers

Experiments should be designed to make use of the judgment and flexibility of trained observers.

Background:

The solar experiments on the ATM were designed to give a wide choice of action to the astronauts. As a result, they were able to record flares and other dynamic solar events which could not be forecast and which required instantaneous analysis, decision, and action. On the other hand, the earth resources experiments were added late and were designed to have little effect on the already built hardware. The result was a conscious decision to design a set of experiments which used little, if any, judgment on the part of the crew. The astronauts were primarily operators of the experiments and were not part of the experiment. As a result, the outputs were not felt to be as productive as the Visual Observations Program (VOP) which was added to Skylab 4 to better use the capabilities of man. The ability to look, observe, and decide what were the important features enhanced this experiments.

29. Lesson: New Manufacturing Techniques

Be vigilant when forced to use new fabrication techniques. Use soldering techniques, welding methods, painting processes, and other such processes which have ample experience to prove that the method is satisfactory whenever possible. In particular, be careful of having manufacturer "A" use manufacturer "B's" process.

Background:

Every program manager has his list of horrible examples. In Skylab, a typical example was encountered in the earth resources control panel. Here, because of volume constraints, a new soldering technique was used to increase the packing density. The resulting solder joints failed in test and a new design had to be made. The wire ends were to be soldered to posts and the actual operation was done "in the blind." As a result, a percentage of the joints failed and none could be adequately inspected.

The technique probably would be fine, after considerable experience was accumulated. But, for an operational program, it was a poor choice without more experience.

On the other hand, during the development tests, the paint on one of the major modules was found to outgas. Since the paint used by another contractor was satisfactory, the first contractor was directed to use the proven paint. However, it was also directed that he use the procedures which were developed by the other manufacturer and also to contract with the first contractor for assistance and help during the application. With adequate caution and controls, the paint was satisfactorily applied.

30. Lesson: New Electronic Components

Avoid the use of new electronic techniques and components in critical subsystems unless their use is absolutely mandatory.

Background:

New electronic components (resistors, diodes, transistors, switches, etc.) are developed each year. Most push the state-of-the-art and contain new fabrication processes. Designers of systems are eager to use them since they each have advantages over more conventional components. However, being new, they are untried and generally have unknown characteristics and idiosyncrasies. Let some other program discover the problems. Do not use components which have not been previously used in a similar application if it can be avoided, even at the expense of size and weight.

31. Lesson: Single Point Ground

A single point ground should be provided.

Background:

A single point ground requires that a copper path be provided for both legs of all electrical circuits joining the ground side of all components. The alternate is to ground all elements to the vehicle structure, similar to the circuits in an automobile. A single point ground is costly in weight but it reduces electromagnetic problems brought about by ground loops and inductive circuits.

32. Lesson: Deorbit

A positive means of deorbiting spacecraft and space debris should be provided for all large elements.

Background:

The Skylab workshop was not equipped with a means of deorbiting at the end of the mission nor was the last stage of the launch vehicle (S-II Stage). As a result, the S-II Stage, the workshop, the payload shroud (four elements), and assorted smaller debris were left in orbit for random decay under the influence of aerodynamic decay. Since the orbit was inclined at 50° to the equator, the potential impact points cover all places on Earth between 50°N and 50°S latitudes. While a large percentage of the hardware could be expected to disintegrate as it travelled through the atmosphere, there is always a finite probability some larger parts will survive and reach the Earth's surface. Thus, while the probability is small, an accident is a possibility.

33. Lesson: Manufacturing Aids

It can be false economy to eliminate manufacturing fixtures, mock-ups, and aids. Efficiency in the assembly and manufacturing processes brought about by the use of these devices can easily off-set the relatively small costs.

Background:

Early in the program, it was decided to minimize these tools and to eliminate all but the most essential. As the program progressed, reevaluations of the needs frequently resulted in the more costly practice of adding the unit to the plan.

As a typical example, without a cable and tubing mock-up, all final fabrication and fitting of cables and plumbing had to be done in the flight hardware. Since the size of the hardware prohibited unlimited access, the fabrication work and the assembly work had to be interweaved.

Three dimensional mock-ups of the spacecraft enabled wire bundles, cables, and tubing to be trimmed to fit in an off-line fixture. Since work space is generally at a premium in a spacecraft and since tight control of access is normal, the final trimming and fitting of long runs of wire and plumbing was time-consuming and caused schedule slip.

Three consecutive programs have found that it pays to add fixtures of this type since it permits parallel work and the extra cost of a mock-up is quickly recovered by not causing a slip in the main flow of flight hardware.

34. Lesson: Redundancy Design

When designing redundancies into systems, consider the use of nonidentical approaches for backup, alternate, and redundant items.

Background:

A fundamental design deficiency can exist in both the prime and backup system if they are identical. For example, the rate gyros in the Skylab attitude control system were completely redundant systems, i.e., six rate gyros were available, two in each axis. However, the heater elements on all gyros were identical and had the same failure mode. Thus, there was no true redundancy and a separate set of gryos had to be sent up on Skylab 4 for an in-flight replacement.

35. <u>Lesson: Combined Environments</u>

Be careful of combined environments. Most ground tests of components and systems are to test the effect of single environments (i.e., temperature, pressure, vibration, etc.) although combined thermal-vaccum tests are frequently encountered. The combined and synergistic effects of environments must, in general, be considered by analysis since combined environment test facilities are expensive and rare. One space environment, zero gravity, cannot be simulated except for brief periods and must be considered by analysis.

<u>Background</u>:

The Skylab attitude control system used rate gryos (two in each axis for a total of six) for angular rate information. These rate gyros had a bellows in the float chamber which contained a fluid which acted as a damper to gyro motion. When exposed to vacuum, the bellows expanded, as designed, and caused the damper fluid to be subjected to low (zero?) pressure. During thermal vacuum tests, excessive gyro drift was noted and was properly attributed to gas bubbles forming at the low pressure. In the one-g environment, these bubbles drifted to one location and the resultant behavior (drift) of the gyro was evident and constant. This drift rate was then compensated for in the software. The anomaly was classified as known, correctable, and acceptable.

However, in zero gravity, when the situation was encountered, the position of the bubble was not predictable or constant and, thus, its effects could not be compensated for in the software.

The problem existed until the replacement of the gyros by the crew.

36. <u>Lesson: Rapid Reaction</u>

Design engineers must be conditioned to react rapidly during anomalous operational situations. A full understanding of off-nominal modes of operation must be developed prior to the beginning of an operation. Design engineers who have become reliant upon large computer programs for system analysis must translate that knowledge to charts and tables for rapid reference to facilitate quick decisions.

Background:

At launch, the workshop micrometeoroid shield was ripped off by the airstream. While the vehicle successfully reached orbit attitude, the shield was an integral part of the thermal control system (Skylab used passive techniques to maintain the interior temperatures at an acceptable level) and the vehicle rapidly overheated. The manned launch was postponed for 10 days to allow time for corrective devices to be designed and built. In the intervening period, conflicting demands of the thermal, electrical, and attitude control systems required rapid assessment of situations and quick responses. The operational forces at Houston frequently had to take action without a complete engineering team, which had been organized to handle more routine situations, and had to readjust its thinking and decision process to react to the new, rapidly changing series of crises. It took a few days to become properly oriented. Future programs should prepare the engineering team to respond to quickly developing situations when the normal engineering tools, analysis, computation, and test are too slow. It should be pointed out that despite the room for improvement, the engineering/operations team did function effectively enough to save the vehicle - a considerable achievement.

37. Lesson: Crew Checklists

Crew checklists used to describe operating procedures should be complete but should be kept simple. Backup procedures, redundant procedures, and trouble-shooting procedures should not appear on the primary checklists but, instead, should be referenced only.

Background:

Complicated checklists which detail alternate or redundant processes become complicated and the crewman can become confused when trying to follow the primary mode. (This should not be construed to preclude simple processes such as a one or two line trouble-shooting scheme.)

38. Lesson: The Size of the Command Task

Spacecraft, such as Skylab, which are designed to minimize flight crew systems control, require that ground commands manage the vehicle performance. Therefore, the sequence for the identification, generation, verification, transmission, and recognition of the commands should fully recognize the size of the task.

Background:

Over 100,000 commands were sent to Skylab during its 8-month active life. The full workload associated with this magnitude operation was not recognized early. Each individual element of the system was sized properly, but the manhours necessary to operate the system was not fully understood.

39. Lesson: Control Moment Gyros

Control moment gyros are excellent devices for attitude stabilization of large vehicles without the requirements for large quantities of expendables.

Background:

The Skylab attitude control system used momentum exchange to maintain close control of the cluster orientation in the face of gravity gradient torques, venting torques, aerodynamic torques, and crew disturbances. Three large control moment gyros (65.8 kg momentum wheels with an angular momentum of 3,000 N-M sec.) provided the momentum exchange mechanism, a digital computer and its associated interface unit, performed the necessary calculations and navigation based upon the intelligence supplied by rate gyros (three in each of three orthogonal planes), five sun sensors, and a star tracker. A cold gas blow-down system provided the impulse needed to occasionally rebalance the system. (Avoid momentum management techniques which require expendables. Magnetic field momentum exchange schemes show promise.)

Some life-time problems complicated the final manned mission but, in principle, the momentum exchange principle is an effective stabilization scheme for long-duration spacecraft.

40. Lesson: Lubrication of Rotating Machinery

If possible, positive lubrication methods should be included in the design of long-life rotating machinery, such as control moment gyros.

Background:

Two of the Skylab CMG's experienced bearing anomalies (temperature increases) and one (CMG #1) failed on day 194. Analysis indicates that poor lubrication caused bearing failure. The CMG's were designed with an automatic lubrication metering system which was chosen to minimize the need for active control, to maximize bearing life, and to prevent contamination by containing all oil. Life tests conducted on the ground far exceeded the required life.

In retrospect, it appears as if the forces on the oil in zero gravity caused it to seek different locations than in one-g where full lubrication was possible. Since fluid flow in zero-g is not yet fully understood, it appears prudent to design a system with positive control.

41. Lesson: Investigate All Failure Modes

Do not let concern and investigations of "probable" failure modes divert attention from less likely failures.

Background:

Because of the nature of the micrometeoroid shield deployment, the light and flexible design, and the difficulty in simulating zero gravity deployment, there was a general uneasiness with this system and its proper operation. As a result, at least three independent reviews were held, all concentrating on the deployment. Questions concerning whether it would stay on were answered with a statement that the tight rigging would assure it behaving as an integral part of the skin and that flutter analysis had given the design a clean bill of health.

The aerodynamic design of the tunnel was not questioned.

42. Lesson: Designers Should View Their Product

White room restrictions inhibit the detail designers from examining the hardware they are responsible for. Access to assembly areas should be controlled, but not eliminated.

Background:

Skylab, like all space vehicles, was built with careful control of access to keep the vehicle clean, to inventory all material brought inside, and to prevent interference with the assembly and checkout crews. As a result, designers rarely viewed their final product in the as-built condition. Perhaps such access might have resulted in discovery of the design error in the auxiliary tunnel.

43. Lesson: Vent Port Location

The location of vent ports on a space vehicle should be carefully designed and controlled from the initial design. Improperly located vents will cause contamination of experiments and instruments or can obstruct the field of view. Improperly designed vents will result in torques on the spacecraft.

Background:

Because of the evolutionary development of Skylab, vents for the environmental control system, waste management system, urine dumps, tanks, and fuel cell water were not controlled initially. The principal investigators eventually demanded that controls be established. After a review, the problem was recognized as being real and the designs were changed. Vents were relocated so as not to be in the field of view of experiments, a storage tank was provided for fuel cell water, urine was stored in bags in the waste tank, and overboard dumps were rerouted to the waste tank. These measures, taken late, were more costly than necessary. The requirement was not recognized early enough.

Nonpropulsive vents are easier to conceive than to design. The major vents on the Skylab waste tank were diametrically opposed orfices protected from clogging by two screens which were designed such that clogging of the screens would not result in a pressure differential between the vents. This was a very satisfactory design.

44. Lesson: Structural Analysis Instead of Test

Structural analysis in lieu of test can provide adequate assurance of structural integrity for simple structures. The use of weight (mass) to increase the factor of safety is an effective way to decrease both test and analysis verification.

Background:

The Saturn V used to place the Skylab cluster in orbit had enormous weight lifting capability. This capability was used judiciously to reduce design, testing, and analysis costs by designing to a larger factor of safety. For example, in Skylab, the payload shroud was formed from one-inch thick aluminum plates. No acoustic tests were made since the thickness provided the necessary attenuation.

45. Lesson: Eliminate B-Nuts. Braze All Fluid Lines

All plumbing should be brazed or welded and B-nuts (mechanical connections) should be used only when no other solution is possible in order to minimize the number of joints where leakage can occur.

Background:

Skylab used B-nut fittings extensively on the airlock module coolant loop. This allowed for ease of manufacturing but it was impossible to assure a complete seal. Despite stringent controls during manufacture, a coolant loop leak developed in flight. The location of the leak was never discovered but it could have been internal to the cabin (a trace of coolant was found in the ECS charcoal absorber which was brought back for analysis).

46. Lesson: B-Nuts

Where B-nuts must be used in fluid lines, insure that a known torque can be applied during assembly and that the torque can be rechecked later. Design in a positive lock to insure that launch vibrations do not loosen the nut. Do not safety wire two movable parts (e.g., nuts) together.

Background:

The CSM RCS line leak probably stemmed from a B-nut which was not properly installed and torqued. Subsequently, checking of B-nuts on later vehicles revealed that the torque was difficult to apply, was hard to measure, and in many instances, was below specification value. Some of the nuts could not be checked because of the location. At least one instance was found where safety wire was installed in such a manner as to not inhibit opening of the nut.

47. Lesson: Fluid Lines and Cables

Insure that fluid lines and cables cannot inadvertently be installed backwards.

Background:

The Skylab 3 CSM developed a leak in the RCS oxidizer line (in the thruster housing) because of a series of misadventures which began with the installation of the plumbing upside down, which prevented a good fit.

Cables should also have indexed connectors which will prevent adjacent cables from being interchanged.

48. Lesson: Stress Corrosion

Do not use stress corrosion-susceptible material in any component, the failure of which would result in a Category 1 (crew safety) or Category 2 (mission success) failure.

Background:

Many of the Apollo components were built with high strength-to-weight ratio materials. Subsequently, these materials were found to be susceptible to stress corrosion. As a result, stress corrosion cracks were searched for throughout the operational phase and, indeed, were found on the fins of the Saturn IB vehicles. Components fabricated with these materials, with the problems of stresses from usage or residual fabrication stresses, must be assumed to be incipient failures. Cracks can appear any time after the last inspection and launch, no matter how late the inspection.

49. Lesson: Sliding Aluminum Surfaces

Avoid sliding aluminum surfaces. Where necessary, anodize the surfaces prior to applying solid lubricant.

Background:

The aperture doors on the solar observatory were closed when the instruments were not in use to prevent contamination from depositing on the instruments. The fiberglass doors had an aluminum tapered latch which engaged a latch ramp. The aperture doors had a history of hanging up during flight. Flight doors were returned for failure analysis which showed the latch ramps to be galled. No explanation is available for the in-flight failures, despite success of the 5,000 cycle qualification tests. Misalignments due to manufacturing tolerances or thermal expansions could have caused high stress loads which, in turn, could cause the galling.

50. Lesson: Small Orifices

Small orifices should be avoided in fluid lines since they are easily blocked by contamination.

Background:

Metering orifices are frequently used to limit the flow in fluid systems such as in attitude control thrusters. When these become very small (on the order of thousands of inches) the likelihood of clogging is relatively great. When orifices are required and cannot be eliminated, microfilters should be placed immediately upstream of the orifice and chemical and acoustic cleaning should be used to eliminate any loose or potentially loose particles from the line.

During flushing operations, it should be remembered that in the absence of gravity, particles which have been lodged in low spots, blind tubes, corners, and the like, will be free to enter the fluid flow. Also, brazing flashes which may form during fabrication can break loose in time due to fluid and line vibrations.

51. Lesson: Use Fire Control Techniques When Designing Cables

All electrical cables should be encased in noninflammable cable trays with fire stops at intervals, or other fire prevention techniques and practices should be used.

Background:

The Apollo fire which took the lives of three astronauts demonstrated the devestating effects of fire in a spacecraft. As a result, extensive design attention was focused upon fire initiation and propagation in Skylab. All internal cables were enclosed in metal cable trays to prevent abrasion and wear. In addition, fire stops were located at intervals to constrain fire propagation.

In flight, the crewmen noted a tendency to use as handholds all protrusions making it important to armour cables. Also, they each noted that the tendency was to control the position of the upper torso as they moved about, allowing the feet to follow along without control, often hitting whatever equipment was along the way. By the end of the mission, the Skylab 4 crew reported some bending of lightweight secondary structure located along frequently used paths.

52. Lesson: Window Design

While single-pane windows can be designed with sufficient strength to be safe, enough uncertainty exists that dual windows, i.e., double glazed, should be used wherever possible. The Johnson Space Center standards for window design should be used.

Background:

Twelve windows were built into the workshop cluster. The JSC design specifications resulted in satisfactory windows throughout. Only minor and infrequent fogging and condensation occurred. However, the multispectral photography experiment window in the Multiple Docking Adapter was a single high-quality optical pane to prevent distortion. The 18" x 23" borosilicate glass pane was 1.6" thick and no leaks, cracks, distortions, or problems occurred. However, uncertainties as to use, potential damage, unknown manifestations of fracture mechanics led to the installation of a removable inner pane and an external cover was also provided.

53. Lesson: Gaseous Oxygen and Nitrogen

The use of gaseous oxygen and nitrogen in lieu of cryogenic storage simplified the design of the life support system. Gaseous storage, required for long-term storage, was perfectly satisfactory.

Background:

When the dry workshop concept was adapted, cryogenic storage of O_2 and N_2 was discarded in favor of gaseous storage. The simplification permitted the use of Saturn and Gemini tanks as well as simplifying the test and verification program. A multiple bottle storage facility was designed for ease of isolation (and to use existing tanks). No micrometeorite punctures or leaks of any sort were experienced.

54. Lesson: Caution and Warning Memory

The caution and warning annunciator should have a memory system such that if an out-of-tolerance parameter subsequently returns to normal, the crew can interrogate the system to find the malfunction.

Background:

The original design did not have this capability and it was added during the development cycle as a result of an analysis, and Apollo experience that some failures were intermittent and would not be found without this capability. It worked well in flight.

55. Lesson: Adjustable Caution and Warning Parameters

Caution and warning parameters should be capable of being adjusted in flight or of being totally inhibited if desired. An indication of the warning level and of the status should be provided to insure a parameter is not inadvertently set outside the useful range or turned off accidentally.

Background:

Earlier caution and warning systems (Gemini and Apollo) had fixed parameters and could not be inhibited. Malfunctioning sensors could not be removed nor could adjustments be made as greater understanding of the systems was generated. As a result, entire parameters were cut from the system to prevent false indications. The Skylab C&W system was designed so that parameters could be inhibited but not adjusted. No problems were encountered although a number of false warnings were generated. None were due to C&W malfunctions.

Great care must be used in the formulation since it would be easy to generate a false security by improper adjustment of parameter level. Both flight and ground indication of the level should be provided. This adjustment capability was proposed after the basic C&W system design was complete. In the case of Skylab, the addition of a readout capability was judged to be prohibitively costly at that time.

56. Lesson: Waste Management Facility

A separate and private toilet facility, properly vented, is required for long missions.

Background:

The Skylab concept for a separate waste management facility was considered to be mandatory when compared to the Gemini/Apollo plastic bag approach. The desirability of a private compartment for toilet facilities does not seem to require much debate. There was a general consensus that the Apollo bag system was acceptable for short duration, exploratory missions but a separate facility was required if spaceflight was to be routine.

57. Lesson: Medical Requirements for Collection of Feces and Urine

The collection of feces and urine for medical purposes is a very difficult task which requires a complex and costly development. The collection of the waste products and the in-orbit handling and processing is very time-consuming. The requirement for such processing should receive close examination before it is implemented.

Background:

Skylab medical experiments required the collection, processing, storage, and return of the astronauts' waste products. The techniques needed to collect, sample, freeze, and store the urine, and those needed to collect, dry, and store the feces, were complex and required costly development programs. The Skylab medical results were positive and satisfactory. A repeat of the experiments or an expansion which requires new techniques should have a large gain before it is undertaken.

The relatively simple waste elimination process on Earth is a timeconsuming and difficult process in zero gravity. It is complicated further by the experiment requirements.

58. Lesson: Software Development

Software development should receive the same attention and rigor as hardware development. Ground software should not be an exception. Milestones should be established and tracked with critical attention.

Background:

Space missions are just as dependent upon timely and successful development of software as upon hardware. It is traditionally difficult to establish firm milestones which are definable and definite, and there is, therefore, generally less understanding and visibility in the status and progress of this less understood element.

The launch of Skylab was almost delayed due to the status of the mission control center software. The basic programs were available but many of the auxiliary programs were not operable. A major effort was made on the last weeks preceding the launch to speed up the software development, but on launch day, two programs were still inoperable.

The maturity of the development (i.e., the nearness to completion) is difficult to assess using only the traditional approach of measuring the number of hours of test. One reasonable measure is the number of program open anomalies or program notes, which define computing situations which should be avoided.

59. Lesson: Timing Systems

A single accurate, universal timing system should be provided for telemetry, navigation, and experiments.

Background:

Two timing systems were provided in Skylab: the laboratory time-reference system which provided onboard displays and time correlation with the instruments; and the solar observatory time-reference system which provided computer generated timing signals for navigation and control and for the solar experiments. The two systems were time correlated (to a degree) by: (1) a 1-pulse-per-second interrupt signal which loaded the computer with mission timing for further transfer, one a second, to the experiments; and (2) by a 24-pulse-a-second signal which generated a 50 bit computer status word which was ultimately telemetered to the ground.

While these systems were satisfactory, greater analysis of some experiment data could have been made had there been closer synchronization of the computer and telemetry timing.

60. Lesson: The Need for a Teleprinter

A teleprinter should be provided for data transmissions. The teleprinter should have the capability of reproducing line drawings.

Background:

Previous space programs used voice transmission for data transfer. Skylab's one-way teleprinter, which allowed for alphanumeric transmissions, allowed the crew to collect and read permanent hard copy messages at their leisure, thus increasing crew efficiency and message accuracy. However, frequent instances of need arose where line drawings, schematics, and sketches would have simplified the messages and increased the information flow and comprehension.

61. Lesson: Message Identification

A single teleprinter message identification system should be devised to allow the crew to relate the message to a task.

Background:

Messages were generally sent at night so the flight crew would have timely data for the day's activities upon awakening. Messages were sent sequentially and the crew cut the paper into message segments. Subsequent amendments or additions necessitated an identification system to assure the crew had the latest instructions.

62. Lesson: Teleprinter Workload

The teleprinter should be designed for a heavy workload and the system should be designed to accommodate many messages and much paper. A complete traffic analysis, maintenance concept, and hazard analysis should be initiated prior to hardware design.

Background:

Over 300 messages, using 3,600 feet of paper were sent on Skylab. During the design phase, the evolving realization of the usefulness of the teleprinter necessitated design changes due to the increasing stowage (use forecast), the increasing fire hazard (footage of paper), increasing reliability requirements (replaceability of units), and maintenance understanding (head cleaning).

63. Lesson: Two-Way Color Television Requirement

Two-way color television should be provided for all future space programs for effective data flow and communications. The required bandwidth and power should be made available.

Background:

Air-to-ground color television was added to Skylab relatively late in the development cycle. As a result of the design and operational compromises required by the timing of the decision, the potential communications capability was not realized.

During the mission, numerous occasions arose where the flight crew and ground would have benefitted by seeing problem situations in addition to talking about them. This was particularly true in the repair of malfunctioning equipments. A slow scan system would be acceptable.

64. Lesson: Television Tape Recorder Requirement

Since ground networks cannot provide full orbit communication coverage, a tape recorder for television should be provided. The tape recorder should provide ground and flight indication of its status and should be controllable from the ground or flight. The recorder should be capable of rapid dump, or the system should be capable of playback at the same time real time television is being transmitted. Playback should be backwards so that recording will not overplay undumped television previously recorded.

Background:

A tape recorder provided for 30 minutes of delayed transmission. Playback was controlled from the ground, but recording was controlled by the crew. This was a timeconsuming function particularly when the television camera station was remote from the recorder.

A one-to-one record/playback speed was designed in Skylab. Since television could be transmitted either live or through the recorder, and since transmission was limited by ground network coverage, no additional television time was made available and the recorder was useful only in that it permitted flexibility in flight planning.

Front-to-back playback meant that extreme care had to be exercised to prevent premature erasure of previously recorded video. Since playback was accomplished during relatively short ground passes, television recording was generally not accomplished during playback periods.

The segmented playback to multiple ground stations (some of which did not have the capability for real time retransmission of the received signal to the mission control center) put a burden on the ground editing system to develop an accurate, sequential product, with no gaps or duplications.

65. Lesson: Television Camera Dynamic Range

The television cameras must be designed with a wide dynamic range to accommodate out-the-window scenes as well as the relatively dimly lit interior scenes.

Background:

The Skylab cameras were adequate but not exceptional. Interior lighting is always less than out-the-window lighting.

66. Lesson: Spacecraft Lighting

Spacecraft lighting should be designed to give correct color temperatures for television viewing, color photography, and for everyday living.

Background:

Skylab illumination was designed for lighting for everyday living. As a result, additional measures were needed to assure color fidelity in all mediums. Special spot lighting was provided. A standard color bar was permanently located at various stations around the spacecraft. This gave the ground technicians a standard setup to use to adjust the signal.

67. Lesson: Private Communications

The capability to conduct private communications should be provided. Secure communications is not needed.

Background:

Circumstances arose during the missions where it was important to conduct frank and open coversations without full public disclosures in real time. (Paraphrased coversations were always distributed to the press). Such open discussions, particularly between the flight crew and the surgeon, helped in a full understanding of the in-flight activities. Skylab ground system required considerable reconfiguration for such interchanges. Future systems should be capable of rapid reconfiguration.

No scrambling of messages was provided and, while obviously potentially more private, the basic purpose of the private communications was met by using the existing system and only requiring that all monitors be shut down.

68. <u>Lesson: Cummunications for Morale Purposes</u>

For long missions, the crew should have regularly scheduled radio communications with their families for morale purposes.

<u>Background</u>:

Every few days, each crewman was scheduled for private telecommunication with his family. By being scheduled regularly, no "emergency" was implied and, therefore, no inhibition was placed upon these messages.

69. <u>Lesson: End-to-End Communications Tests</u>

Large vehicles, such as Skylab and space stations cannot have end-to-end communications tests performed prior to liftoff since they are never configured to be in the operating mode while on the ground. Therefore, a communications test laboratory must be provided to simulate the system from voice to ear.

<u>Background</u>:

At no time during the test and preparation of the vehicles were all components available for an end-to-end test; i.e., voice, intercom assembly, transmitter, ground receiver, network, mission control center, and listener. The need for a simulation facility was not recognized until late in the development cycle at which time a laboratory was equpped. Late identification of major facility requirements strains a financial system.

70. <u>Lesson: Configuration of Test Articles</u>

All test items used in qualification test programs should be <u>identical</u> in configuration to the flight test article and should be fabricated and assembled with the same techniques and procedures as the flight article.

<u>Background</u>:

Frequently, there are minor differences between test specimens or between the test specimen and the flight unit. This is particularly true when the test program is tightly constrained by time or money and is aggravated when the test articles are expended in the test.

As an example of the trap, the Scout program initiated an improvement program which involved the redesign of the nozzle of the third stage motor. After one successful ground test, a second firing resulted in a burn through of the nozzle. Engineering analysis concluded that a new propellant had been used which invalidated the nozzle test. A third test was successful and the motor was judged to be qualified. On the first flight test, the nozzle experienced a burn through and the stage was destroyed, losing the spacecraft and the mission.

The true message of the second test was obscured and misinterpreted.

71. <u>Lesson: Experiment Objectives</u>:

The true objective of an experiment should be identified at the time of its inception, not just the data which is desired.

<u>Background</u>:

All too frequently, experimenters concentrate their efforts on the instruments they are building and the data they wish to acquire without sufficient thought about the knowledge they are really after. This results in the late addition of corollary activities such as ground-truth programs, calibration activities, or control experiments. Since these activities can require facilities and equipment, the costs can become a significant portion of the total.

The post-data-collection activities are generally understated and poorly thought out. Data reduction and analysis must be included in the experiment costs.

72. <u>Lesson: Schedule Reviews</u>

Schedule reviews and examinations of data to insure their accomplishment.

Background:

Major reviews, such as PRR's, PDR's, CDR's, etc., are normally scheduled and tracked since the accomplishment is a major milestone. However, periodic and regular reviews of lesser events (such as residual safety concerns, program requirements, contract status, weight status) can easily be forgotten. Important items should be identified and scheduled so all participants are aware of and are prepared to discuss them fully. In Skylab, "Base line Reviews" and Configuration Control Reviews were frequently used as the scheduling medium.

73. Lesson: Schedule Adjustments

The most efficient and least costly program is accomplished as expeditiously as possible with a minimum of premium labor. Schedule extensions to save current year resources will result in program extensions and resulting cost growth. Adjustments to program content should be explored before the schedule is adjusted.

Background:

Every program is eventually faced with the need to reduce current expenditures of resources. Initial program plans generally establish the pace of a program by the facilities, support equipment, and tooling planned. Variations of that pace use the tools inefficiently and stretch out a program or increase the use of manpower to increase the pace. Either is costly since the latter requires premium labor costs or the use of too many men to do a job. The former requires that tools remain idle and the work to be accomplished in later years. Even if efficiency and inflation costs were constant (which, of course, they are not) the overhead continues at a relatively constant rate.

Program content can frequently be adjusted to bring costs in line while maintaining the schedule. Backup units, spares, test program adjustments, and experiments can each be examined. Caution: When reducing the program content, it is necessary that the effects be analyzed and minimized. For example, when reducing backup units it should be recognized that the flexibility of the test verification program may be reduced unless alternate plans are available.

The reduction of near term funds at the expense of schedule stretch out and cost growth must be recognized at the highest levels of decision. All too frequently, Congressional appropriations are reduced because of today's program, and then there is great surprise when the program grows. When inflation effects are included, deferment of costs is, indeed, inefficient.

74. Lesson: Crew Time

Crew time in orbit is a valuable commodity and should not be wasted by systems (and experiment) designs which consume time without a positive benefit from the presence of man. Design systems which use the mental ability of man use man's mechanical abilities for routine functions only when it results in a significant simplication of the system or experiment.

Background:

Skylab was designed for one-shift operations for the three-man crew. Thus, 48 man-hours a day were available for useful work. From this total, the "overhead" had to be subtracted for eating, personal hygiene, recreation, exercise, discussions with ground personnel, preparations for experiments, EVA, housekeeping, and cleanup. The time spent collecting experiment data averaged about 17 hours a day.

Many experiments wasted crew time by requiring them to perform tasks which could have been easily mechanized. In some instances, the use of simple timers and sequences would have freed the crew for other tasks.

These experiments which were designed to permit crew interaction and to use the decision-making capabilities of the crewmen produced some of the more meaningful data. Notable were the solar experiments and the visual observation program. In both programs the crew was able to enhance the results of observations and analysis.

COMMENTS BY SKYLAB OFFICIALS

A. Introduction

Skylab, as is any large project, was the result of much hard work, inspiration, dedication and genius of many men, both in Government and industry. It was the product of the management and technical skills of many experienced people. It was felt to be appropriate to solicit from these individuals any comment which they felt appropriate and wished to submit for inclusion in this paper. Accordingly, a letter was sent to each senior manager, asking him to submit a short summary of what he considered the most significant lessons learned on Skylab of a technical managerial nature. A short letter was requested. Most indicated that the desired brevity of their replies caused them to be discriminatory in their choice and that more lessons were available if more space would be provided. The replies are reproduced here, with comments as appropriate.

B. Mr. Dale D. Myers

Mr. Myers was the Associate Administrator for Manned Space Flight at the time of Skylab. Of his observations, I judge the most important to be the admonition to assign responsibility and authority and allow the individual to do the assigned job. This principle was followed during the ten days when the stricken Skylab workshop was on the brink of disaster right after launch. Mr. Myers resisted "taking over" and permitted the well-trained Skylab team to prove itself. He was there for counsel and guidance and he was always in charge, but he understood the chain of command.

C. Dr. Christopher C. Kraft, Jr.

Dr. Kraft was (and is) the Director of Johnson Space Center. His comments appropriately address the major finding of the Skylab mission: a space station is a practical and proper tool to be exploited by our nation. In addition, Dr. Kraft recognizes keeping the end use (operations) clearly in focus as the program is being developed.

The management of the flight activities suggested by Dr. Kraft deserves serious attention and has been difficult to initiate early in a program. In Skylab, a 6-month long review was undertaken in 1972 to coordinate the flight control activitiy with the design activity. For flight management, the Flight Management Team was developed because Skylab was a multidisciplined space station. Such an approach is recommended in a future space station.

Real-time data analysis requires an early definition of the operational philosophy. If an autonomous space station is planned, little ground analysis is needed. Conversely, if the ground is to support systems management, or if earth-based scientists are to participate in experiments, extensive real-time data analysis is needed. Real-time analysis is a costly undertaking.

D. Mr. Leland F. Belew

Mr. Belew was the Skylab Program Manager at the Marshall Space Flight Center. His comments concern the future uses of space station and can be summarized as suggesting that future programs have greater flexibility than Skylab by having systems which require less development involvement by the users (principal investigators) and, thus, develop more versatility. As Mr. Belew points out, the student experiments were a "new" approach to involvement by the investigator and could form the basis for future space station experiment development. The student experiments were accommodated by virtue of NASA assuming all development responsibility. (This was logical, since high school students had no resources of their own). An alternative approach for future space stations is to provide flexible accommodations and to maximize the participation of the investigator in the experiment development. In this way, the investigator will have all responsibility for the success of his experiment and for the funding and development as well.

E. Lt. General Thomas W. Morgan, USAF

Lt. General Thomas Morgan was the Skylab Program Manager at the Kennedy Space Center during most of the development phase. Of General Morgan's many appropriate comments, I believe the observation that the successful development of a large program is dependent upon a clear understanding of the magnitude of the undertaking and an acceptance of the task at all levels. Programs with marginal support and funding have traditionally suffered from overruns and cancellations.

General Morgan's observation concerning the magnitude of the effort involved in the experiment portion of Skylab is particularly valid. Frequently experiments were proposed, and accepted for development and flight, which did not have a well thought out set of objectives or even a design. The program costs could not be adequately estimated. After several experiences, Skylab instituted better controls and better evaluations prior to acceptance of the task.

General Morgan correctly states that Skylab technology was conservative, as a matter of policy. For long duration spacecraft, it was felt that tried and proven approaches were proper.

F. Mr. Richard G. Smith

Mr. Smith, currently the Deputy Director of the Marshall Space Flight Center, was the manager of the Saturn project for Skylab (and much of Apollo as well). The thoughts outlined closely parallel many of the lessons learned. Since Mr. Smith's experiences closely parallel the author's, that is not surprising. It is appropriate to emphasize the point regarding systems engineering. Experience has shown that the individual who truly thinks as a "systems engineer" is rare indeed. The talent does not seem to be one which can be taught--it must be acquired. A program manager should be careful to include an excellent systems engineer on his staff. Mr. Smith did not cite it as a "lesson" but his observation concerning technical "checks and balances" deserves highlighting. Overlapping responsibilities and interests have typified NASA developments. While costly, his approach does result in a higher success ratio since there are two factors working for technical excellence: the check of one organization on another, and the knowledge of one organization that another will be looking at their product.

G. Mr. Eugene F. Kranz

Mr. Kranz was the Director of Flight Operations for Skylab and was responsible for the flight operations. The point made regarding "scale effect" should be seriously considered in any space station design. Adequate design practices for small spacecraft may be improper for a large station. The previously mentioned bussing of the electrical power systems (workshop and ATM) is a good example. Using the logic which was adequate for Gemini and Apollo, the systems were designed as independent systems, and it was only mid-way in the development cycle that the decision was made to join the two.

Mr. Kranz' last point regarding the inclusion of operations personnel early in the development program parallels the observation of Dr. Kraft and should be reemphasized. The inclusion of the "user" (i.e., operations personnel) must be made in the initial design. All too frequently the operation is brought into the program after the initial design concepts are formed, and the operational requirements are changes to the design and, as such, are costly in time and resources.

H. Dr. Walter Kapryan

Dr. Kapryan was Director of Launch Operations at the Kennedy Space Center. The most vital lesson outlined is that only flight-ready spacecraft should be shipped to the launch site. In Skylab, this objective was modified in some instances when the experiment integration was accomplished at the factory using non-flight equipment. At KSC seemingly minor changes in the experiment resulted in interface mismatches. Accomplishing the initial experiment integration at KSC would be possible only if the spacecraft interfaces were kept flexible and the experiment interfaces were simple.

For a space station such a design philosophy is mandatory since it will be impossible to forsee all of the instruments to be flown. Thus, the design must be flexible and versatile.

I. Captain Charles Conrad, Jr., Astronaut

Captain Conrad was the Commander of the first manned Skylab mission. Captain Conrad also seems to believe that the usefulness of man in space is the primary lesson of Skylab. The Skylab-2 crew which he led proved that man could repair and fix hardware in space just as well as on the ground. The fourth point of Captain Conrad's comments is related to data flow. The amount of data accumulated on Skylab was large ($3x10^{12}$ data bits of telemetry alone) but it does not compare with the data capacity of future systems (Shuttle will transmit $50x10^{6}$ bits/sec.). The telemetry data plus the recorded data plus the data recorded by film was not reduced to a form suitable for analysis by the principle investigators for over a year after the last recovery. The data reduction task had been underestimated.

J. Captain Alan L. Bean, Astronaut

Captain Bean was the Commander of the second Skylab mission. His comments can be summarized as an expression that the activities man is capable of on earth can also be accomplished in space if the designer adequately translates his design thinking to the new environment. Earlier manned space flight experience with EVA, for example, led many (including the author) to be extremely wary of it as a routine operational tool. Skylab proved that it is an extremely useful and flexible operational mode. It does require adequate hand-holds and restraints and the designer must "think in zero gravity" and remember fundamental principle of force, momentum and reaction. As Astronaut Bean states, proper preparation in a neutral bouyancy facility is also required.

He also voices the difficulty in communicating from space where all thoughts must be expressed by words, and those words are also interpreted by uninitiated newsmen who may be seeking the sensational. The ability to have private communications on future space stations should be included in the designs.

K. Col. Gerald P. Carr, Astronaut

Col. Gerald Carr was the Commander of the third Skylab mission. He too argues that Skylab proved the case for man in space. Col. Carr and his crew, among other things, serviced the leaking coolant loop. Without coolant Skylab would not have been able to carry on. Without a man in orbit to locate the coolant line, to attach the valve for fluid transfer, to test the system for leaks, and to transfer the coolant to the system, the equipment would have been extremely complex and ponderous if it could have been designed at all. Col. Carr expresses most succinctly the need for considering long duration space flight as a "routine operation" as contrasted with the more event-oriented missions of Mercury, Gemini, and Apollo. The high-tension, heroic activities of the past had to be replaced by lower key, day-to-day routines with adequate time for work, thought, and relaxation.

L. Dr. Robert A. Parker, Astronaut

Dr. Parker was the Program Scientist for Skylab. He argues for early inclusion of the scientific community in the development, particularly in the operations development. It is vital that the operations personnel (ground and flight crews) understand the objectives and problems of the investigators. Conversely, the investigators can better plan their experiments if they know of the operational constraints.

To Dr. Parker's observation that science planning be under a single individual, it should be added that that individual must have the trust of each investigator as well as the understanding and confidence of the operational personnel. Such an individual is not easily found, and Skylab was fortunate in having Dr. Parker.

Dr. Parker also recognizes the need for private communications in future programs and the desirability of excess consumables.

M. Mr. Kenneth P. Timmons

Mr. Timmons was the Manager of the Martin Marietta Corporation effort on the Skylab Multiple Docking Adapter. Mr. Timmons observations are well founded. Orderly documentation produces an orderly program. Documentation is frequently identified as being a cause of excess program costs. Excess documentation, in the form of unnecessary reports and paperwork is costly and should be eliminated. Orderly control of a complex program requires control documentation, and a large program cannot be successfully concluded without the proper "paper" controls. Control documentation should be planned early in the program. The second item is one which each manager must bear in mind. Frequently, the design engineers become enamored with sophisticated computerized analyses and simulation (a typical load analyses on the Shuttle program takes weeks to perform on the most sophisticated computers) and forget to use the simplest of physical and mechanical principles first.

N. Mr. Raymond A. Pepping

Mr. Pepping was the Manager of the McDonnell-Douglas Astronautics Company efforts on Skylab. The control and assessment of changes in a development program is always difficult. The change summary package was a useful management tool and should be considered for large programs. Also, Item 5, the use of a Trade Study "bank account" made it possible for the module manager to get quick studies underway without a long negotiation.

The Airlock Module was initially under the technical direction of JSC and, subsequently, the direction was changed to MSFC. This was a difficult transition and Mr. Pepping advises against it in the future.

O. Mr. Fred Sanders

Mr. Sanders was the Manager of the McDonnell-Douglas Astronautics Company orbital workshop project. Mr. Sanders' observation concerning subsystem managers is appropriate and always timely. This observation was made on Gemini, Apollo, Skylab, and recently, on Shuttle. The identification of subsystem managers should be given early attention. The observation that decisions should be scheduled is worthy of considerable attention. The NASA has recently adopted the practice of preparing a "countdown" for major decisions. Each and all of the steps needed for a decision are listed and scheduled. Obviously such a process is not necessary when the decision is one which only requires a clear cut selection of an option. However, most key decisions are characterized by a number of prior actions (i.e., completion of studies, costing of options, identification and agreement by affected parties) which must precede the decision and are required to insure the correct decision is made. The use of a written countdown can organize the decision process.

P. Mr. Haggai Cohen

Mr. Cohen was the Director of Reliability, Quality and Safety for the Skylab Program. Mr. Cohen's considerable missile and space system experience has resulted in some appropriate comments. For emphasis, I would highlight his second observation: the more you plan ahead, the less you will be surprised.

Q. Mr. Kenneth S. Kleinknecht

Mr. Kleinknecht was the Skylab Manager at the Johnson Space Center. His point regarding commonality of systems is worthy of considerable note. Skylab was designed by different design teams, at different locations, at different times. Switches were different, displays varied, methods of operation were not comparable. A stronger control of minor design standards should have been instituted earlier.

The statements concerning zero gravity should be reviewed carefully by space station designers. Zero gravity can be used as an aid, if properly considered. In Skylab more could have been done to utilize the environment. Skylab used "one-g" orientation in the workshop and little use was made of walls and ceilings for storage. This was done consciously to provide the crews with an orientation; however, more innovative use of storage areas was possible.

R. Dr. George E. Mueller

Dr. Mueller was the Associate Administrator for Manned Space Flight through the Gemini and Apollo Programs. He also directed the initial and formative stages of Skylab. It was he who first conceived of the cluster concept and gave it the initial start. The importance of providing a habitat which encourages long duration space missions is one which he emphasized in those early days. The Loewy-Snaith Associates were under contract in the design phase to develop comfortable living quarters. The wardroom concept, with separate sleep compartments was one result. Unfortunately, Skylab was built more like a naval ship than a home. More should be done on the next space station to encourage the permanent use.

As can be seen from his comments, Dr. Mueller is a staunch advocate and supporter of a permanent earth orbiting space station. His comments concerning materials processing highlight a most promising application. The Skylab materials processing experiments have just begun to explore the field of new processes and products formed in zero gravity. The formation of large, pure crystals, the formulation of material mixes not possible on earth, the separation of materials with closely similar densities by electrophoresis--each has the promise of great economic benefit in the future.

S. Mr. John H. Disher

Mr. Disher served as the Deputy Director of the Skylab Program from its earliest inception (as Apollo Applications) through the completion of the flight phase. His experiences, therefore, cover all phases of program development. The observation that the lessons of development are learned and rehearsed is particularly appropriate and the objective of the Skylab "Lessons Learned" documents is to help transmit those experiences from program to program. Experience is, unfortunately, a very difficult commodity to market. The very difficult task of establishing proper communications between interdisciplinary design groups has been of concern on all large projects. The use of subsystem project managers is strongly urged when the subsystems are complex with interdisciplinary design interfaces. The designation of a project "chief engineer" with no programmatic responsibilities other than design has been adopted in NASA. It is hoped that an experienced engineer, unencumbered by financial, contractual, or schedule responsibilities, will be able to provide a top-level interdisciplinary examination of the project engineering details.

A word of caution concerning Mr. Disher's proposal for a continuing review of design requirements: when changing design requirements, extreme caution must be used to insure that the stability of the design is not seriously perturbed. Lack of stability in requirements means lack of stability in design. Schedule slips and financial overruns can easily result. A review of design requirements on critical systems and on systems which are encountering development difficulties can be fruitful. Frequently the design or the design-verification tests can be simplified, resulting in improvements in performance and schedule and reductions in cost requirements.

Dale D. Myers
President

North American Aircraft Operations
2230 East Imperial Highway
El Segundo, California 90245
(213) 647-5595

Rockwell International

'75 DEC -8 PM 3:05
RECEIVED

December 4, 1975

Mr. William C. Schneider
Deputy Associate Administrator
for Manned Space Flight
National Aeronautics & Space
Administration
600 Independence Avenue, SW
Washington, D. C. 20546

Dear Bill:

Responding to your request, here are some thoughts I've had on managerial lessons for program managers. I'm sure many of them sound like motherhood, but as you know, some of the most obvious ideas are the hardest to carry out.

(1) Get good, experienced, dedicated people who can communicate well.

(2) Give them a clearly understood, agreed to set of objectives and stable funding.

(3) Give them the authority to carry out their part of the program, but insist on "no surprises".

(4) Understand program progress by asking the right questions.

(5) <u>Control</u> major changes at the top. Don't make changes to the objectives; only the means of reaching them.

(6) Encourage and demand team work; give awards to the "stars".

(7) Keep the balance of cost, schedule and performance. Attack all three, all through the program.

(8) Don't forget the Russian slogan, "The 'better' is the enemy of the 'good'." Sophisticated engineering is that which produces the simplest device to meet the requirement.

(9) Never give up! Necessity is the mother of invention, and the saving of Sky Lab's mission is a great example of what a well trained team can do in the face of what initially looked like insurmountable obstacles.

(10) Plan ahead. Stay ahead of today's problems with some of your time and energy, looking for the problems (and opportunities) which will come up in the future.

Finally, be of great courage -- like a guy I know who is undertaking a Doctor's thesis at this stage in his career.

Best of luck,

Dale

Dale D. Myers
President
North American Aircraft Operations

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

OFFICE OF THE DIRECTOR

September 24, 1975

Mr. William C. Schneider
NASA Headquarters, Code MD
Washington, D. C. 20546

Dear Bill:

Enclosed are my thoughts on the most important managerial or technical lessons learned from Skylab.

Good luck on your thesis.

Sincerely,

Chris

Christopher C. Kraft, Jr.
Director

Enclosure

1. Man can work and operate for periods up to 3 months in space at zero gravity with no serious physical or mental effects.

2. The space station is an ideal platform for conducting observations of the Earth and for future uses of the space environment.

3. Future activities in space involving large facilities should be designed for proper manned interfaces to allow appropriate use of man as a trained observer, laboratory technician, experimentor and maintenance mechanics.

4. Preplanned activities are extremely important to assure proper dividends on the investment. This includes careful attention to the need (or lack of need) for real time data analysis.

5. Managing such an activity in flight (space station) is as important as the inflight activity itself and should be given adequate thought and planning.

6. Continuous manned space stations at varying inclinations and at synchronous altitudes would give this country a tremendous potential for technological and economics gains. To remain pre-eminent in the world one must plan to conduct this kind of space activity.

7. A whole new era of space manufacturing will begin when space stations and their supply become economically feasible.

8. Space stations are obviously an integral part of the next generation of steps to be taken in the exploitation and exploration of space.

'75 OCT 28 AM 10: 52
RECEIVED
NASA CODE M

Marshall Space Flight Center
Code EA01
Marshall Space Flight Center, AL 35812

OCT 21 1975

Action Copy to ________
Info Copy to MD

Rec'd in Code M 10/28/75
Control Number ________
Response date ________
Prepare reply for
signature of ________

Mr. William C. Schneider
NASA Headquarters
Code MD
Washington, D.C. 20546

Dear Bill:

The lessons learned from Skylab, relative to space flight development and operations programs, that are somewhat unique and of particular importance to future space station activities are:

a. Establish interface definitions (requirement) between the user (experimentors/PI's/commercial, etc.) and the space craft (space station/space lab) early.

b. Provide a data system that eliminates or minimizes the involvement of intermediate processing prior to receipt by the users (experimentors/PI's/commercial, etc.).

c. The management concept for future space station activities must accommodate a much broader sector of users that relate to the more basic national needs. Skylab forms a sound base of reference to more fully develop the future management concepts. As an example, the student experiments and earth resources instruments were accommodated very successfully at a relatively late date in the Skylab Program.

d. Skylab provides a sound basis for planning the future activities of man relative to space stations. There appears to be no reasonable limit to what man can do in space. This was not known before Skylab.

e. Skylab demonstrated the ability to successfully respond to a broad spectrum of problems and to seize upon unplanned opportunities. There is a tendency to continuously undersell what can be done. It is suggested a more optimistic approach be taken on future space station programs.

f. Maximum use of existing hardware, concepts, designs, facilities, equipment, etc., coupled with more analyses, as compared to additional testing, is a sound approach. This approach must be pursued to help keep development and hardware costs under control.

Much success in your pursuit of a doctor's degree in Aeronautical Engineering. Having survived Skylab with much success, you have more than earned the degree!

Sincerely,

Leland F. Belew

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SPACE AND MISSILE SYSTEMS ORGANIZATION (AFSC)
POST OFFICE BOX 92960, WORLDWAY POSTAL CENTER
LOS ANGELES, CALIFORNIA 90009

75 SEP 23 PM 3:54

19 September 1975

RECEIVED
SA CODE

OFFICE OF THE COMMANDER

Action Copy to
Info Copy to MD

Rec'd in Code M 9/23
Control Number
Suspense date
Prepare reply for signature of

Mr. William C. Schneider
NASA Headquarters
Code MD
Washington, DC 20546

Dear Bill

I was surprised to learn that you are now back in school again. I must say you have more courage than I to undertake the rigors of the academic environment again.

You had asked that I give you my thoughts on what I felt were the five most important managerial or technical lessons learned from Skylab about space flight development and operations programs. I will certainly be happy to give you my thoughts on this subject though they are not necessarily listed in order of priority.

1. I suppose the one thing in today's environment that sticks out in my mind most vividly is that one should not undertake a major space effort such as Skylab without adequate funding and support by both the Congress and the people. Marginal or submarginal support drives many programmatic decisions in a very adverse way and, in my opinion, the shuttle today is suffering from this type of environment.

2. Once a national program such as Skylab is formulated, it should have a strong management team uninhibited by local center prerogatives. I felt that on Skylab many times our decisions were compromised by this factor.

3. Management of the experiment program, I think, caught many of us by surprise in that we underestimated the magnitude and complexity of this effort. In a program such as Skylab where you have a large investigator/experimental community vying for such things as power, space, and orbital considerations, it is essential that this be closely controlled.

4. Many times I felt we were not bold enough in applying the latest technologies in the development of our Skylab program. Since this was a national effort and represented the cutting edge of our country's technology, I think we could have more profitably exploited new concepts, materials, and design approaches.

5. I suppose the final point I would make, and it was as true in Skylab as it is in many of our current space programs, is the importance of highly reliable electronic components in the many systems and subsystems that go into such a vehicle. This is where I think we need to spend more of our dollars and more of our manpower resources in producing highly reliable, quality hardware.

I hope you find the above useful in preparation of your thesis, and I am looking forward to seeing you again in the near future.

Sincerely

Tom

THOMAS W. MORGAN
Lt General, USAF
Commander

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

'75 DEC 22 PM 12:41

RECEIVED

REPLY TO
ATTN OF: DD01

December 17, 1975

Mr. William Schneider
Office of Space Flight
Code: M
NASA Headquarters
Washington, D.C. 20546

Dear Bill:

I apologize for being so delinquent in responding to your request for lessons learned on Skylab as they apply to future space stations. You asked that I give my opinion on the five most important managerial and technical lessons learned. I find boiling it down to five to be rather difficult, yet at the same time, when I look at the more important aspects, in my opinion some of them fall into the category of lessons relearned. I hope they will be of benefit to you.

1. In retrospect, I find that there has been a lack of complete system engineering. I feel that the agency, and in this context our contractors, are excellent subsystem system-engineers as compared to total systems engineers. We sometimes let the less than obvious slip by causing near catastrophies or expenses later in the program. Obviously, from the Skylab standpoint, the heat shield is the most outstanding example, but I believe in looking at the program that there are many cases of interaction of subsystems causing a program problem and later costs that could have been avoided with appropriate analyses at the beginning.

2. Skylab Program, as most programs, underestimated the complexity of the software required. The operational software used in the support equipment during the mission was basically the responsibility of the using organization. On the surface this sounds like an ideal arrangement, but in fact, the operations people of Skylab were also the operations people of Apollo, therefore, sufficient attention was given to the early development of the software and a crisis evolved after Apollo and through most of the Skylab mission.

I believe that it is of vital importance to any program that the tools, whether they be software or hardware, be developed independent of the operating organization. This approach does two things: (1) It eliminates the problem of lack of attention if the operating people are involved in a current program, (2) Probably more important, it creates the environment of a check and balance where the using organization exercises the tools given to it and has an opportunity to find deficiencies, yet at the same time interact those deficiencies with the designer. Quite often the operations people overlook some subtle requirements from a technical standpoint in order to improve the operational position. This is not by intent, but oversight, in order to make the operations more efficient.

3. If you look at the Skylab Program, it had a long evolution from a wet workshop, which I think never would have worked, into a very complex one-of-a-kind space station. I am not being critical of the evolution of the Skylab Program, but I think in retrospect, it is obviously not the way to do a low cost program. One needs to do a thorough job in establishing requirements of the program prior to initiating it. I think you can use Skylab as an example of evolution without being critical of it since we all understand the why and wherefore, but obviously programs cannot proceed this way under today's budgetary constraints.

4. The Skylab Program demonstrated beyond any shadow of a doubt the flexibility and adaptability of man to solve problems. With any complex long-life hardware, you greatly benefit from the capability of man to do on-the-spot repairs, even though not previously planned. The contrary argument to man, of course, is the additional complexity that he adds to a system to support his life, but I think this complexity is far offset by what benefits he brings.

5. This item may relate somewhat to item one, but we should never underestimate the importance of the small details in the success of the program or experiment. Each element, no matter how apparently insignificant it appears, more often than not is a single-point failure in the successful operation of a total system. I think that if we were redesigning Skylab today, we should add the capability for man to enter many more subsystems than we did with the actual design. These details add complexity, yet add flexibility and maintainability.

Each one must be weighed independently to see whether it benefits or detracts from the operation of the system. I was once told by an individual that I was worrying too much about the details and not enough about the big picture. The only problem was that the details were what was killing me, not the big picture. We should not allow anyone to belittle the small details because they can be the governing factors before the program is over.

Bill, I hope these thoughts are of some help to you. I am not sure that they are the most outstanding lessons learned, but they are, in my opinion, important ones that are applicable to the space station and Shuttle, or any other program. Again, I would like to reiterate one point. I know that we always try to organize in the most efficient manner to get the most cost-effective job, but failure is never cost effective, and we should never allow ourselves to get in a position where we don't have a check and balance in the system. An example of what I mean--I think Kappy, Ike Rigell, and launch vehicle people have always looked at us at Marshall thinking "those guys don't really know what they are doing and I am going to satisfy myself that they have done a good job." That attitude causes a lot of questions to be asked. Many are easily answered and are no problem, yet, a few bring to light oversights that could be catastrophic. That element of one group designing and another group operating gives a check and balance that I think should never be lost. It is a friendly competition that both sides enjoy and appreciate. It keeps both the designer and operator on their toes and more productive.

Good luck on the thesis!

Sincerely,

Dick

Richard G. Smith
Deputy Director

SEP 29 1975
Johnson Space Center
Code CA
Houston, TX 77058

Action Copy to__________
Info Copy to __MD____

Mr. William C. Schneider
NASA Headquarters
Code MD
Washington, DC 20546

Dear Bill:

I thank you for the opportunity to comment on the "lessons learned" during Skylab and their applications to future programs. "Lessons learned" frequently exist only as an impression and, as such, my comments will range from specifics of those things that we should do or not do to an impression that essentially states "I do not fully understand--but I should try to be more aware in the future." In other words, in many cases, I had an impression that may or may not have application to a future task. The "lessons learned" that I will subsequently discuss are as follows:

a. Large space vehicle scale effects.

b. Generic versus specific task training.

c. Integrated systems design and operations.

d. Standardization and commonality.

e. Premission preparation operations.

To a great extent, the above listing has impressed me sufficiently that in developing our operations concepts, establishing flight systems requirements, and defining specific operating plans, I have utilized the Skylab "lessons learned" quite extensively. To a great extent, the application of these "lessons learned" can be seen throughout our Shuttle planning.

a. Large space vehicle scale effects - This topic is probably the most difficult to discuss because it constitutes an impression and implies that maybe we should approach future flight systems design in a different way. Prior to Skylab, all of the space vehicles NASA designed were relatively small and, as such, the flight systems required unique packaging and to a great extent, vehicle design, assembly, and testing was done at a few locations. These spacecraft had relatively short cable runs, fluid lines, and the resultant design lended itself to analysis. On Skylab, for the first time, we were faced with extremely long cable runs and fluid lines, considerations of different vehicle dynamics and other large systems design. The designer was given significant latitude in the layout of components and, in general, the resultant design did not lend to easy analysis. During Skylab, I believe many of our problems could directly be traced to the fact that we expected the flight systems to perform with the reliability that was achieved during "Apollo," which was a small spacecraft. However, we did not adequately consider in either the design or operations the fact that this spacecraft "Skylab" was a beast of a different type. I have probably explained this very poorly, so let me try to put it in fewer words. Our manned space flight, design experience prior to Skylab was in the design, test, and operations of small spacecraft. Overnight we moved into a spacecraft that was several orders of magnitude larger. We did not adequately temper our small spacecraft experience when we applied this experience to the Skylab vehicle. There are many conclusions you can draw from the above. For instance, is it better to develop a single thermal control system that services the entire spacecraft or is it better to develop several thermal control systems to serve areas of the spacecraft? The same question can be applied against the power generation and distribution system. When it comes to testing, can we achieve reliability in large spacecraft design when formal testing of the integrated system is either impossible or would result in high test and checkout costs. How does the test and checkout problem impact systems design? There are many questions of a similar nature that could come under this scale effects "lessons learned." I consider this to be the major concern relative to the design of the basic Orbiter and some of the larger payloads. Overall, I feel uneasy since I believe we should have learned more in this area.

b. Generic versus specific task training - All previous space programs utilized a highly optimized training program for flight crew personnel. We took this same basic approach for all areas of flight operations; that is, the level of training and proficiency in all tasks was set as "the highest that could be achieved." During the Skylab Program, the crews adequately performed many tasks for which they had not been specifically trained. I believe it is possible to significantly cut crew training time and costs by taking a more generalized approach to training for non-time critical tasks. In this latter case, I can include almost all phases of flight with the exception of launch, rendezvous, docking, and reentry. I believe it is practical to decrease specific training in some areas of flight systems, flight dynamics, and crew tasks such as EVA. As a result, I would expect that crew training times will decrease by at least 20-30 percent from previous programs, and possibly by as much as 60-75 percent as the Orbiter and crew training program matures.

c. Integrated systems design and operations - In essence, the "lessons learned" here is that systems must be managed from a central control position within the spacecraft. In Skylab, we essentially had three locations for control of power generation and distribution. There should have been only one location. The same can be said for most Skylab systems with the exception of the attitude and pointing control system, and the experiments themselves. The Skylab design approach was costly from a standpoint of design, checkout, procedures development, crew training, and flight planning. I believe that you also felt strongly about this when you made the decision to manage Spacelab mission independent systems as an integral part of the Orbiter systems. Significant cost savings can be achieved in design of future spacecraft by taking the above approach. It may be noted, however, that this approach may contradict some of the conclusions from the "scale effects lessons learned" described previously. Considering this "lessons learned" and the "scale effects lessons learned," it may be worthwhile to consider each system from both standpoints rather than trying to establish a generalized design guideline.

d. Standardization and commonality - One of the more beneficial aspects of the Shuttle Program involved a higher degree of standardization in the way flight operations does its business. To a great extent, all consoles, displays, communication keysets, offline reports, and ground procedures were standardized for Skylab. Significant standardization was achieved in methods and techniques for training (at least for the flight controllers). In essence, we eliminated a considerable portion of the personal tailoring of facilities and training programs to an individual's desires. As a result, I believe we obtained the confidence that an even higher degree of standardization was possible and practicable for the Shuttle Program. As a result, we are baselining standard flight control rooms, standard console facilities, standardized modular procedures, and flight plans. To do the Shuttle job requires an approach as described above. The initial steps in Skylab have given us the confidence that our goal is achievable during ths Shuttle Program.

e. Premission preparation operations - This "lessons learned" is probably the most valuable one derived from Skylab and it is simple to define. All previous operations planning was done on an organizational basis; that is, flight planners developed their plans semi-independently of systems and trajectory personnel. The systems planners, in developing their consummables, worked semi-independently of the flight planners and trajectory personnel, and so on, and so on. As a result, significant disparities frequently resulted and an almost endless series of coordination meetings and reviews were needed to put it all together. During Skylab and, in particular, due to the overlap of Apollo and terminal Skylab preparation, we needed to "put it all together" on a more effective basis and with fewer personnel. We took a team approach where all team elements were working under the direction of a flight director. This required a lot of agreements at lower supervisory levels, cutting across organizational lines. The overall effectivity of the initial planning efforts from July 1972 through

January 1973 improved significantly. During the period between Skylab missions, we collocated representatives of each of the operations planning discipline and the overall planning quality and efficiency further increased. The key thing is that the operations planning is a job that needs an integrated approach. Trajectory, consummables, systems, network, and flight planning and training personnel must be working as an integrated team to be effective. The integrated team concept is the very heart of the Shuttle operations phase baseline operations plan. This approach is one of the techniques in reducing operations manpower costs.

The above "lessons learned," I believe, are the most significant from my viewpoint. There are many, many others; however, the process of translating these "lessons learned" into an application is frequently difficult. My greatest frustration is in seeing programs continue down the line quite independent of recent experiences, but I guess thats life. I am interested in getting your list of what you think were the principle "lessons learned" during Skylab.

Best of luck in continuing toward your degree. Hope to see you next time I am in Washington and maybe I can clarify some of the words I have used above.

Cheers!

Eugene F. Kranz

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHN F. KENNEDY SPACE CENTER
KENNEDY SPACE CENTER, FLORIDA 32899

'75 OCT 28 AM 10:48

RECEIVED
CODE M

REPLY TO ATTN OF: LA-PLN-2/294-1

OCT 22 1975

Mr. William C. Schneider
NASA Headquarters
Mail Code: MD
Washington, D. C. 20546

Dear Bill:

The attached is in answer to your request for my opinion on the five most important managerial or technical lessons learned from Skylab. You will note that my submissions are within the bounds of those areas that affected KSC operations. Frankly, I found it quite difficult to arrive at the five single most important lessons, for in general, I have found that each program contributes a large number of small lessons, which combined, set our course to some extent for follow-on programs. Some lessons are learned over and over again, and although are correct in theory, are rarely resolved or implemented because of circumstances beyond our control. Other lessons, especially in the technical areas, are readily implemented, but new problems arise and new lessons are learned. I believe it is this wealth of lessons learned, resolved and implemented that constitutes our reservoir of experience and knowledge in Manned Space Flight and has accounted for a large measure of our success. More than ever before, we must now concentrate as diligently on management lessons as we have the technical lessons in order to fulfill our responsibilities with lower budgets and less manpower.

I hope the attached will be of some assistance to you and I am sure you will recognize each of these lessons from your experience as Director of the Skylab Program.

Sincerely,

W. J. Kapryan
W. J. Kapryan
Director of Launch Operations

Enclosure:
As stated

Action Copy to ________
Info Copy to MD
Rec'd in Code M 10/28/75
Control Number ________
Suspense date ________
Prepare reply for signature of ________

145

SKYLAB LESSONS LEARNED

1. A lesson that was not unique to Skylab but was again high-lighted in Skylab can be summarized as follows: Vehicle modules that are well designed and checked out at the contractor's plant and are accompanied to the Launch Site by Management and Supervisory personnel that know the hardware and the operations methods at the Launch Site will generally result in little or no problems in meeting the launch schedule. This lesson was vividly exemplified in Skylab by virtue of the diversity of modules and experiments and associated contractors involved in the program. An almost continuous around-the-clock effort was required in one contractor's area with an associated contract overrun while in another area, little difficulty was experienced in maintaining the schedule. This lesson is particularly applicable to a one or two of a type vehicle program since application of a learning curve is not feasible.

2. Experiments installation and checkout integration should be performed only one time and could be more effectively accomplished at the Launch Site utilizing flight hardware. This function, as it was performed at the module factories, was generally not satisfactory due to use of non-flight hardware; late qualification testing; and failure to detect, resolve and close-out certain anomalies. For numerous experiments, this function was essentially repeated at KSC.

3. Experiments qualification testing should be completed prior to installation of the flight items into the spacecraft and should begin early enough to allow for contingencies. Qualification testing required more time than allotted and often ran in parallel with actual flight hardware testing. Twenty-six percent of the total experiments were removed and repaired or modified as a result of design inadequacies or qualification test failures.

4. Experiments should be designed to allow for easy removal. Approximately 62 percent of the total experiments were removed at KSC for troubleshooting, repair or modification. Twenty-six percent of the total experiments were removed and repaired as a result of failures detected at KSC and four percent were repaired in place.

5. Operational Documentation Systems requiring participation by, or contributions from Inter- and Intra-Center organizational elements and their contractors should be precisely developed, coordinated and detailed in one

document for total system availablity to all concerned, and should be made binding on all concerned organizations by higher level directives.

Several Operational Documentation Systems were developed during the Apollo Program and were required to be continued for the Skylab Program, but with involvement of different organizational elements from the other Centers. Some systems that were only superfically defined in various Inter-Center Agreements and Center Directives and for which there was no single recognized system document were re-negotiated and again only superficially documented in various agreements and directives. Implementation of these systems was difficult, time consuming and created confusion and a need for meetings to "straighten things out." One system in particular had been thoroughly developed, coordinated and documented in an officially recognized handbook for Apollo and needed only minor updating for Skylab. For this system there was no attempt to reinvent the system for Skylab because it had worked well for Apollo and implementation was accomplished for Skylab with a minimum of effort and problems.

AMERICAN TELEVISION & COMMUNICATIONS CORPORATION
360 SOUTH MONROE STREET • DENVER, COLORADO 80209 • PHONE (303) 321-2224

CHARLES CONRAD, JR.
Vice President — Operations

December 11, 1975

Mr. William C. Schneider
NASA Headquarters
Code MD
Washington, D.C. 20546

Dear Bill:

It certainly was good to see you in Houston the other day. As I told you, I had jotted down some thoughts and here they are:

1. Obviously, as we mentioned, the controversy regarding man's usefulness in space should be put to bed altogether after Skylab. It should remain forever at the head of the list in the future advances of space technology.

2. The managerial/technical advances which have been made across all the programs in the interfacing of complex systems being designed and manufactured by such a wide variety of different contractors.

3. Managerial/technical manner by which data was passed back and forth between Skylab and the ground, i.e., the procedures for handling storage between ground and Skylab, the development of the Joint Observing Programs for ATM, the use of the teleprinter, voice and video circuits that were available. The flight planning procedures, check list, etc. These, I feel, contributed greatly to smooth daily operations and helped maximize the collection of information.

4. It is also obvious that we designed and flew a system that in a relatively short period of time collected data which will take a relatively long period of time to evaluate. I understand it will take possibly 8 to 10 years to evaluate the ATM data which was collected over 170 days of manned flight in Skylab. The Shuttle is capable of collecting an infinitely greater amount of data. We need to consider a better system for digesting as rapidly as possible all the data that will be returned in order to maximize our use of it.

5. We learned the expensive lesson of short cutting due to budget reasons. More extensive test and analysis probably would have turned up the faulty design of the meteroid shield. I feel this is an area where the Shuttle is already deficient.

Nothing earth shaking there Bill, but I hope it will help.

Sincerely,

Pete

Charles Conrad, Jr.

CC:gr

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

'75 NOV -3 PM 9:07

RECEIVED
CODE M

REPLY TO ATTN OF: CB

October 30, 1975

Action Copy to
Info Copy to MD
Rec'd in Code [illegible] 11/3/75
[illegible]
[illegible]
Prepare reply for
signature of

Mr. William C. Schneider
NASA Headquarters
Code MD
Washington, DC 20546

Dear Bill:

I've been giving some thought to your request regarding items for the preparation of your thesis, "Skylab Lessons as Applied to Future Space Stations." I think I'd like to direct my reply to the five items from just a crewman's point of view, rather than from a program point of view, as I know you have a better idea of those than I do. I guess I'd have to list them as follows:

1. A man in space can do anything a person on earth can do if you give him a place to stand. Special restraints are frequently needed to provide the body positioning.

2. No special tools other than those used in similar earth applications are necessary to perform maintenance tasks if the astronaut is inside the space station and not in any restrictive clothing.

3. Scientists and astronauts can work together well and the designers of the experiments should be made aware of this fact so they can take advantage of this fact in the design of equipment and procedures. We can obtain better scientific data if we think of the astronaut onboard as a pseudo-scientist rather than as a button-pusher and design the hardware accordingly.

4. An astronaut can do any job EVA that can be accomplished in a neutral buoyancy facility. It seems that man can mentally extrapolate easily what he can do in the 0-g environment from what is possible in the 1-g environment as long as he's not encumbered by a pressure suit. When the added complications of the pressure suit are added, he can extrapolate partially but often overlooks important details that can only be found and circumvented by actual practice of the task in neutral buoyancy.

5. The feedback that one normally receives in day to day face to face contact with others is not present during space flight. Having the public and press looking over your shoulder often has an inhibiting

effect on both the people on the ground and in space. There must be a free exchange of ideas and feelings between the crew in orbit and the controllers on the ground to maximize mission return.

Hope things are going well for you. I couldn't imagine anyone that could have a more interesting or apropos doctoral thesis than the one you're proposing. It's one heck of a research effort with a lot of help.

Be good to yourself.

Alan L. Bean
United States Astronaut

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

REPLY TO
ATTN OF: CB

October 8, 1975

Mr. William C. Schneider
Code MD
NASA Headquarters
Washington, DC 20546

Dear Bill:

So you're really going to go through with it! I admire your perseverance in pursuing a doctorate.

I guess the most outstanding lesson I can draw from Skylab is the utility and versatility of man in space. Had the workshop been an unmanned satellite we would have had to kiss the whole program goodbye when the workshop started shedding parts during the boost phase. The efforts of all three crews to deploy wings, restore thermal balance, reservice the coolanol loop, and maintain attitude control in spite of CMG casualties, I think, support the argument quite eloquently. The efforts were results of management decisions based on good technical recommendations which exploited man's versatility.

Another managerial consideration which was pointed out in Skylab, particularly in our mission, is that the manner in which you do business on a short duration mission differs significantly from that for a long mission. The go-go-go, every second counts mode of operation is tolerable for a limited period of time, but if the mission duration involves setting up housekeeping and following a daily routine for longer periods, then you have to relax timeline rigidity. You need to give the man some time for himself and allow enough flexibility for him to exercise judgment and creativity.

As I remember, we worried and argued long and hard over the spacing between the three manned missions. It was indeed a significant managerial problem balancing economic considerations against the need for time to allow for scientific feedback from one mission to its successor. I'm sure that the decisions made pleased neither proponent. It appears to me that the lesson here is not to allow the situation to force management into similar compromises in the future.

It's interesting to me to note that in spite of the lessons we learned in Skylab, it appears that management has legislated against inflight maintenance as a design consideration for Shuttle. I certainly don't understand that, but I feel confident that when the chips are down and we are in danger of terminating a mission and losing scientific data to the tune of mega-bucks, man's versatility will be exercised again.

Best of luck to you in your endeavor, Bill.

Sincerely,

Gerald P. Carr
Colonel, USMC (Ret)
NASA Astronaut

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

75 OCT 21 PM 3:22

RECEIVED
[illegible] CODE M

REPLY TO ATTN OF: TE

October 20, 1975

Action Copy to __________
Info Copy to MD
MT

Rec'd in Code M 10/21/75
Control Number ________
[illegible] Date ________
Prepare reply for
signature of ________

Mr. William C. Schneider
Deputy Associate Administrator
for Space Flight
National Aeronautics and Space
Administration
Washington, D.C. 20546

Dear Bill:

The following are the six managerial type lessons that I consider most important from my area of Skylab.

1. First and by far the most important, was the operational confirmation once again of the extreme importance of the very basic ideas of communications and teamwork. The development of this understanding is certainly aided by having everyone concerned at one location. This relationship gradually developed between the scientists and the engineers in the Apollo Program and, subsequently, again in the Skylab Program; maximum achievements were not realized until teamwork was developed. Both the operations personnel and the scientists must understand their respective problems and objectives and must be willing to provide that extra effort to aid one another. When the situation warrants, the engineers must be prepared to be less conservative in setting the systems operational limits, and when that is not enough, new methods of operating the hardware must be devised. The scientists must be willing to reexamine experiment constraints and objectives continually in terms of the particular mission situation.

2. The demonstration of the usefulness and feasibility of flexible daily flight planning in order to meet changing circumstances, and changing requirements.

3. The efficiency of organizing all science planning inputs under a single individual who could personally exercise the science judgments before making inputs to the operational side of the flight team, and

the corresponding efficiency of organizing the inputs to this person under a single representative from each discipline area.

4. The crowded hectic nature of the early phase of each mission (approaching two weeks for Skylab; approaching TBD days for Shuttle!?) due to the acclimatization of the crew and the overhead of setting up shop and gaining proficiency in many daily tasks. This problem strongly suggests that only those activities which have bona fide requirements for early accomplishment be planned for the beginning of a mission.

5. The very great usefulness to be able to talk to the flight crew in a free, and unstilted fashion (to call a spade a spade) - a task that we have repeatedly found difficult or even impossible to do over the "open" comm loops. This suggests that either we have got to change our human nature and learn to do this over an open comm loop or we are going to have to get routine, i.e., non-crisis oriented use of a "privileged" loop.

6. The great usefulness of having "extra" supplies of consummables, e.g., extra film whose use is strictly speaking not planned for, and in a parallel sense the usefulness of tools whose use may not have been completely preplanned just because in both cases we can never really preguess the circumstances that will later arise - particularly on a long mission.

I have mostly just listed these without long explanations, except where my pencil got carried away with itself, since you are at least as familiar with these as I am. Good luck.

Best regards,

Bob

Robert A. Parker
NASA Astronaut

MARTIN MARIETTA CORPORATION DENVER DIVISION

POST OFFICE BOX 179, DENVER, COLORADO 80201 TELEPHONE (303) 794-5211

October 16, 1975

Mr. William C. Schneider
Code MD
National Aeronautics and Space Administration
Washington, D. C. 20546

Dear Bill,

I'm proud of you! We'll be pulling for you all the way to your doctorate, and you have a lot of friends here to pull for you.

I've listed very tersely some of my personal favorite lessons from Skylab, and you know that I'll be happy to elaborate on any of them you may wish further to pursue. (Where I critize, don't take it personally. On your watch, the program came in under budget.)

Sincerely your,

Ken Timmons

Kenneth P. Timmons
Program Director
Large Space Telescope

KPT/bbh

Enclosure

SKYLAB

1. System's engineering, as evidenced by the orderly control of tiered documentation, can result in minimum-energy control of a massive program.

   I believe that Belew, for example, learned to love a system's specification which allowed him to introduce a required perturbation into a "paper model." This model of the multi-contractor, multi-agency, multi-module Skylab then triggered changes in subordinate documents (EIS-ICD) which resulted in the modeled program and hardware responding and complying.

2. In a sophisticated and regimented test environment, a return to basics can be a refreshing and productive venture.

   After weeks of data analysis and eradite discussions of a clinical nature, we wiggled cables (horrors!) and probed connector pins (treason!) on a flight module, and an overwhelming problem was solved in a few minutes of very basic testing and simplistic data analysis. (EREP testing, KSC, April 1972.)

3. Steadfast adherence to provincial or parochial approaches can gnaw away at problem dollars.

   Test procedures for the Skylab Multiple Docking Adapter were generated at Martin Marietta and used for pre-delivery checkout. These procedures had to be re-written to McDonnell Douglas requirements and formats for use in the combined checkout at McDonnell Douglas, then these re-written procedures had to be re-written again to the Kennedy Space Center requirements and formats for final checkout at KSC. Why didn't we back up from the end requirement and use KSC procedures all the way? The test procedures are just one example of the failure to use common currency on a single program.

4. Neglect of adequate planning and verification for data handling, processing, and reduction can push a tidal wave of program problems and dollars toward the end of a program.

   Skylab S-192 data are still being shipped around the country in search of capable data reduction. Other examples abound.

5. A recent government study* has shown an embarrassing result - a positive correlation between overruns and technical accomplishment. Skylab was no exception if we look back at earlier estimates, but if the program had remainted "wet," if the entire earth resources package had not been flown, or if the student participation had not been accommodated then the program probably would not have been perceived as the outstanding success that it was. The program allowed growth to occur, the growth increased the cost, but it will long be remembered because of the growth items.

* "Factors Affecting Project Success," by Murphy, Baker, and Fisher, Boston College, 1974, for NASA (GCS 18-74) D-1

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

EAST

St. Louis, Mo. 63166 (314) 232-0232

'75 NOV -3 PM 9:08

RECEIVED
NASA CODE M

RAYMOND A. PEPPING
VICE PRESIDENT
SPACE PROGRAMS

31 October 1975

Action Copy to
Info Copy to MD

Rec'd in Code M 11/3/75
Control Number
Suspense date
Prepare reply for
signature of

Mr. William C. Schneider
Code MD
National Aeronautics and Space Administration
Washington, DC 20546

Ref: Letter dated 10 October 1975 requesting information for preparing a thesis on "Skylab Lessons as Applied to Future Space Stations"

Dear Bill:

The material presented, Attachment 1, is from the Airlock Module, MDAC-East experiences only. Fred Sanders indicated he is providing similar information on our OWS, MDAC-West experiences.

The examples selected tend to take the form of solutions to specific Airlock Module problems. Unfortunately, the theme of a broad lesson learned which would have application to future space stations doesn't come through too well in all cases. To supplement this, I have enclosed a copy of pages from the Airlock Module Final Technical Report on Airlock Program "Lessons Learned" which I thought would provide good background data. Maybe some of these items have more appeal than those covered by Attachment 1. Incidentally, Bill, we understand there is similar material from the other major module MSFC contractors who participated in the Skylab program.

In addition, I thought it might be worth mentioning a number of areas which come to mind, Bill, where more than the usual emphasis by management is called for on a program of the Skylab type -- a large, fast moving, fast changing, highly technical program with one or two flight articles and a substantial amount of concurrency between production fabrication and major development and, of course, where the available resources do not support doing everything you would like to do. I thought you might work some of these items, Attachment 2, into your general theme. They are all along the lines of achieving and maintaining the ability to respond rapidly to the dynamic, changing situation and at the same time endeavoring to avoid the pitfalls which might arise from moving rapidly.

Best wishes in the preparation of your thesis.

Sincerely,

Ray

MCDONNELL DOUGLAS

1. Communication of Potential Changes:

A change summary package was transmitted to the NASA Program Office that consisted of the following categories.

- o Authorized Program
- o Considered Authorized
- o Potential Changes
- o Cancelled/Disapproved Changes
- o Identified Documentation Changes

In addition to providing NASA with a weekly update of dollar value and schedule, this summary also provided a list of potential changes that were collected from the various Skylab meetings. It was by this list that many changes were flushed to the top so that NASA Management could provide authorization or disapproval in a more efficient manner.

2. Expedited Airlock Closeout Procedure:

In lieu of processing the closeout activity by mail, an Open House activity was employed which proved to be less time consuming and more efficient. The actual Open House activity took one week and approximately 32 bidder groups (about 67 people) surveyed and bid on equipment. By the time the lowest priority bidders arrived, the items selected by the high priority bidders was already identified via the computer list. This prevented duplicate bids and resulting confusion.

The use of NASA 811 Form identified items to be made available for Open House display, as scrap or other agency use. This identified items for the Open House and was much less time consuming than the DD540 series screening process.

An Open House Plan was prepared and equipment was staged in one location. Equipment descriptions were given to NASA-MSFC, and they, in turn, sent notices etc. to POD, NASA Centers, NASA Contractors, and GSA Agencies. Bidder priorities were assigned to each bidder. A computer program was developed (very low cost) to assist MSFC and GSA in their priority screening. This computer program also permitted sorting by bidder, by part number, etc. The total computer cost was under $900.

3. Airlock Shipments to KSC:

When the first Airlock was delivered to KSC and the remote site planning books were reviewed, it became obvious that a large number of parts ranging from raw material and pan stock items to components and equipment were involved. It became apparent that these parts, together with the anticipated configuration changes, would require close attention.

The first listing was put together manually and work started on a Direct Access Computer program (DAC). The resulting computer listing was sent to MSFC and KSC and MDAC-E people at KSC so that common data on parts needed, date shipped, or expected ship date was available to all parties at all times. This was rapidly expanded to permit our people at KSC to show hardware receipts and reference their test and work planning sheets by each part.

Shortly after, a nearly identical system was established between our people at KSC and Huntington Beach to reflect similar information on the OWS. MDAC-E helped in this by providing programming help and obtaining output data for distribution.

4. Keep Interfaces Simple:

Complex multi-module spacecraft which have physical and functional interfaces should be configured and contracted to minimize these interfaces.

In Skylab, the interface between the Apollo Telescope Mount and the Deployment Assembly was a very simple 4 bolt structural attachment. The electrical interface was the simple routing of wire bundles and location of connector. The coordination between the Marshall Space Flight Center and McDonnell Douglas Astronautics-East to firm up these interfaces was smooth and quickly accomplished. On the other hand, the interface between the Multiple Docking Adapter (MDA) and the Airlock was complicated by interfaces in the structure, functional gas and fluid systems, and operative electrical systems. These were more difficult to get resolved.

Recognizing that these interfaces would be more difficult to resolve between two companies, MSFC organized their program office to have the Airlock and the MDA under the same project manager. This management technique of putting complex interfacing modules under the same manager minimizes conflicting requirements and directions and allows changes to be handled at a lower level of change board.

Interface requirements should be established and documented in advance of firm system design release to minimize the redesign required when the interface requirements are coordinated and baselined after-the-fact.

- o ICD's should show only the information required to control the interface requirements.
- o Electrical interface control specifications should be established for end-to-end definition of all power, control or signal lines crossing a module interface. Function description at intermediate connectors should be omitted.
- o Electrical power quality requirements should be defined as early in the program as possible to permit orderly and economical systems development.

5. Quick Implementation of Trade Studies:

A quick method to initiate industry participation in inter-module optimization study activity without the hassle of contractual hang-ups was needed in the early formative stages. This was instituted by the Airlock NASA management by negotiating into the initial contract, a pool of money that could be spent only on authorization of a study by the NASA project manager. The amount allocated to each study was agreed to by the NASA Manager and his counterpart in industry. Strict accounting of the utilization of these funds was maintained and reported to the NASA so that it could be monitored.

This "bank account" method of managing the study activity of an evolving program was felt to be extremely efficient in:

- o rapidly getting study results
- o minimizing the contractual paper flow and/or in-scope/out-of-scope hassles that often accompany these type of activities.

6. <u>In-flight Maintenance</u>:

In-flight maintenance and hardware replacement proved to be much easier than anticipated; therefore, where feasible, provisions should be made for in-flight repair and/or replacement of components.

7. <u>Don't Change Contracting Center</u>:

A reassignment of the responsibility for a major hardware item between NASA Centers during the period of performance of an on-going program should be avoided, if possible. The advent of a new cast of players who did not have the opportunity of participating in the decisions leading to the existing configuration and whose mode of operation is based on a different organizational structure with somewhat different requirements and operating procedures is a trying experience for the people involved. A significant amount of time and energy must be devoted to the familiarization of the new people with the specification, the hardware, and the history of how the configuration was developed.

Human nature being what it is, plus the natural inclination of Homo sapiens to distrust those things which they have not personally been involved in, leads to a considerable amount of 'second guessing' and the subsequent need of data to substantiate the prior decisions. Program objectives are often viewed differently by the new blood which can cause a de-emphasis of some things and an added emphasis to others.

All of these lead to a loss of headway, inefficient operation and, in general, add to the overall program cost as well as often impacting the schedule.

Some examples of the problems which can arise are:

- o Loss of the established rapport and trust built up between the involved parties.
- o Disruption of program continuity
  - ° Different requirements
  - ° Different procedures
- o The 'not invented here' syndrome.
- o Different philosophies; different ideas.
- o New people not part of the program history; a reluctance to be responsible for 'that other guy's' decisions/mistakes.

Areas of High Emphasis by Management
on Skylab Type Programs

Motivate team members to surface issues promptly so as to address the matter well before it develops into a crisis, yet allow the technical people time and the opportunity to solve the surfaced problem.

Force close monitoring of major technical problems so as to select the proper moment for yielding to a new design concept or giving up on making the old concept work.

Press for solidifying the design and establishing a configuration which can be manufactured to balance the inherent tendency toward seeking technical excellence.

Force close communication and cooperation and emphasis on the highest priority areas (as the conflicts between late engineering drawing release and behind schedule manufacturing increase) through the guidance of a task force made up of representatives from engineering, planning and scheduling, and manufacturing; don't rely on the functional system for normal operation.

Recognize at the onset that a higher than usual amount of special attention and people dedicated to expediting will be required with a program of this type in order to keep activities moving well.

Devise review teams to dig out or uncover questions or issues that somehow were dismissed or overlooked and were never fully resolved.

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY
5301 Bolsa Avenue, Huntington Beach, CA 92647 (714) 896-3311

'75 NOV -4 PM 9:29
RECEIVED
NASA CODE M

October 17, 1975

Mr. William C. Schneider
NASA Headquarters
Code MD
Washington, D.C. 20546

Dear Bill:

In response to your request for five managerial and technical lessons learned from Skylab, I am enclosing a list.

Good luck on your doctoral program. It's good to see one of our Skylab boys moving up into higher strata intellectual neighborhoods.

Sincerely,

Fred

Fred Sanders

Enclosure

Action Copy to ________
Info Copy to MD

Rec'd in Code M 11/4/75

163

MANAGERIAL AND TECHNICAL LESSONS LEARNED FROM SKYLAB

1. The Skylab meteoroid shield failure investigation revealed the need for assuring that even structural subsystems be approached as a total management problem. We treated it as a structural element rather than an operational subsystem. I believe the results would have been better if we had a company-wide subsystem manager assigned to it similar to the way we had approached the solar arrays, waste management and other subsystems.

2. NASA to contractor interfaces were at the module contract level. For example, the Orbital Workshop was managed by an MSFC program manager who interfaced with the contractor program manager. This was complicated by the fact that MSFC had the development responsibility while JSC had the operational responsibility. This sometimes made the decision making process at the module level too cumbersome. A NASA program manager in charge of a prime contract must have support from all elements of NASA as well as clearly defined interfaces with other modules to permit timely decision making. This strong centralized management must also exist within the contractor organization to make the whole system effective.

3. Experiment hardware furnished by the scientific community often lacks even such rudimentary configuration controls as part numbers. In addition their one-of-a-kind nature causes the hardware to travel extensively. Since they also tend to be GFE to a module contractor, they are caught up in the cumbersome GFE authorization procedures of installation/removal/rework/release. This could be improved if experiment developers would team with an aerospace manufacturer to instill configuration discipline. In addition, GFE handling procedures should be streamlined.

4. NASA and contractors often placed too much emphasis on hardware and software and overlooked the effect that a late decision could have. Both NASA and the contractor should have a schedule for decisions and should track it in the same fashion as drawings and parts.

5. Most large programs suffer from an overabundance of "stoppers" and a lack of "starters". We need to increase the number of people who can say yes, and decrease the number of people who can say no, through strong centralized management on both sides.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO
ATTN OF: MQ

OCT 31 1975

MEMORANDUM

TO: MD/Deputy Associate Administrator for Space Flight

FROM: MQ/Director, OSF Reliability, Quality and Safety

SUBJECT: Skylab Lessons Learned

Per your request, the following are my first reactions to significant lessons learned.

1. Importance of including design margins for unexpected contingencies.

Demonstrated by ability to get out of meteor shield problem with a whole group of design margins which made it possible. For example:

a. RCS fuel - which let us complete mission in spite of orientation control usage before we got the heat shield out.

b. Breathing gases - which gave us enough margin to purge volume after overheat and still have enough for extended crew visit missions.

c. Electrical power - which gave us enough to survive with only ATM solar panels at first and then enough to do entire mission with only one of two solar wings on OWS.

2. Adequate contingency planning.

Had looked carefully at many "what if" situations that actually occurred. When these situations occurred (as the following examples show), we were ready for them:

a. Loss of one CMG - We knew in general terms that we could do this and had a background of ground simulation to fall back on. It's true we spent some RCS fuel before we learned how to fly on only two CMG's but, nevertheless, were reasonably prepared to do this.

b. Similarly, we planned redundancy on the rate gyro package in each axis because of expected life limitations. We then ran into the gyro heater and drift problems which turned out to be a common failure mode in each. Only because of our contingency planning did we have the time to come up with a spare package that we could fly up and install.

3. Wisdom of providing for rescue if all else fails.

Even though we went to great pains to provide redundancies and contingency planning, we realized that combinations of failures or simply ones we had not been smart enough to anticipate, might do us in. As a result, we searched for a reasonable rescue scheme which we baselined and then found that it really was a most important contributor to mission success. This occurred when we ran into what appeared to be a common mode failure in the CSM RCS jets. At this point, having the ability to initiate a rescue mission (which we did) bought us time to further evaluate the failures and determine that they were not, in fact, common mode failures.

4. In-flight maintenance.

The wisdom of being able to repair malfunctioning hardware in flight was demonstrated repeatedly through the Skylab missions. This included the provisioning of spares originally along with tool kits and test instruments to do the job. More significant, however, was the resupply capability of revisit flights to bring up tools and spares to repair what subsequently malfunctioned. This resulted in numerous experiments and basic Skylab system malfunctions which were repaired and then utilized. This salvaged a great deal of the mission as a result. Future space station missions should plan for in-flight repair and resupply as a matter of course.

5. Adaptability of the crew member.

The presence of a crew member's judgment and decision-making capability repeatedly demonstrated the value of having men on a long-duration space mission. They were used for damage assessment, on-the-spot procedure writers, worked under all kinds of adverse conditions (extreme heat, prolonged EVA, weightlessness, etc.), taking advantage of targets of opportunity (solar flares, Comet Kohoutek) and vastly enriching the data return because of their skilled presence.

Hope this is of value to you.

Haggai Cohen

System Development Corporation
2500 COLORADO AVENUE · SANTA MONICA, CALIFORNIA 90406
TELEPHONE (213) 829-7511

January 5, 1976

Mr. William C. Schneider
11801 Clintwood Place
Silver Spring, Maryland 20902

Dear Bill:

May I say first how pleased I am that you are pursuing your doctorate and assure you that I will do everything I can to help you achieve that goal.

On the subject of the five most important lessons derived from Skylab, I offer the following:

1. Man is capable of living in a zero-G environment indefinitely.

   a) Health may be maintained by proper diet and exercise.

   b) Happiness may be nurtured through interesting and recreational activities.

   c) Interpersonal relations (psychological stability) may be maintained by the proper space environment and by suitable communication with the ground.

   The importance of this verification is hard to over emphasize. It opens the way to permanent manned space stations and establishes the basis for manned flight to the planets.

2. Spacecraft can be developed to maintain very precise pointing accuracy, even with men moving freely about the craft.

   This is of extreme importance in the ability to use manned space platforms for astronomical and terrestrial observations as well as those processes which require a minimal acceleration environment.

3. It is possible to build and operate a reuseable space station with the resulting economy of use as well as the ability to add additional capabilities to the assembly with each flight.

4. Processing materials in space is feasible and yields materials different than those that can be produced on earth. The exploitation and utilization of this capability may, in the long run, prove to be one of the most direct economic benefits from space flight.

5. It is possible to maintain and resupply space stations/vehicles. This is the heart of economic development of space activities and is basic to the successful implementation of all the above.

With that, let me urge you to move out and finish your thesis. If there is anything I can do to help, please call on me.

Sincerely,

George E. Mueller
Chairman and President

NASA Johnson Space Center
Houston, TX 77058

January 5, 1976

Mr. William C. Schneider
Deputy Associate Administrator for Space Flight
National Aeronautics and Space Administration
Washington, DC 20546

Dear Bill:

In answer to your request for a listing of the five most important managerial or technical lessons learned from Skylab about space flight development and operations programs, I submit the following:

1. In the design and development of multimodule systems, extreme care should be exercised to assure that systems such as environmental control, electrical power, propulsion, and communications are similar from the operational standpoint. That is, the systems should be designed compatible to the extent that they can be interconnected, as required, and a common or uniform operation and control procedure can be used by the crew in order to reduce the complexity of training and the potential for operational errors due to multiple procedures.

2. Zero-g is an aid to manned space flight activities rather than an encumbrance as long as systems and components are designed for accessibility. Quoting Alan Bean, Commander of Skylab II, "If man can do it on the ground, he can do it in space with the same tools."

3. It is mandatory to have a system such as a television uplink with onboard hard copy capability to provide for transmittal of information, instructions, and procedures from the ground during low activity periods, thus unburdening the flight crew from copying complex messages.

4. The program flight control organization must be the final authority for establishing onboard integrated procedures, inflight constraints, and sequence of flight activities where there is an interaction between spacecraft and experiment operations.

5. All experiment/science hardware should be tested both as a subsystem in accordance with experiment/science requirements and finally at the integrated system level to assure the equipment operation, accuracy, and validity of the data as well as to verify that there is no electromechanical interference.

My apologies for being late with these remarks. I hope they will serve your purpose and good luck on your thesis.

Sincerely,

Kenny

Kenneth S. Kleinknecht
Director of Flight Operations

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO ATTN OF: MT

September 22, 1975

Mr. William C. Schneider
Deputy Associate Administrator
for Space Flight
NASA Headquarters
Washington, D. C. 20546

Dear Bill:

In your letter of September 15, 1975, you invited my thoughts as to what were several of the most important managerial or technical lessons learned from Skylab about space flight development and operations programs. My thoughts on this follow: For the most part, these are not new lessons, but lessons learned in different circumstances and surroundings. The fact that they are not new is of course a lesson in itself - we must continually strive to benefit from past experiences and structure our management so that past related experience can be brought to bear on current problems.

First, I would point to a lesson from our meteoroid shield failure:

That lesson relates to the importance of interdisciplinary communication among designers. The shield failure was traced to an "aerodynamic sneak circuit" wherein the structure design and fabrication inadvertently provided a path for air from a high pressure region on the vehicle to travel to a critical load area. The aerodynamicists, load engineers, and structural designers had not adequately cross-communicated in their reviews of the integrated system during design and during reviews of the completed hardware after fabrication. The lesson is the continued necessity for integrated cross-discipline reviews of designs and hardware led by an overall system oriented "chief engineer."

On the subject of the meteoroid shield, another lesson comes to mind and that is the need for continued hard review of design requirements. In retrospect, the requirement that led to the provision of a meteoroid shield was questionable. The shield was required in order to meet the arbitrary numerical design goal with the limited environmental knowledge then existing. Certainly with the benefit of hindsight, however, the shield was not necessary.

A second lesson "relearned" relates to the importance of judicious design margins and provision for contingencies. The Skylab electrical power system had a substantial margin in power available for basic housekeeping and experiment requirements. As a result of this margin, it was possible to operate the Skylab, with judicious power management, at full effectiveness in spite of loss of one complete solar wing following the meteoroid shield failure. Had we not had these power margins in the basic system design, the loss of the one solar wing would have greatly reduced or completely negated our mission capabilities.

Conversely, it is important to plan for maximum utilization of contingent capability. This was illustrated by Skylab weight management. Early in Skylab, a weight design margin and contingency of about 30 percent was provided. As the system matured, it became evident that the experiment complement and expendables provisions could be substantially augmented within the limit weights. This was done and as a result, mission duration and content of the experiment program were increased substantially at no increase in program cost. Specifically, it was possible to increase the final mission duration by 50 percent.

Another lesson relearned relates to the benefits of non-identical system redundancy. The pros and cons of identical and non-identical redundant systems have, of course, been argued for years and the merits of the argument on both sides, depend on the particulars. However, in the case of Skylab, the merits of non-identical redundancy were evident in the electrical power system.

The electrical power systems on the ATM and OWS, although both solar cell-battery systems, were quite different in their implementation. Failures occurred in both systems, but the failures were complementary to each other so that total system capability was not reduced to the extent it would have been with identical systems of either design. Conversely, the risks of identical redundancy were evident in the multiple failures of the control gyros for the attitude control system. Had it not been possible for the crew to repair the gyro problems in flight, the mission would have been prematurely terminated.

I hope these thoughts will be helpful to you; I believe your treatise will be a most valuable addition to the art and science of complex technical program management.

Sincerely,

John

John H. Disher

Enclosures

AXIOMS

Introduction

This section represents Lessons Learned at the most gross level. In retrospect they represent the accumulation of experiences without specific background and are, instead, a composite set of attitudes and approaches which have been used with some success. Other managers may have other approaches which, likewise, have been used with some success.

These axioms, just as for Lessons Learned, are presented for the consideration of the reader so that the applicable axiom can be used or adapted for the peculiar problem being addressed.

1. No one knows more about what you are doing than you.

2. No expert is so knowledgeable about everything that you can't question his opinions.

3. A question unasked is an answer not given.

4. When you think you understand the problem, ask at least one more question.

5. Always keep a devil's advocate somewhere on your staff to insure that alternate approaches are explored.

6. There is no such thing as a change which doesn't have an impact on the program somewhere.

7. Close configuration control of development applied too early inhibits design decisions and, therefore, delays schedule. Configuration control applied too late permits unnecessary design optimization and, therefore, results in cost overruns.

8. The more complex a system is, the more important it is to appoint a systems manager with responsibility for all aspects.

9. Mechanical systems, levers, gears, cams, etc. can be as troublesome as complex new electronic developments--sometimes more troublesome since there is a tendency to pay less attention to well-understood mechanical principles.

10. The key to an orderly program is careful and orderly documentation.

11. Documentation is very costly.

12. Constantly review documentation processes to insure that the paperwork is accomplishing a necessary task.

13. Be careful when one organization plans the work of another.

14. A good contract is more important than an early contract. Be wary of letter contracts with poor definition. Insure a well thought out statement of work.

15. Wherever possible, an incentive feature should be incorporated into development contracts since such features insure the contractor knows what the customer thinks is important as well as informs him as to how well the customer thinks he is performing. Besides, it gets the attention of the contractor's top management.

16. Award fee contracts provide great flexibility since the customer can specify what the most important feature is for each upcoming quarter of a year.

17. Avoid complex incentive clauses in contracts. Incentives should be easily understood and readily translatable to the workforce.

18. Level of effort contracts are easy to administer but are inefficient in that they tend to continue a workforce after the job has been completed.

19. Responsibility for a decision must accompany the authority for a decision.

Conclusion

The fundamental conclusion of the Skylab Program has not been addressed in this paper, but it is basic to the issues which have been discussed. Skylab has shown the worth and benefits which the Nation and the World will derive from a manned, long-duration, earth orbital space station. A space-based observation post has proven to be a practical method of providing services to the Earth's population in a variety of ways--Landsat, Intelsat, ATS, OAO and OSO are just a few of the better known unmanned spacecraft currently serving mankind. Skylab showed that a multidisciplined spacecraft can practically serve the same purposes. Skylab demonstrated conclusively the value of the presence of man to modify, correct, change, repair, maintain, and add to experiments and sensors. Reference 5 contains numerous examples of the flight crew contributions as a scientific observer, an operator, and as an engineer/technician. The value of integrating man into the experiments can be illustrated by contrasting the solar observations with the earth resource observations. The former set of instruments were designed such that the trained observer could and did monitor the solar activities to choose the areas of most interest and the instrument of most value. As a result, the data collected was enhanced and improved. In contrast, the earth resource experiments were designed to minimize the impact of the Skylab systems (they were a late addition to the program) and, as a consequence, the flight crew had little control over the data collection, and their involvement was little more than to turn the instrument on and off. As a result, the data was not enhanced and probably could have been better collected by an unmanned satellite. (Before an erroneous conclusion is reached, it should be emphasized that the presence of the manned operator simplified the instruments since no computer or command system was required and the crew could service the cameras and tape recorders. Also, the crew repaired the instruments when they malfunctioned.)

The possibility of material processing in zero gravity has just begun to be explored. The Skylab experiments showed clearly that certain processes benefit from the absence of the forces of gravity (and convection). The growth of crystals, the formulation of metal combinations, the separation of serums, and vaccines are activities which will be conducted in the space stations of the future.

The development and operation of such a facility will be a large and complex undertaking. The lessons learned in Skylab should be directly applicable. Specifically, the experiences with the control moment gyros should improve the design of the attitude control system; the findings on habitability and living should enable the designer to develop a more efficient space base; the successes achieved with extravehicular activities should permit the planners to use that capability without reservation (but with proper precaution); the manner in which the flight crews enhanced the data from the solar instruments should encourage the integration of man into the design of the sensors and instruments of the future; and the repair and maintenance of the systems that was accomplished should reduce the cost of instruments and experiments since redundancies and assurances can be reduced.

It is also hoped that the experiences documented herein will assist in the management of what will be a diversified development. The experiences in testing components at a number of sites dictate the use of a common test procedure in the future; the early definition of the criticality of a subsystem and, thus, the identification of the proper degree of control and documentation should result in lower costs; the design oversights which may have been detected if the designers had been exposed more directly to their product should encourage engineers to become more physically familiar with the hardware they design; and finally, the results of Skylab should dictate that space stations of the future be designed to be flexible and multipurposed.

ACRONYMS

AM - Airlock Module; also Amplitude Modulation
APCS - Attitude and Pointing Control System
ATM - Apollo Telescope Mount
BMMD - Body Mass Measurement Device
CM - Command Module
CMC - Command Module Computer
CMG - Control Moment Gyro
CSM - Command and Service Module
DA - Deployment Assembly
DAC - Data Acquisition Camera
db - Decibel
DCS - Digital Command System
ECS - Environmental Control System
EEG - Electroencephalogram
EPS - Electrical Power System
EREP - Earth Resources Experiment Package
ESS - Experiment Support System
EVA - Extravehicular Activity
FAS - Fixed Airlock Shroud
FM - Frequency Modulation
GMT - Greenwich Mean Time
GSFC - Goddard Space Flight Center
HCO - Harvard College Observatory
HHMU - Hand Held Maneuvering Unit
IU - Instrument Unit
IVA - Intravehicular Activity
JSC - Johnson Space Center
KSC - Kennedy Space Center
LO - Liftoff
LSU - Life Support Umbilical
LV - Launch Vehicle
MCC - Mission Control Center
MDA - Multiple Docking Adapter
MSFC - Marshall Space Flight Center
NASA - National Aeronautics and Space Administration
NRL - Naval Research Laboratory
OMSF - Office of Manned Space Flight
OWS - Orbital Workshop
PCM - Pulse Code Modulation
PI - Principal Investigator
PS - Payload Shroud
RPM - Revolutions Per Minute
S-IC - First Stage of the Saturn V Launch Vehicle

S-II - Second Stage of the Saturn V Launch Vehicle
S-IVB - Third Stage of the Saturn V Launch Vehicle
S-IB - First Stage of the Saturn IB Launch Vehicle
S-IVB - Second Stage of the Saturn IB Launch Vehicle
SAL - Scientific Airlock
SAS - Solar Array System
S/C - Spacecraft
SL - Skylab
SM - Service Module
STDN - Spacecraft Tracking and Data Network
TACS - Thruster Attitude Control System
TCS - Thermal Control System
TM - Telemetry
TV - Television
UV - Ultraviolet
VHF - Very High Frequency

APPENDIX 1 - Hardware Description

The Skylab cluster was made up of four major units which were launched by a two-stage Saturn V rocket. The cluster consisted of the Orbital Workshop (OWS) (figure 3), Airlock Module (AM) (figure 4), Multiple Docking Adapter (MDA) (figure 5), Apollo Telescope Mount (ATM) (figure 6), and related support structures and thermal and meteoroid shielding. The instrument unit, mounted on the forward end of the OWS, served as the guidance package for the launch vehicle. An Apollo Command and Service Module (CSM), in which three astronauts were launched by a Saturn IB rocket, rendezvoused and docked at the MDA. The entire cluster in orbit, including the CSM, was sometimes called the Orbital Assembly (OA) (figure 2).

The Skylab cluster was 36 meters (118.5 feet) long and weighed 90,607 kilograms (199,750 pounds). The total work space in the OWS, AM, MDA, and CSM was 347 cubic meters (12,398 cubic feet).

In the launch configuration (figure 17) the Skylab workshop elements were mounted directly above the second stage. An 11,794 kilogram (26,000 pound) Payload Shroud (figure 7) covered the ATM, MDA, and AM during the launch phase. The ATM was forward of the MDA until the cluster reached orbit and the shroud was jettisoned. The ATM was then

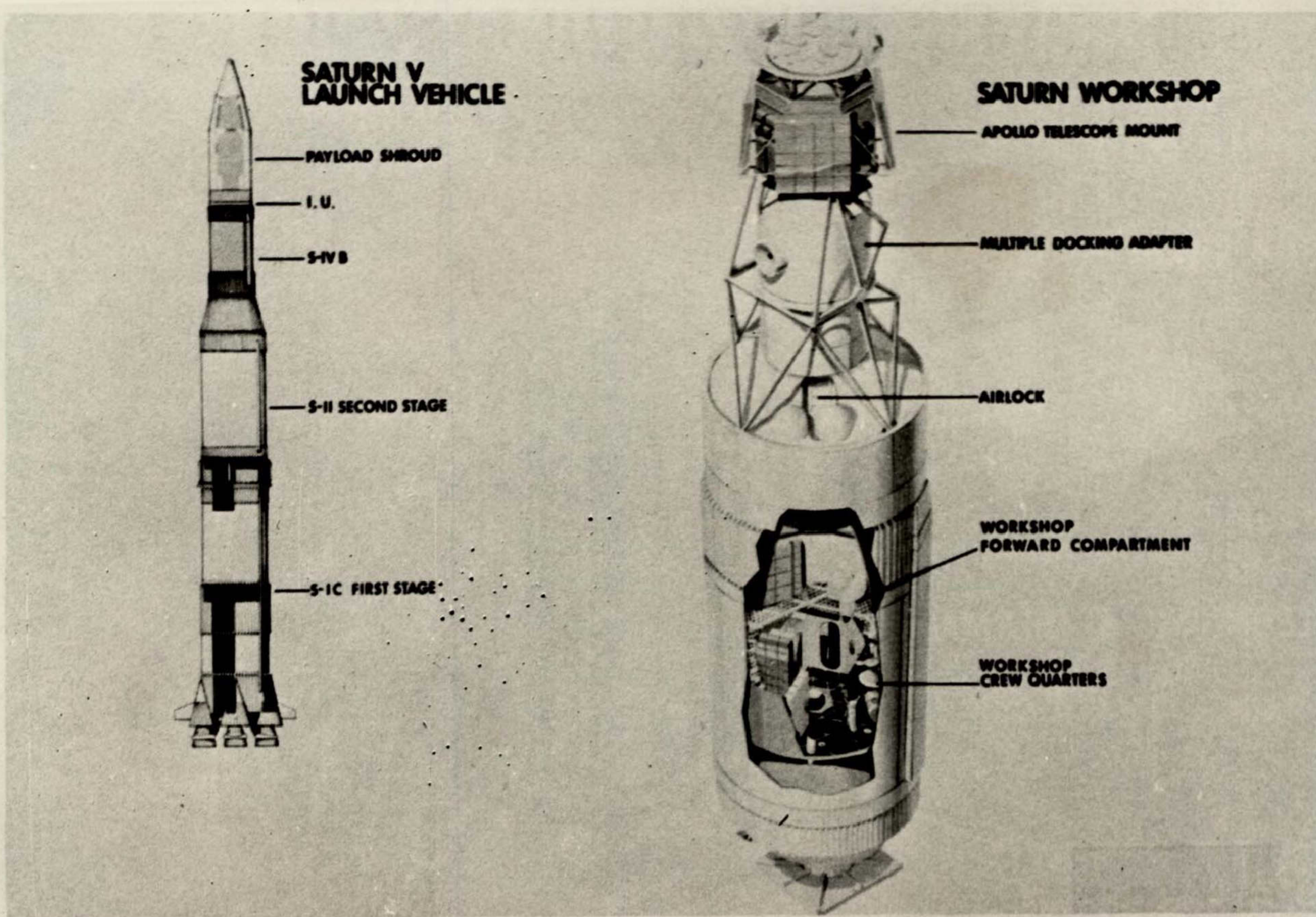


FIGURE 17.—Apollo Telescope Mount (ATM) and other Skylab components in launch configuration on top of Saturn V.

moved by a deployment mechanism 90 degrees to one side. This exposed the docking port on the forward end of the MDA to which the CSM docked. (A port on the side of the MDA could be used, if necessary, for rescue purposes.)

Orbital Workshop

A Saturn IB second stage (S-IVB) was modified and outfitted on the ground as living and working quarters for three astronauts. It contained the majority of the expendable storage, served as a structural support for a large solar array, and carried the cold gas storage and thrusters for the attitude control system. The stage's liquid hydrogen tank served as a 292 cubic meter (10,426 cubic foot) space laboratory. The OWS weighed 35,380 kilograms (78,000 pounds).

The S-IVB converted for Skylab had no engine or propulsive hardware other than the attitude contol thrusters. A reusable access hatch replaced an existing manhole in the forward tank dome. (A personnel hatch was also added to the side of the stage to permit workmen and technicians easy access during the checkout and prelaunch phase. This side hatch was sealed before launch.)

Aluminum open-grid floors and ceilings were installed in the tank to divide it into a two-story "space cabin." An aluminum foil, fire retardant liner was placed on the inside tank surfaces and a meteoroid shield on the exterior. Two solar arrays were mounted on the outside.

Crew quarters (figure 18) were at the aft end of the tank. A ceiling grid separated the quarters from the laboratory area in the forward end. Solid partitions divided the crew quarters into a sleep compartment, wardroom, waste management compartment and an experiment compartment. Lighting fixtures were mounted on the crew quarters' ceiling. The waste management compartment was sealed separately with walls and doors to retain odors and loose particles in the weightless environment. Crew quarters also contained five radiant heaters. Three radiant heaters were in the forward compartment.

The wardroom had about 9.3 square meters (100 square feet) of area; the waste management compartment had 2.8

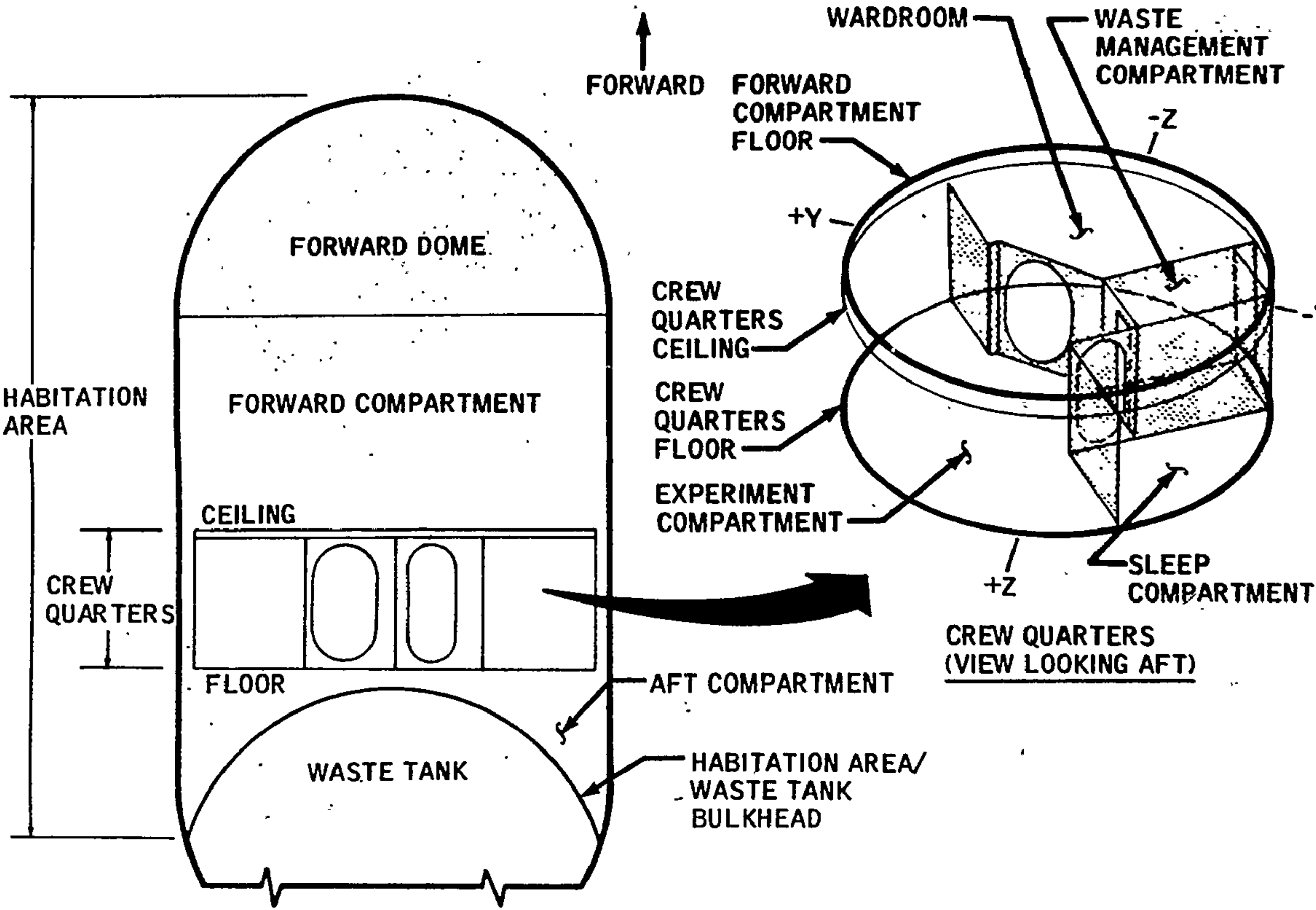


Figure I-8 – OWS Habitation Area

square meters (30 square feet) of floor space; the sleep compartment about 6.5 square meters (70 square feet); and the experiment area about 16.7 square meters (180 square feet).

The workshop's thermal control and ventilation system gave the astronauts a habitable environment with a temperature ranging from 15.6 to 32.2°C (60 to 90°F). A two-gas (oxygen and nitrogen) atmosphere was used with internal pressure kept at 3.45 N/cm2 (five psi). Fans circulated the atmosphere.

Solar arrays on the OWS (figure 19) and ATM provided electrical power for the cluster. The systems were cross-linked for flexibility in handling peak loads and for countering failures. The electrical power distribution system connected OWS areas with power sources in the AM and the solar cell assembly. Light fixtures had individual controls, and portable lights were used for illumination as needed. (One solar array on the OWS was torn loose during ascent to orbit and the interconnected systems saved the mission from immediate failure.) The meteoroid shield was intended to decrease the probability of hazardous punctures of the OWS. A 0.06-centimeter (0.025-inch) aluminum sheet was to be held against the OWS outside surface during launch. Once in orbit, this shield was to be deployed by swinglinks (powered by torsion bars) and held 5 inches from the wall. (At 63 seconds in the flight, this shield was torn off--see Mission Summary.) Another shield was a fixed double wall aluminum alloy covering the Thruster Attitude Control Subsystem (TACS) cold gas spheres on the aft end of the OWS.

Water and food for Skylab's operational lifetime was stored inside the OWS, the water in tanks in the forward experiments area and the food in compartments and freezers in that area and in the wardroom.

The wardroom had a window 0.46 meters (18 inches) in diameter in the middle of its wall. The window, double-paned and heated to prevent fogging, faced the sunlit side of the Earth during the mission.

The liquid oxygen tank of the S-IVB stage was converted into a waste container. An airlock was installed in top of the common bulkhead. The trash disposal section of the tank had 62.5 cubic meters (2,233 cubic feet) of space and the liquid dump area had 7.4 cubic meters (264 cubic feet).

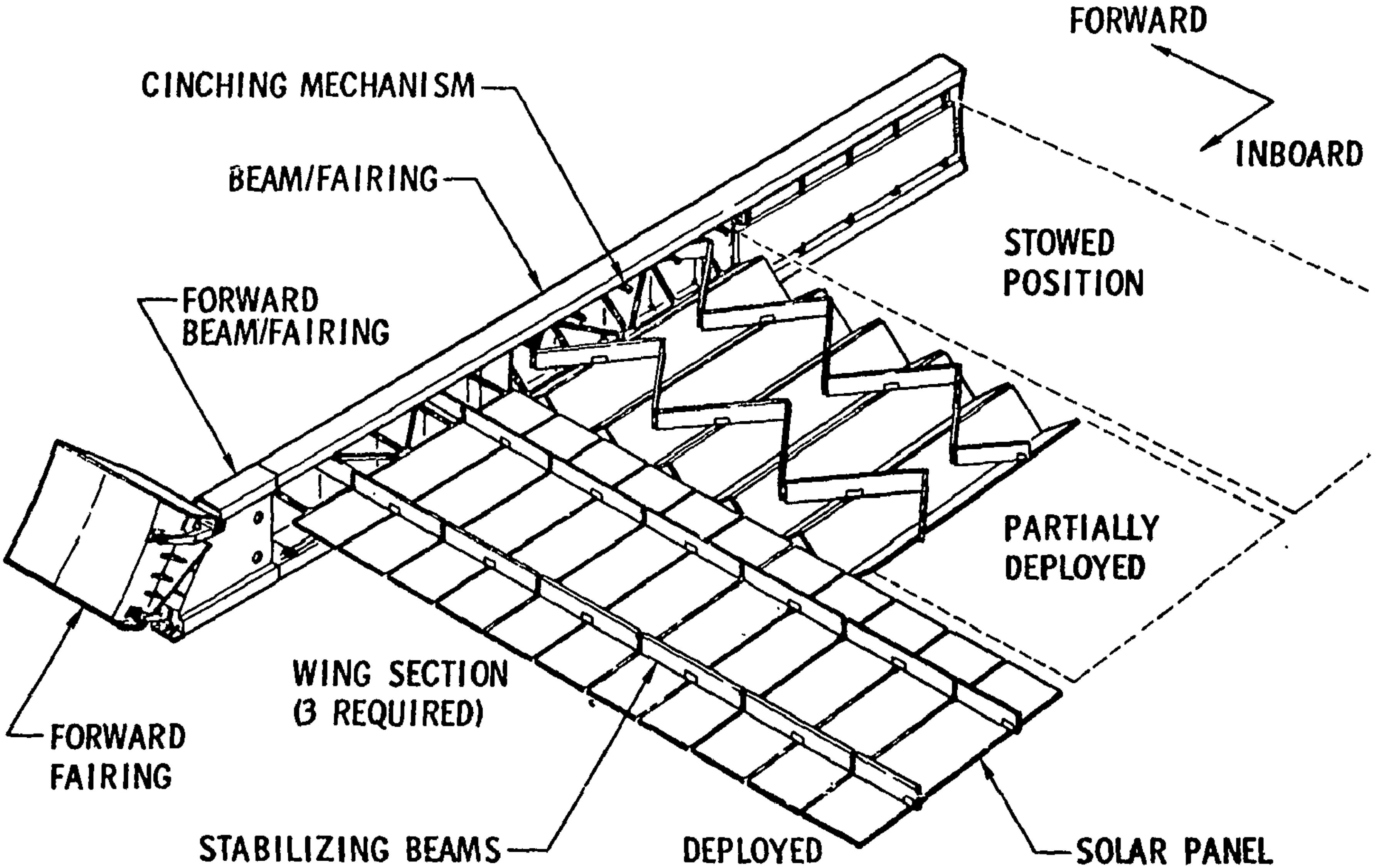


FIGURE 19 **OWS Solar Array Wing Assembly**

Twenty-three spheres containing cold gaseous nitrogen for the TACS and pneumatics were mounted on the aft end of the OWS. These were protected by a thermal shield around the OWS circumference at the aft end and by the aft meteoroid shield. The radiator for life support system (LSS) refrigerators and freezers were mounted aft of the TACS spheres and shield. Two attitude control thrusters of three nozzles each were on the aft end on opposite sides of the OWS.

Two "wings" of the solar panels were originally folded against the OWS on opposite sides for launch. Once in orbit, the arrays were to deploy to expose almost 219 square meters (2,355 square feet) of solar cells to the Sun's rays--enough to produce as much as 10,500 watts of power at 55°C (131°F). (The launch problem caused one array to be torn loose and the other to be held in the undeployed position--see Mission Summary.)

Forward Compartment

The forward compartment (figures 20 and 21) occupied the greater part of the habitation area. It was separated from the crew quarters by an 8-inch beam structure with an aluminum grid on each side. The forward compartment is divided into three main sections--the experiments area, the stowage ring, and the dome.

The main items in the dome section include the entry hatch and the ventilation control system mixing chamber and ducts.

The stowage ring (figure 22) was at the point where the cylindrical forward experiments area joined the dome. Mounted on the ring were ten water tanks, each having a usable capacity of about 272 kilograms (600 pounds) of water. A portable water tank was also available in the forward compartment. Also on the stowage ring were 25 lockers containing supplies needed throughout the OWS.

The forward experiments area contained food lockers and freezers, two Scientific Airlocks, and various items of equipment for performing a number of experiments: the ultraviolet panorama experiment; the body mass measurement device; contamination measurement equipment; photographic

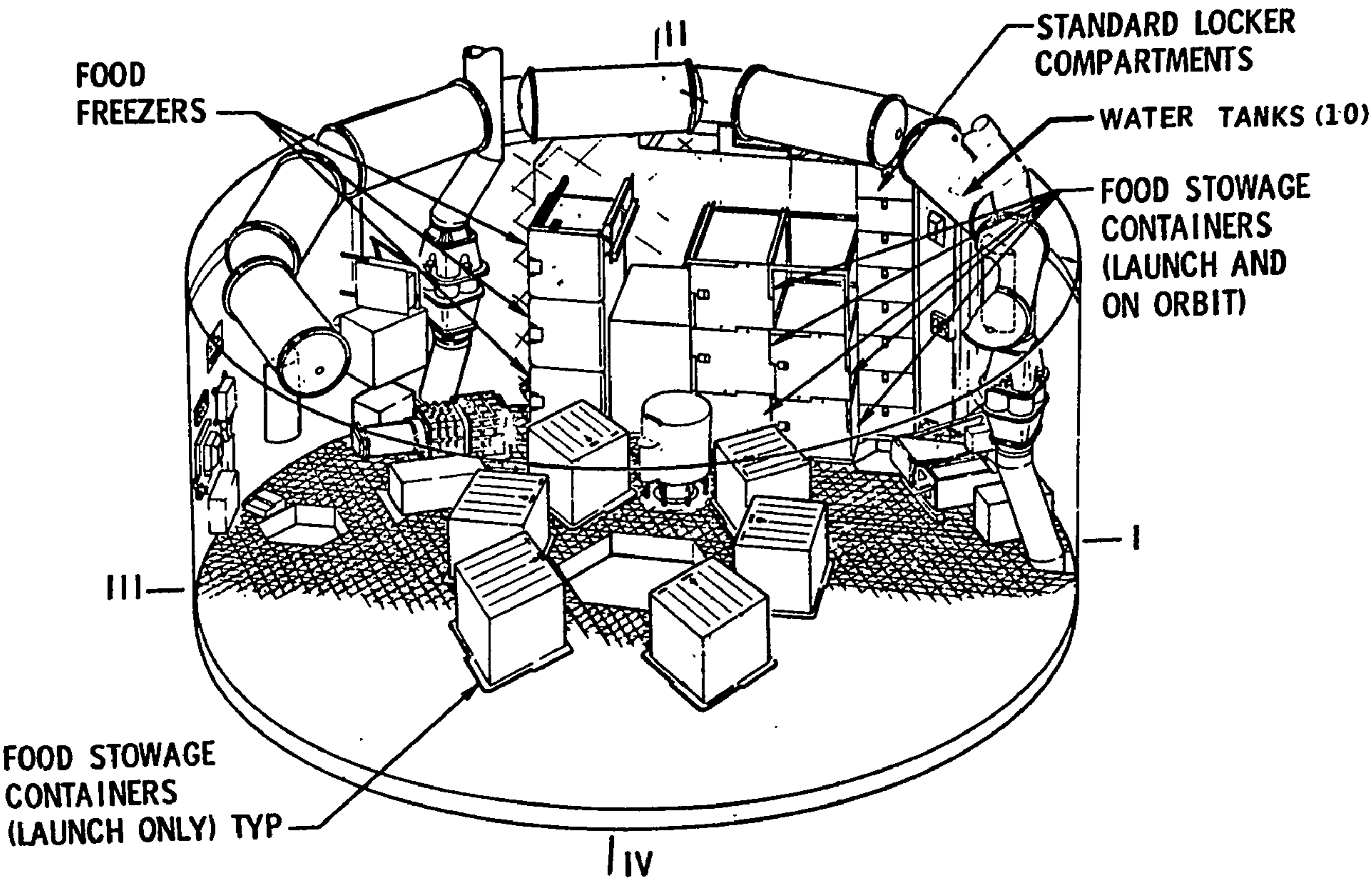


Figure 20 – OWS Forward Compartment, Launch Configuration

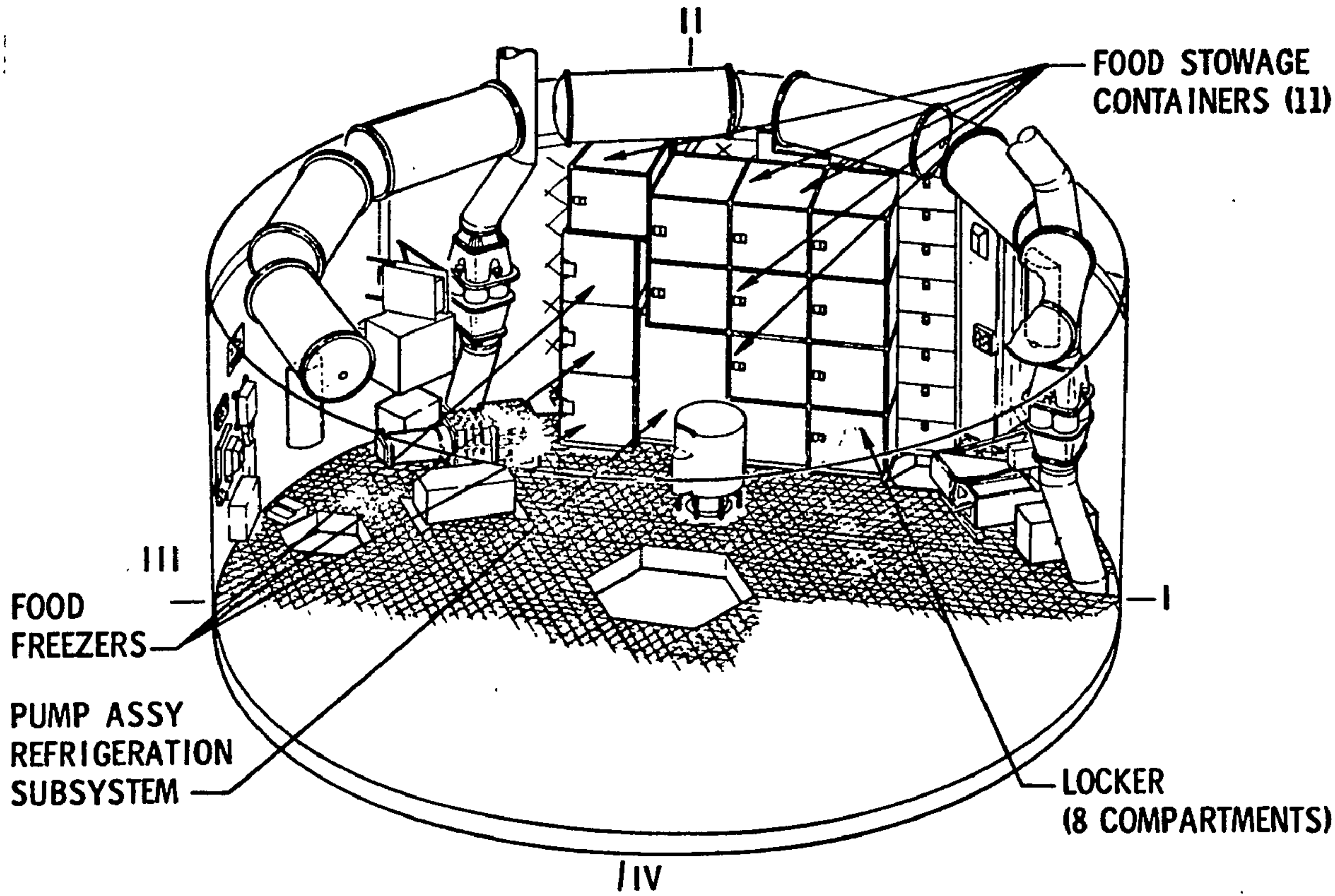


Figure 121– OWS Forward Compartment, On-Orbit Configuration

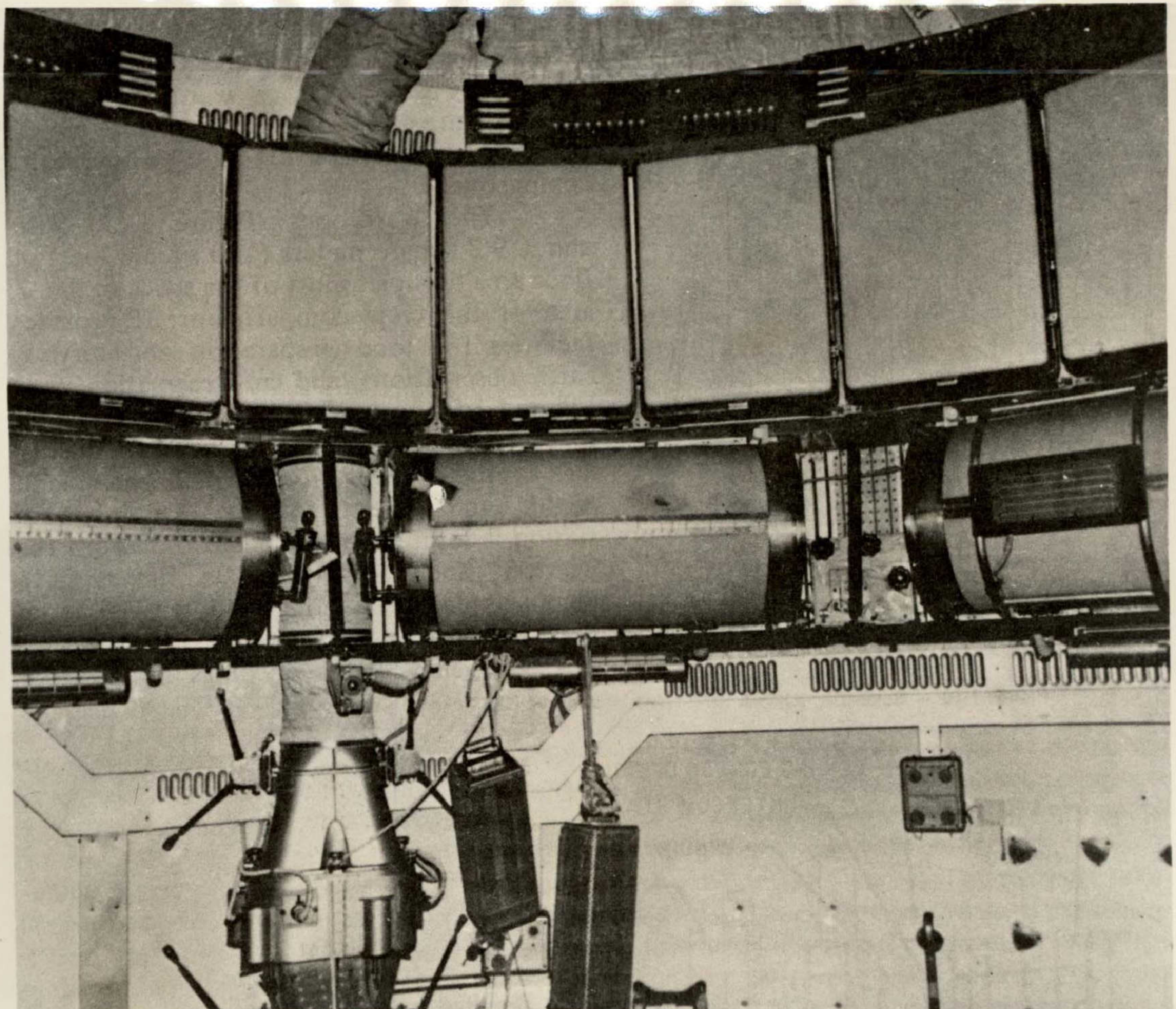


Figure 22 – OWS Stowage Ring

equipment; astronaut maneuvering equipment; EVA suits; film vault and scientific instruments.

Two Scientific Airlocks (SALs) were located in the forward compartment (figure 23). These SALs provide a method of deploying experiments through the wall of the OWS with depressurization.

Crew Compartment

The crew compartment was separated into four basic areas: a wardroom, waste management compartment, sleep compartment, and an experiment compartment.

The wardroom (figure 24) occupied about one quarter of the space in the area of the crew compartment. It provided facilities for food preparation and serving, earth observations, and crew relaxation.

The wardroom had a window, double-paned and heated to prevent fogging. The room had four general illumination light fixtures and emergency egress openings in the floor and ceiling.

The wardroom had 58 stowage lockers, a food chiller and two food freezers, containing food, tissues and wipes, medical kits, off-duty equipment, clothing modules, towels, flight data files, trash bags and scientific equipment. The food management table was located near the center of the room.

The astronauts had three storage lockers available for temporary storage of cans of food, one compartment for storage of snacks and beverages, and a six-well empty food can disposal unit.

Off-duty equipment was stowed in a corner cabinet. On the door was a tape player and tape cassettes. The cabinet contained headsets, microphones, batteries, playing cards, 36 paperback books, a dartboard and velcro-tipped darts, balls, exercising equipment and binoculars.

The Waste Management Compartment (WMC) (figure 25) was a rectangular room between the wardroom and the sleep compartment. It contained fecal and urine collection equipment, waste processing and urine management facilities, personal hygiene facilities, crewman restraint provisions

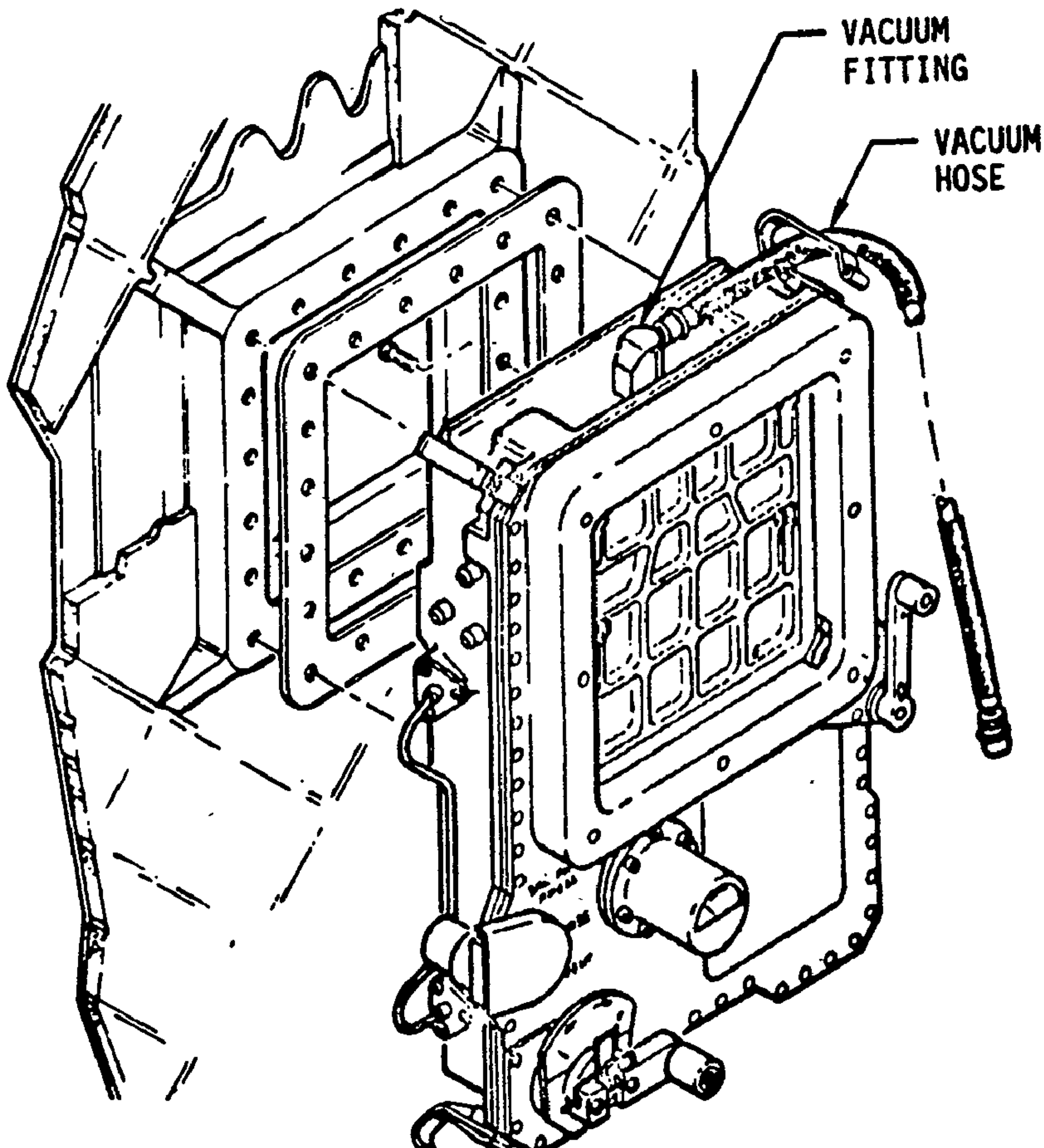


FIGURE 23 **Scientific Airlock**

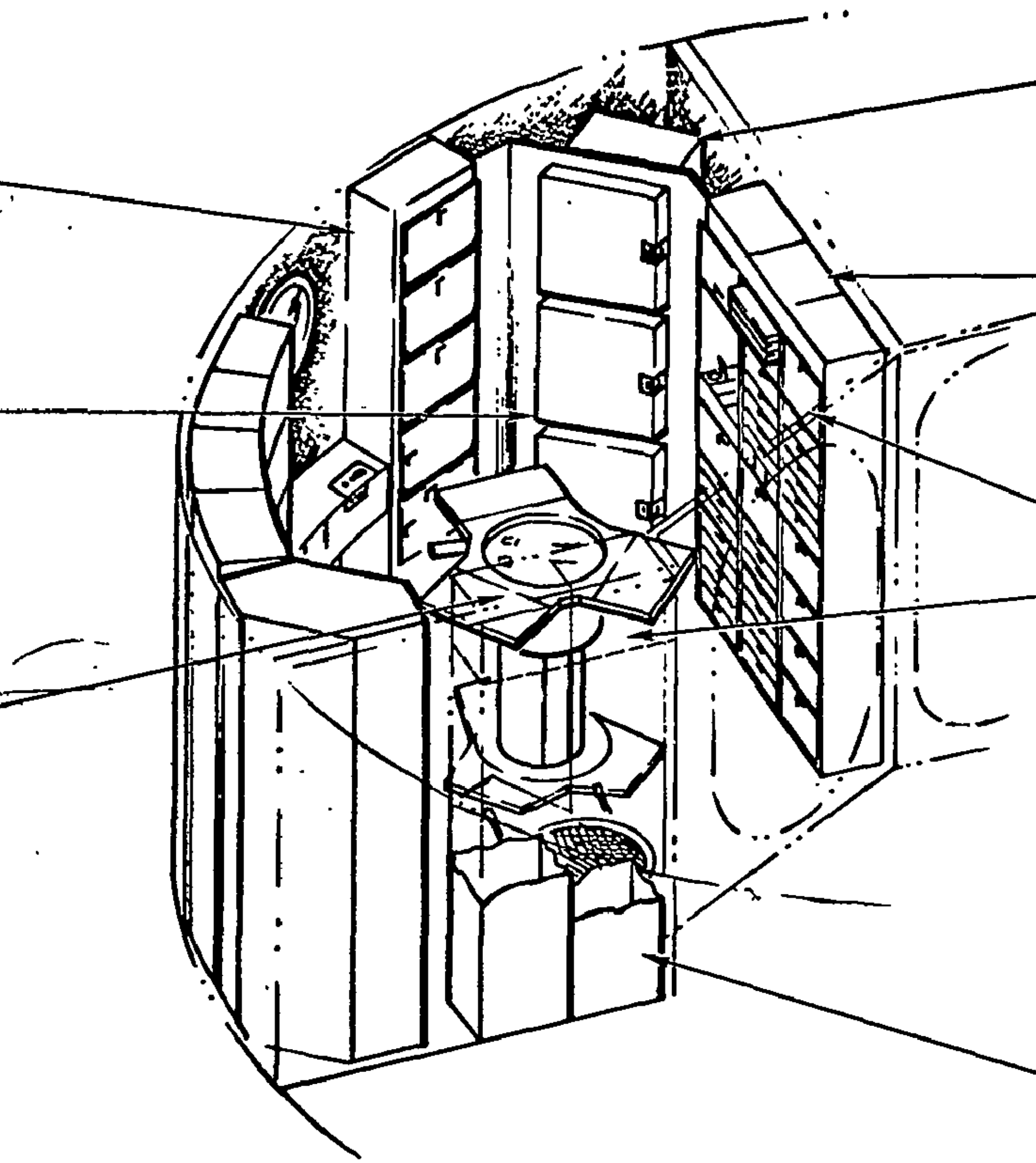


FIGURE 24 WARDROOM

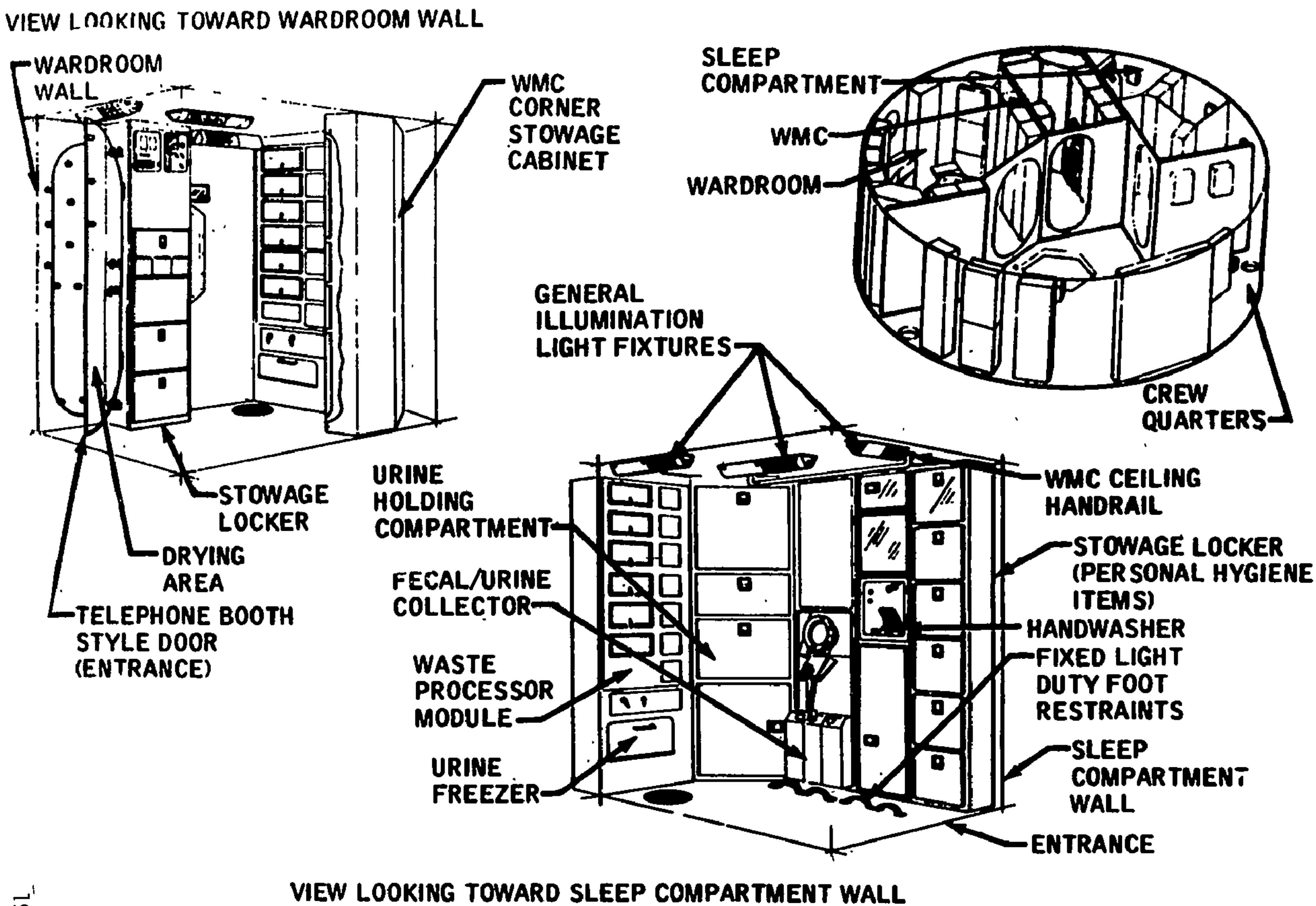


FIGURE 25 **WMC Arrangement**

and privacy and contamination control accommodations. Waste management and personal hygiene equipment and supplies were stored in the WMC.

The WMC had 15 stowage compartments, a urine holding compartment, a fecal/urine collector (toilet), a waste processor module, a urine freezer, a handwasher, food restraints and overhead handrails, sample return containers, a vacuum cleaner and four mirrors.

Three Individual Personal Hygiene Modules (IPHM) were stored in the WMC, containing shaving and dental equipment and supplies, soap, emollient, swabs, hair-groom brush and cream, nail clippers, deodorant and expectorant collectors. Each kit occupied a separate locker. In the same row of lockers was one with washcloths and towels.

The fecal/urine collector was mounted on the WMC wall. The collector, analogous to a toilet seat, was mounted in such a position that the weightless user appeared to be sitting on the wall facing the floor.

Waste processing and urine management facilities included a waste processing chamber, urine holding compartment and urine freezer. In support of the medical experiments, three insulated urine sample return containers were stowed in the OWS forward compartment until transferred into the CM for return to Earth. Specimen containers were bag assemblies that were strapped to CM lockers for the trip to Earth.

The sleep compartment (figure 26) was roughly triangular and was subdivided into three individual private rooms. The compartment provides noise abatement and light baffling provisions, sleep restraints, personal and mission equipment and supplies, individually controlled lighting and emergency egress provisions.

Each of the areas in the sleep compartment held a sleep restraint, a sleeping-bag type arrangement into which the astronaut enclosed himself to keep from floating about the area.

The sleep compartment had light baffles on the ceiling and overhead privacy curtains. The areas were separated by hard walls and fabric doors.

C·3

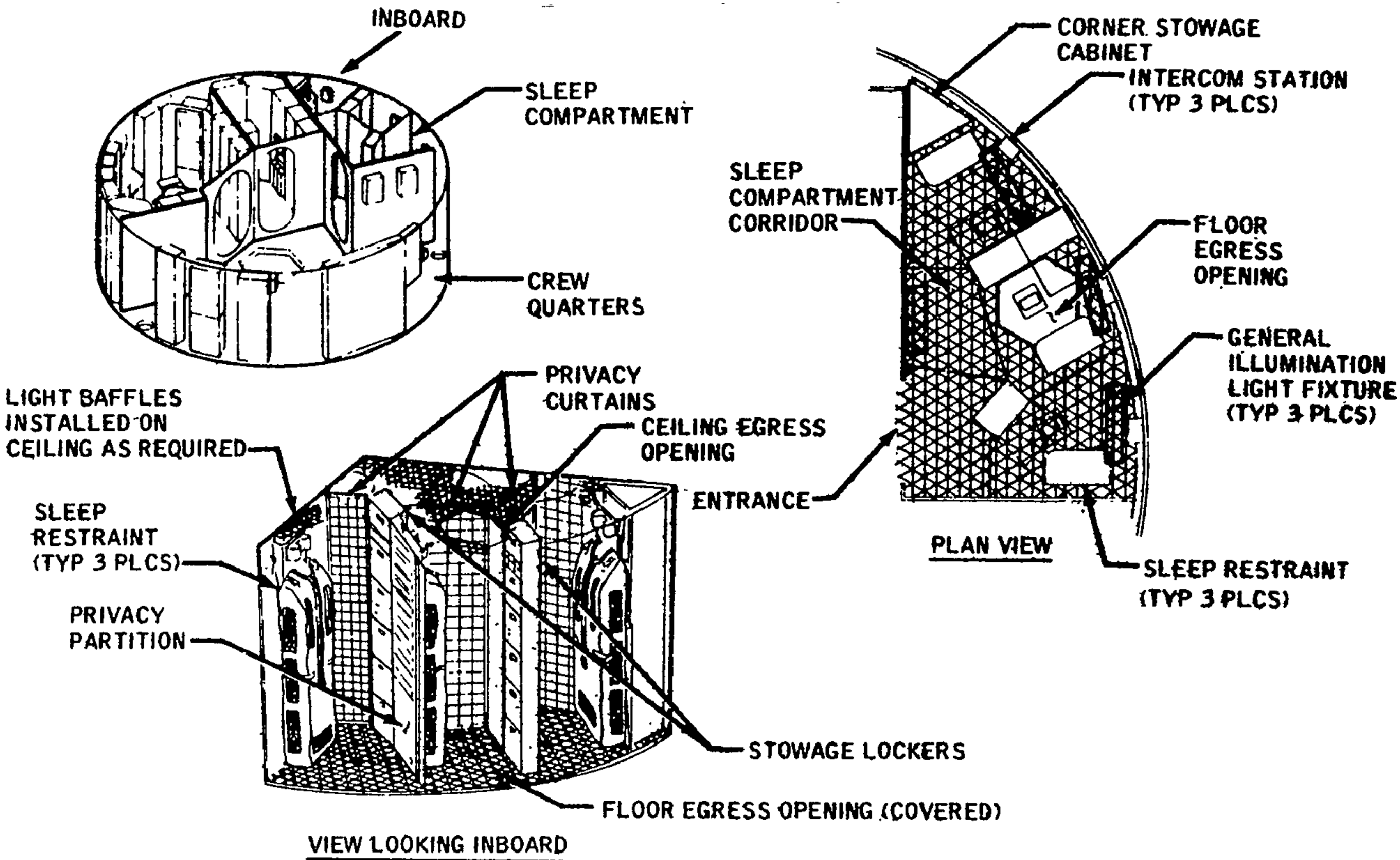


FIGURE 26 **Sleep Compartment**

The experiment compartment (figure 27) occupied about half of the crew's living and working section. This section was the experiments area and OWS control center. It had trash disposal facilities and mission and experiment equipment stowage facilities. It was lighted by general illumination fixtures which could be supplemented by portable lights if needed.

Major items of equipment in the experiments compartment included the trash disposal airlock, a rotating litter chair, lower body negative pressure device, and ergometer, metabolic analyzer and the experiment support system (ESS).

Waste Tank

A "trash dump" was carried on Skylab. The S-IVB liquid oxygen tank was modified to serve as a storage container for solid trash and a dumping facility for waste liquids. It had a total volume of 80 cubic meters (2,826 cubic feet). The waste tank (figure 28) was divided into compartments by screen enclosures, the largest of which was for trash disposal. Uncontained waste liquids entered the liquid dump compartment at three points. The unconfined liquid rapidly evaporated or solidified and then sublimated so that it could be vented overboard as a gas. The tank was vented to space through two nonpropulsive vents.

Multiple Docking Adapter

The Multiple Docking Adapter, or MDA, provided a permanent interface with the Airlock Module and a docking interface with the Command and Service Modules (CSM). The MDA permitted the transfer of personnel, equipment, power, and electrical signals between the docked module, the AM, and the workshop.

The MDA general configuration consisted of a forward conical OWS cylinder, provided a shroud around the aft portion of the AM and structural mounting for the AM and MDA modules the ATM Deployment Assembly and the Skylab oxygen supply tanks. It supported the payload shroud, the ATM, AM, and MDA during boost.

The truss assemblies attached the AM to the FAS and provided exterior mounting structures for battery, electronic, thermal, and experiment equipment.

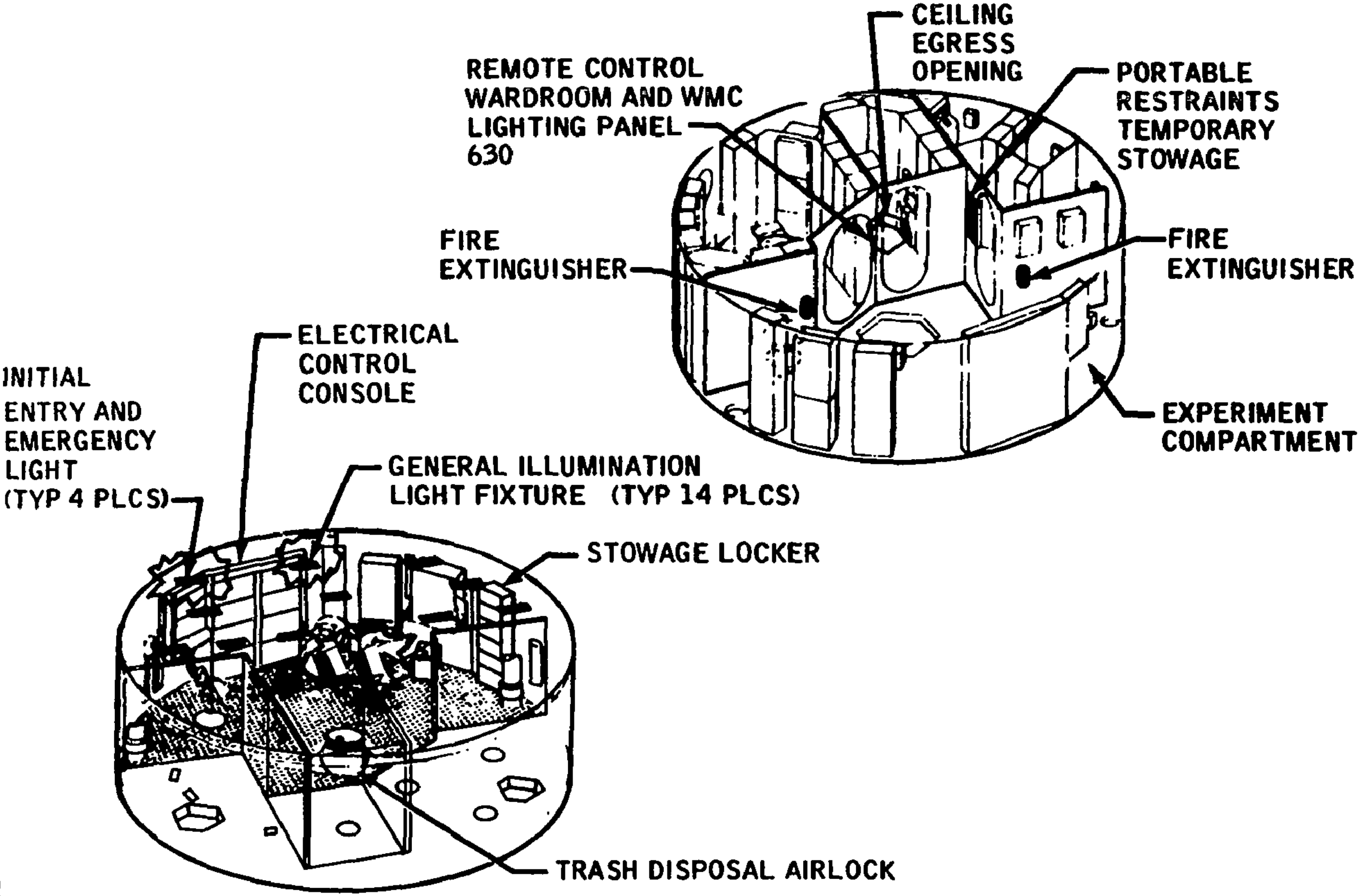


FIGURE 27 **Experiment Compartment**

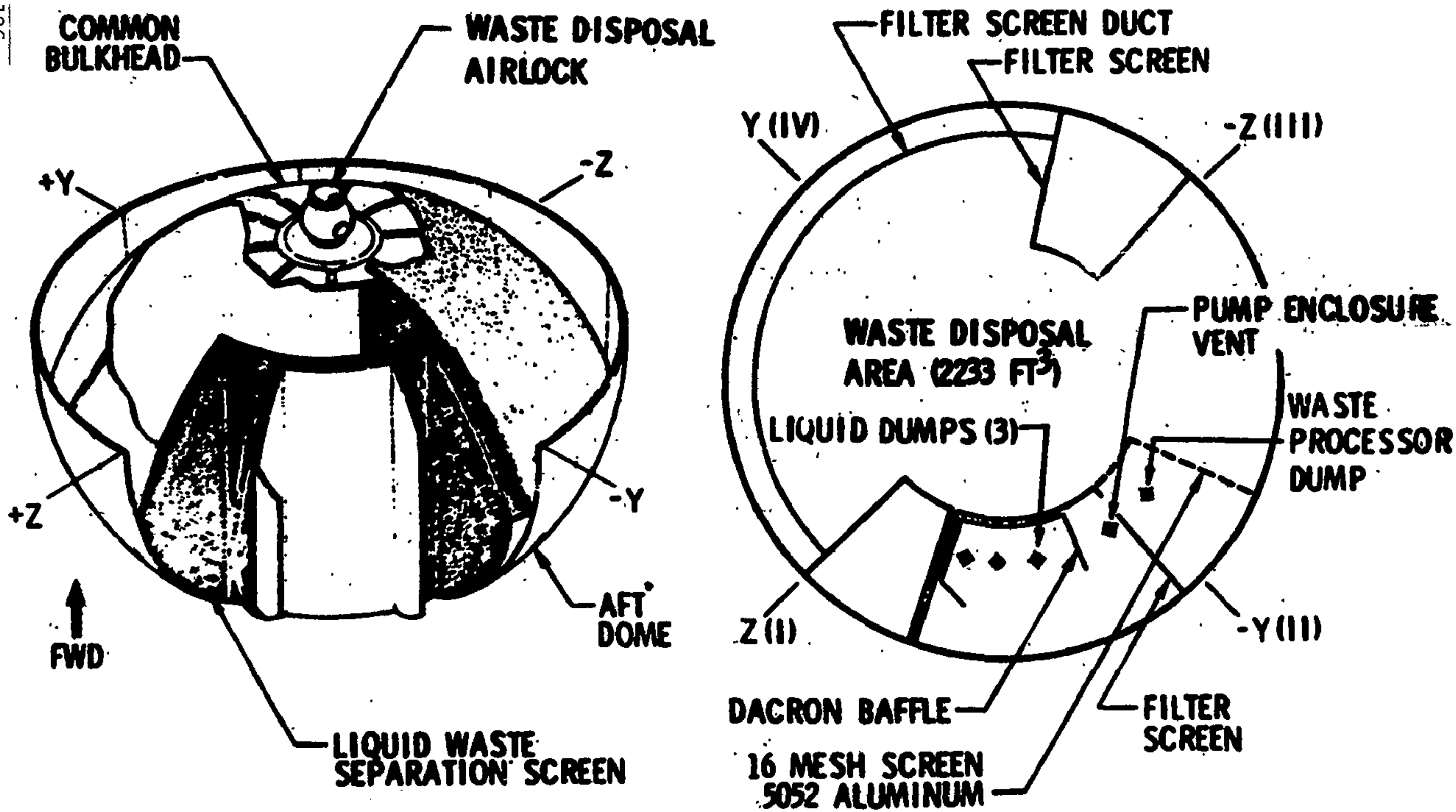


FIGURE 28 OWS Waste Tank

Some of the basic functions provided to Skylab by the AM were: (1) Oxygen and nitrogen storage for atmosphere supply, (2) Thermal control for Skylab atmosphere, (3) Purification of Skylab atmosphere, (4) OWS/AM electrical power control and distribution, (5) Lock, hatch and support for extravehicular activity, (6) Instrumentation for real time and delayed data transmission, (7) Caution and Warning displays and tones, (8) Command link with ground network, (9) Ranging link for CSM rendezvous, (10) Tracking lights, (11) Teleprinter, (12) Experiment support, and (13) Equipment stowage.

Structural Transition Section

The STS was at the forward end of the airlock tunnel and was physically secured to the MDA. It provided the structural transition from the MDA to the airlock tunnel and its trusses. It is constructed as a welded aluminum cylinder of stressed skin in a semimonocoque configuration. Four double pane glass viewing ports, one in each quadrant, were provided for visibility.

Airlock Tunnel Assembly

The AM tunnel assembly provided the passageway from the MDA/STS to the OWS. It was constructed of aluminum and was cylindrical in shape. The tunnel was divided into three compartments by two internal bulkheads equipped with hatches. The forward hatch lead to the STS via the forward tunnel, and the aft hatch to the OWS through the tunnel extensions. The center compartment included a crew hatch for EVA. It was the same hatch originally designed for the Gemini spacecraft and was roughly trapezoidal in shape and curved to match the wall of the AM. It had internal and external hatch handles and a window and was kept closed and sealed by 12 latches. When unlatched, the hatch swung outward.

The two AM internal hatches are quite similar in appearance and function. Both are circular and both swing outward from the lock compartment. Each has a hatch opening of 120.1 centimeters (47.3 inches) in diameter. Each hatch has a bulkhead and a cylindrical structure. The MDA has a primary axial docking port at the forward end and a backup or rescue port.

In orbit the MDA functioned as a major experiment control center for solar observations; metals and materials processing; and the Earth resources experiments. The MDA was positioned with either the +Z axis pointing earthward to provide an orientation for the Earth Resources Experiment Package (EREP) or with the -Z axis pointed toward the Sun for solar observations.

The Apollo Telescope Mount was operated by the astronauts from the Control and Display (C&D) console in the MDA (figure 29). There the crew actively controlled the telescopes.

The "Materials Processing in Space" facility (figure 30) was mounted in the module and provided a furnace or vacuum work chamber with an electron beam generating device.

The external surface of the MDA (figure 31) is covered by a radiator/meteroid shield structure that stands 7.6 centimeters (3 inches) from the pressure skin.

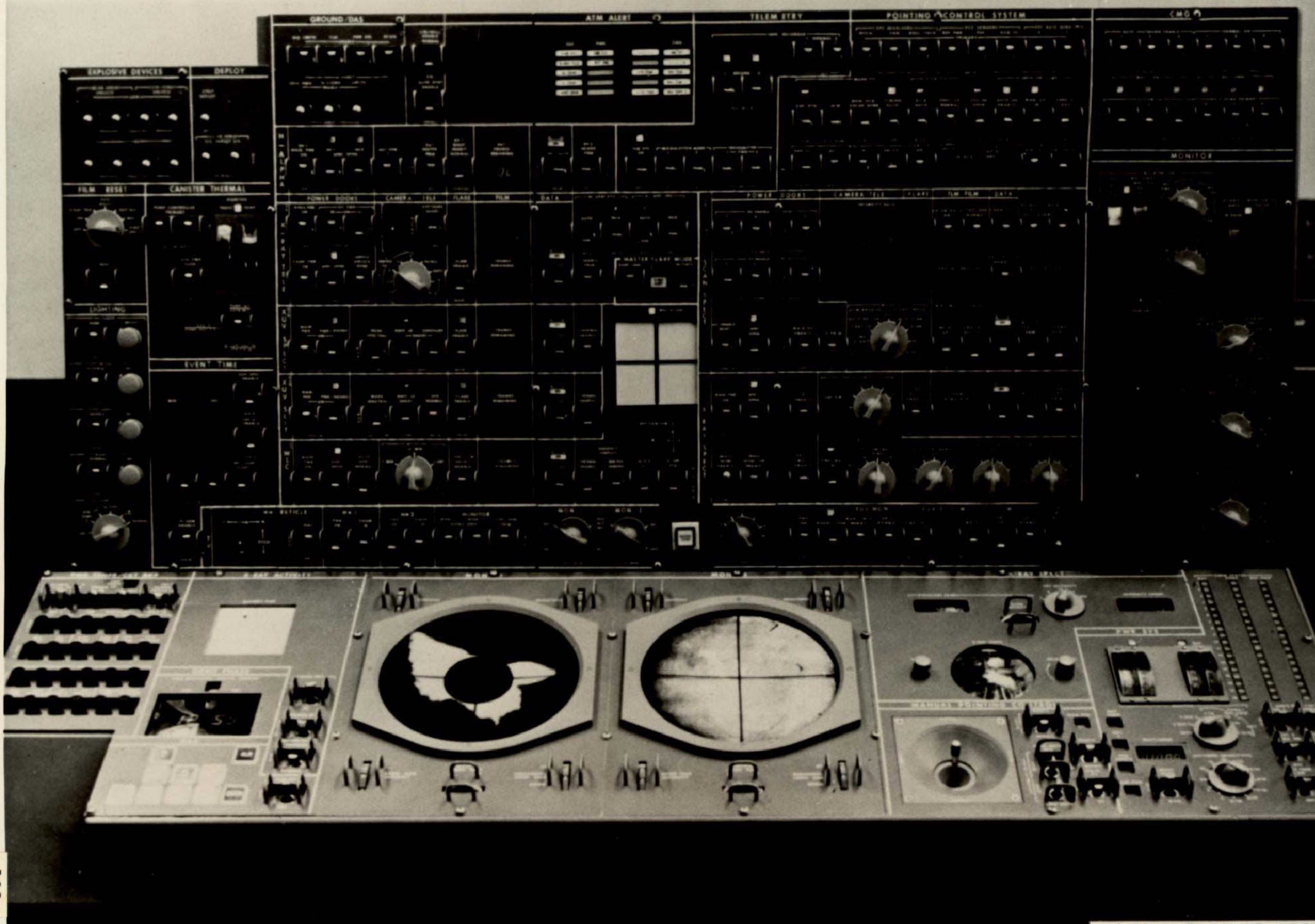
The docking system was a means of connecting and disconnecting the CSM/MDA during a mission and of providing for intravehicular transfer between the two modules. Docking was achieved by maneuvering the CSM close enough to the MDA so that the extended probe engaged the drogue on the MDA (figure 32). When the probe engaged the drogue through the capture latches, the probe retract system was activated to pull the MDA and CSM together. Upon retraction, the MDA tunnel ring activated 12 automatic latches and effected a pressure seal between the modules.

Airlock Module

The Airlock Module (AM) (figure 33) was the structural assembly between the OWS and the MDA.

The Structural Transition Section (STS) connected the tunnel assembly to the MDA structure. The tunnel had hatches at each end to form an airlock to permit the astronauts to perform extravehicular activities without depressurizing the complete spacecraft. Egress to space was through a hatch on the side of the AM. A flexible extension connected the tunnel assembly to the OWS to continue the passageway while isolating structural loads from the OWS forward dome.

ATM CONTROL AND DISPLAY CONSOLE



NASA HQ ML69-6109
9-11-69

Figure 29

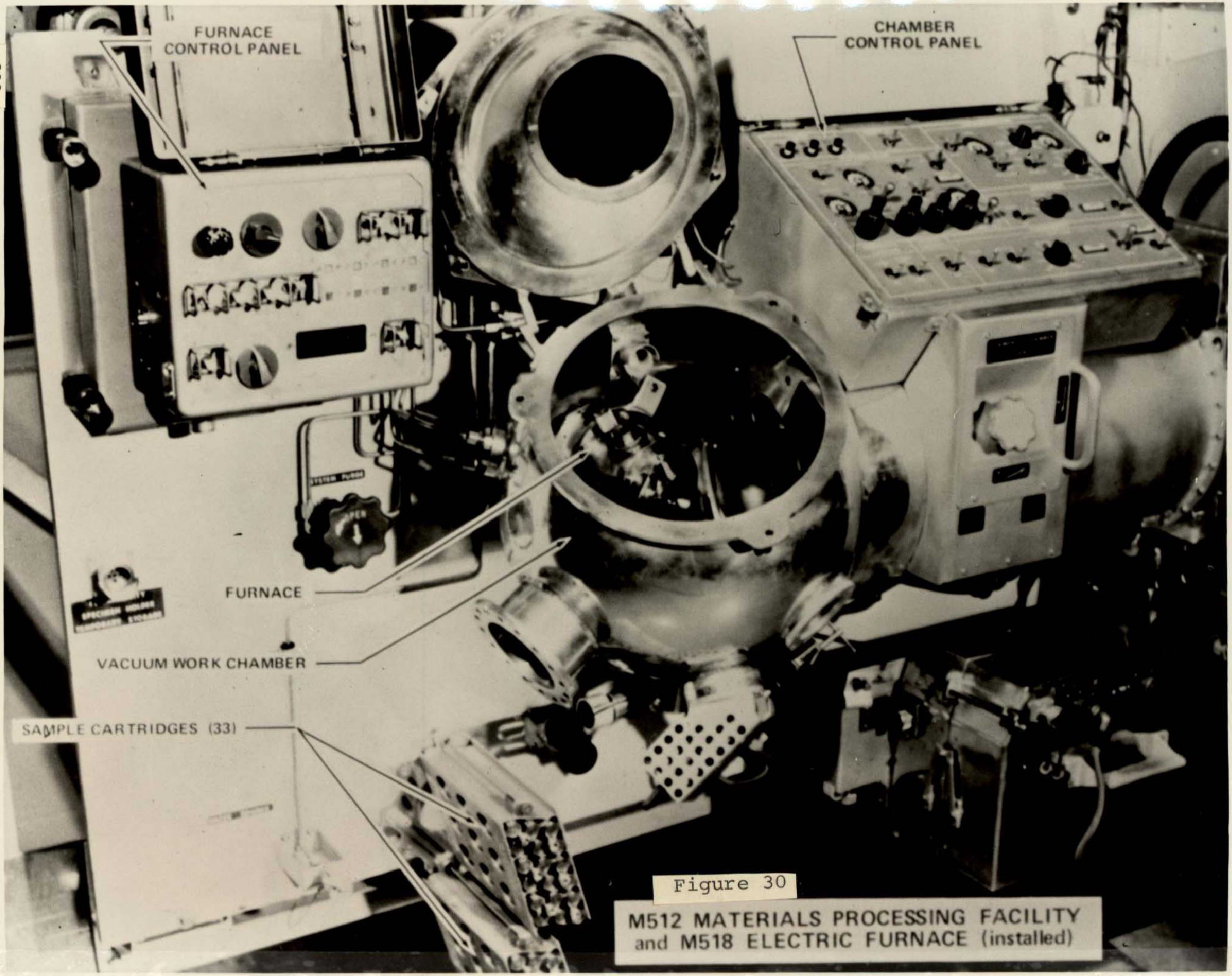
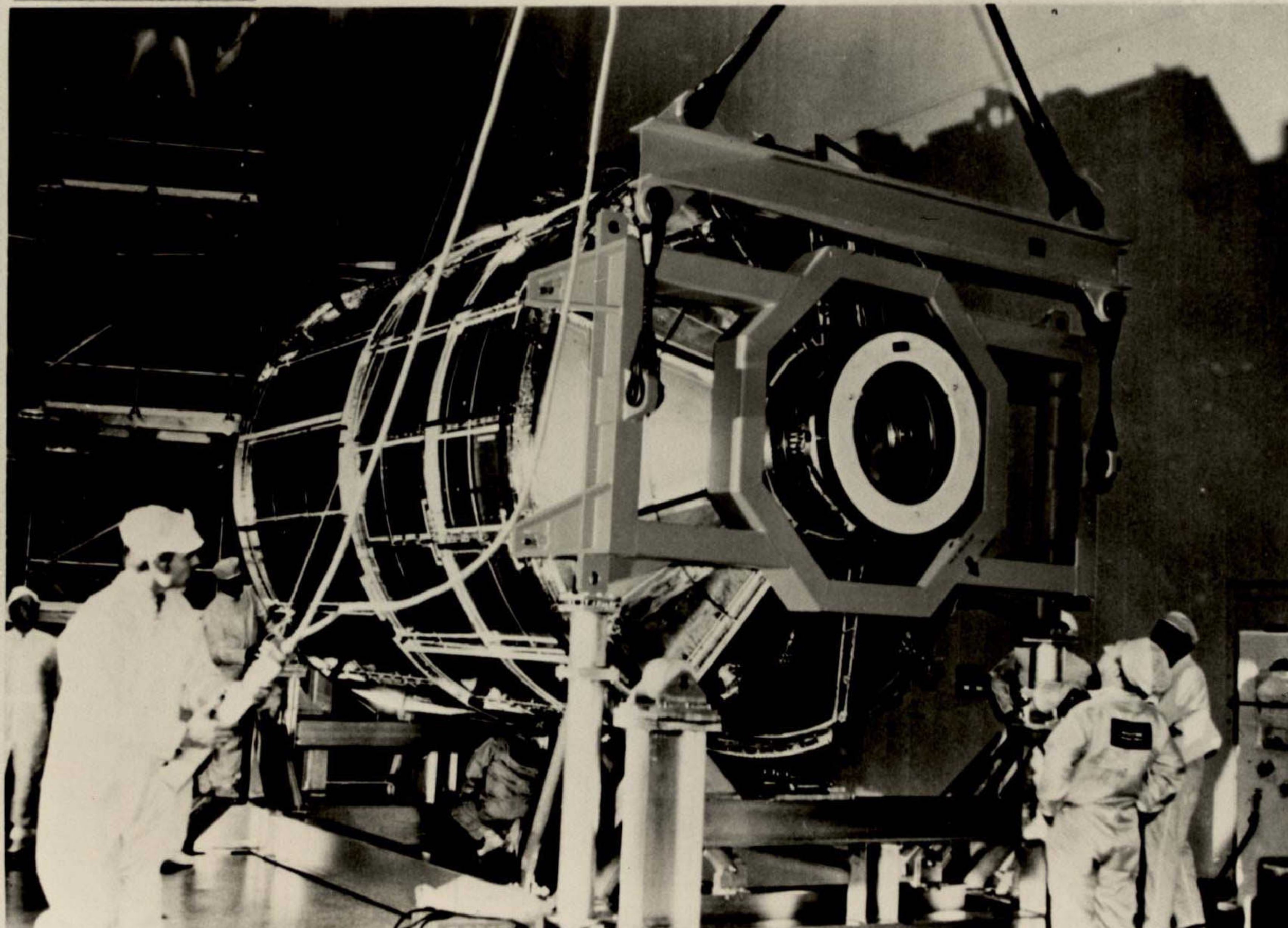


Figure 30

M512 MATERIALS PROCESSING FACILITY and M518 ELECTRIC FURNACE (installed)

MDA FLIGHT ARTICLE



FLIGHT ARTICLE RESTING ON HORIZONTAL FIXTURE PREPARATORY TO HUGHES ANALYZER TEST

Figure 31

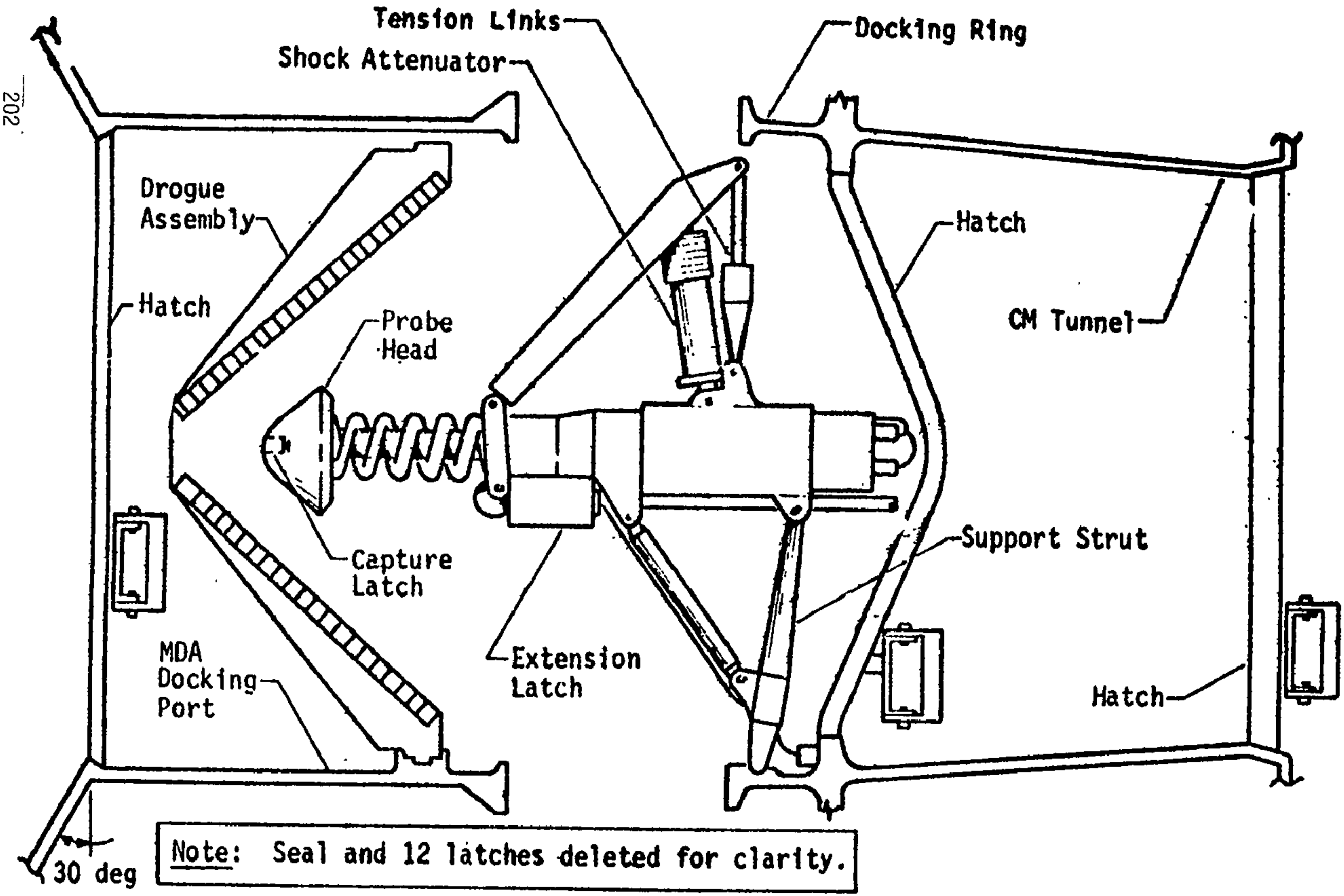
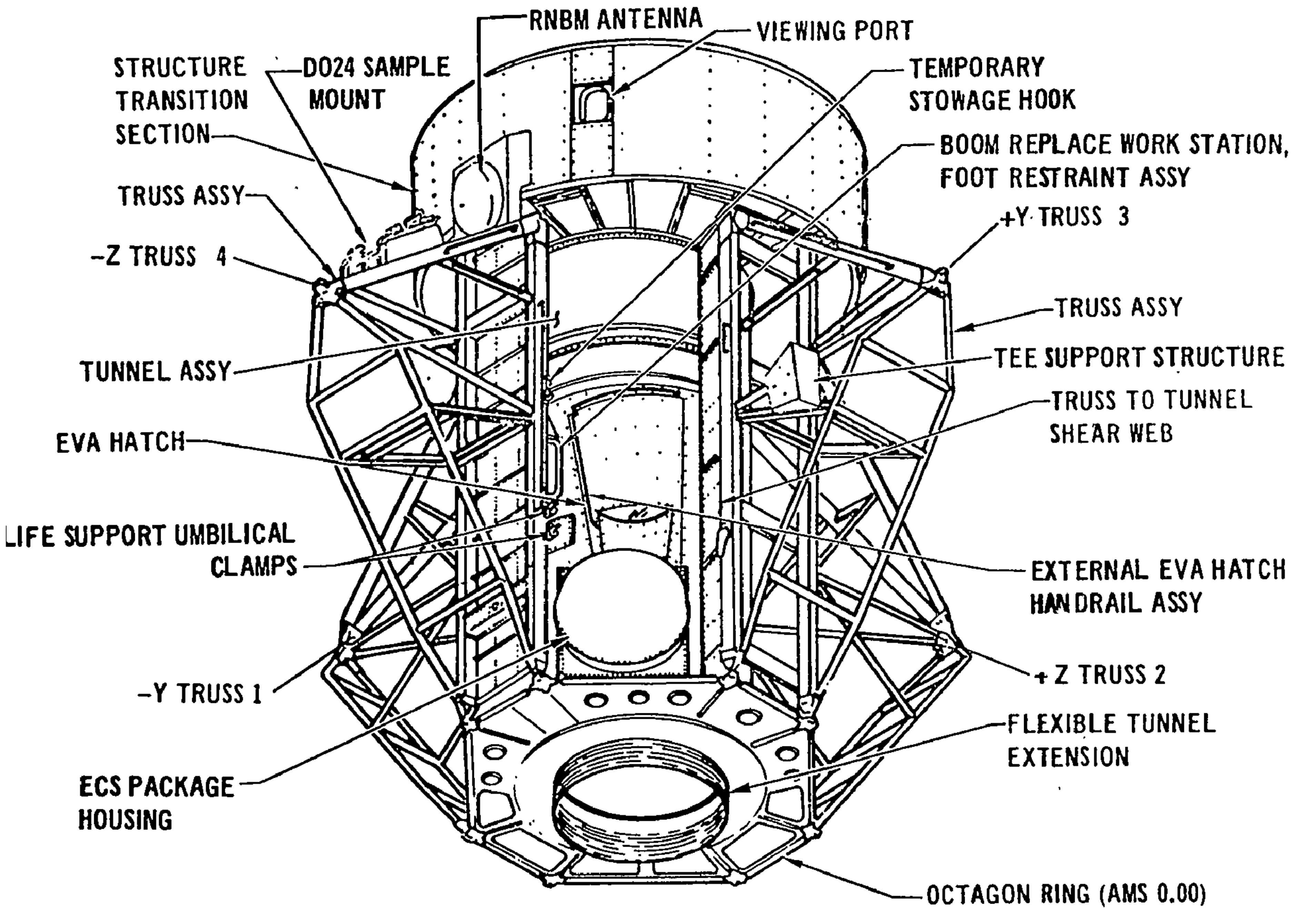


FIGURE 32 **MDA Docking Mechanism**



203

Figure 33 – Airlock Module

The Fixed Airlock Shroud (FAS) which was a continuation of the window, 21.6 centimeters (8.5 inches) in diameter with a stainless steel grid shield, pressure equalization valve, stiffeners and nine latches. The latches are the same type used on the EVA hatch.

Fixed Airlock Shroud

The Fixed Airlock Shroud (FAS) (figure 34) was a cylindrical structure that joined with the IU and extended forward to surround the AM aftercompartment and about two-thirds of the lock compartment. It served as a structural support for the ATM, AM, MDA and Payload Shroud (PS) and supported the mounts for oxygen tanks.

Also carried on the FAS were two discone antennas which were deployed away from the OA once in orbit. The antennas were stowed for launch in the +Y+Z and -Y+Z quadrants halfway between the trusses. Pivot/attach points were on the inside of the FAS wall. Each antenna was in two sections. The sections were folded together at a rotary joint which rested against the AM. In orbit the antennas were deployed--one at 45 degrees from -Z toward -Y and the other at 45 degrees from -Z toward +Y.

Truss Assemblies

The four AM truss assemblies located outside provided the longitudinal support for the AM between the FAS and STS. They provided mounting support for experiments, consumable containers and other hardware. The four trusses are located symmetrically around the tunnel assembly. A single point on each truss attached the assembly to the FAS. Truss 1 is at +Y; truss 2 is at -Z; truss 3 at -Y, and truss 4 at +Z.

Apollo Telescope Mount

The Apollo Telescope Mount (ATM) accommodated a variety of telescopic instruments for the solar investigations. The ATM also had a solar array which generated about half of Skylab's electrical power, and the ATM structure housed primary stabilization and attitude control components for the total spacecraft.

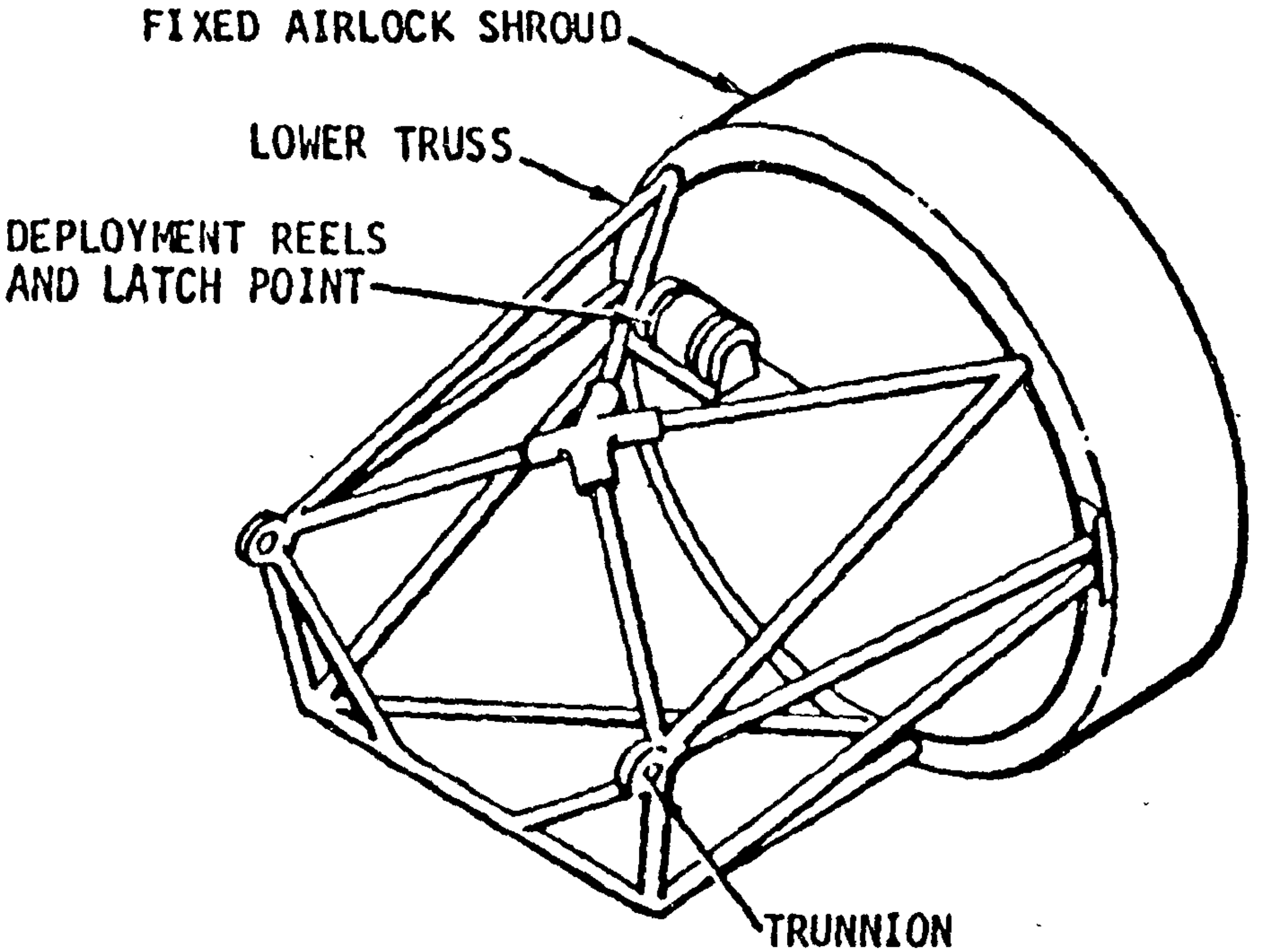


FIGURE 34 **Fixed Airlock Shroud, Deployment Assembly**

The operational ATM (figure 35) system consisted of five major hardware elements: The cylindrical experiment canister (figure 35) which housed the solar astronomy experiments; the Attitude Pointing and Control System; the solar array wings; the Control and Display (C&D) console which was in the MDA and which provided the capability for astronaut operational control and monitoring; and the rack assembly, a large octagonally-shaped structural frame which surrounded the canister and provided structural attachment points for the solar and thermal shields, outrigger assemblies, solar arrays, Deployment Assembly, experiment pointing control-roll positioning mechanism and numerous subsystem components.

The experiments canister consisted of the Spar, the MDA and Sun-end canister halves, and the canister girth ring.

The spar (figure 36) was a cruciform structure constructed of three 1-inch thick insulation covered aluminum plates which provided structural support of the experiments and experiment pointing control components (fine Sun sensor, rate gyros, etc.). Girdling the center of the spar was a girth ring which provided the structural interface between the experiments canister and the rack mounted experiment pointing control-roll positioning mechanism. The girth ring provided attach points for the canister halves which enclosed the spar mounted experiments to provide a contamination-free environment for the experiments.

The MDA end canister half included four film retrieval doors which are used for in-orbit experiment film retrieval and replacement. The Sun-end canister half contained two film retrieval doors and ten aperture doors on the Sun-end bulkhead. These aperture doors covered the fine Sun sensor and experiment apertures during nonoperating periods to prevent optical contamination. (The experiments canister included the EPCS gyros and an active thermal control system to provide a stable thermal environment for the experiments.)

Mounted on the ATM were major elements of Skylab's Attitude and Pointing Control System (APCS) that provided three-axis attitude stabilization and maneuvering capability for the orbiting vehicle. It also provided the capability of pointing experiments at desired locations, such as the Sun, the Earth, and other targets of interest.

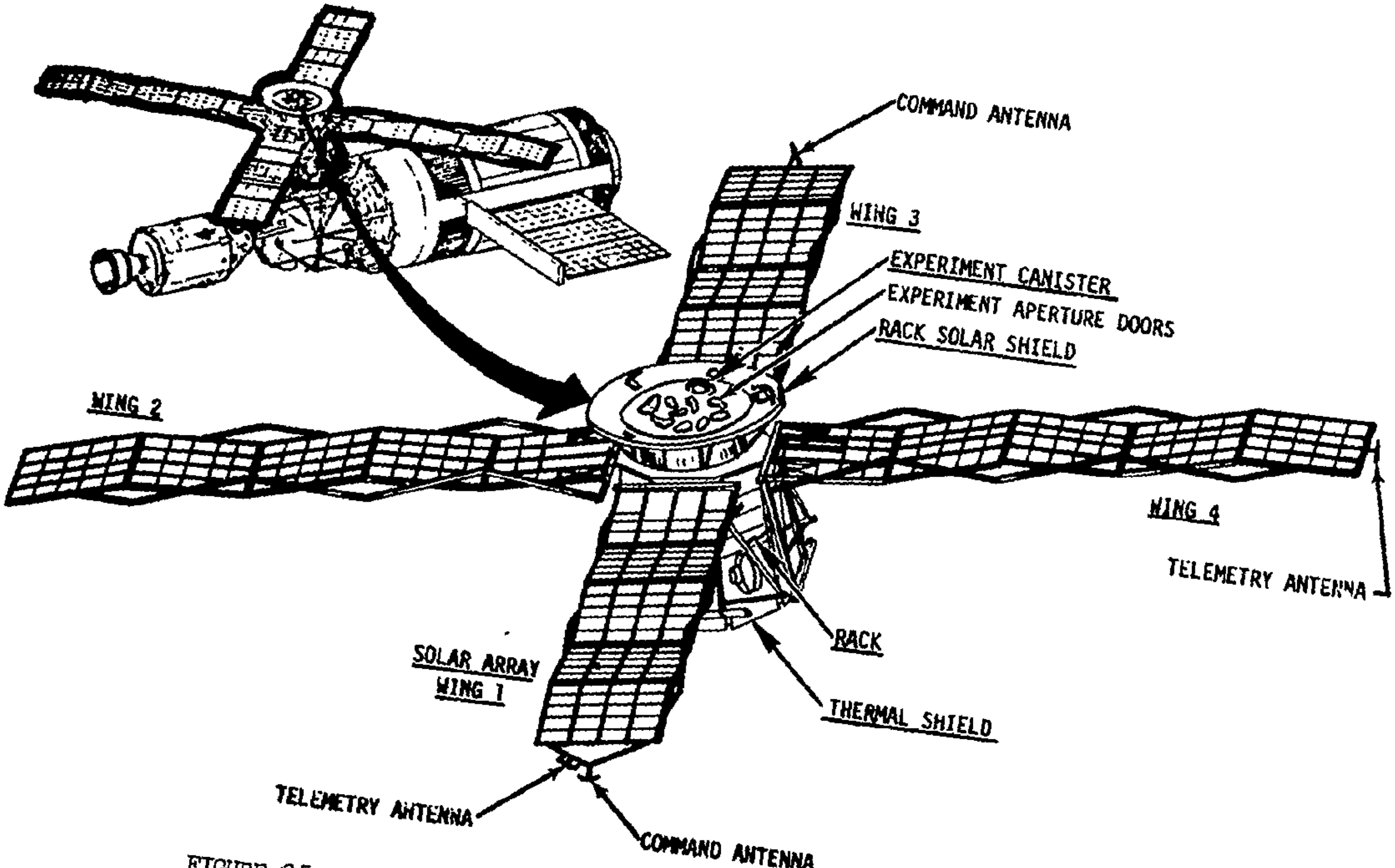


FIGURE 35

Operational ATM

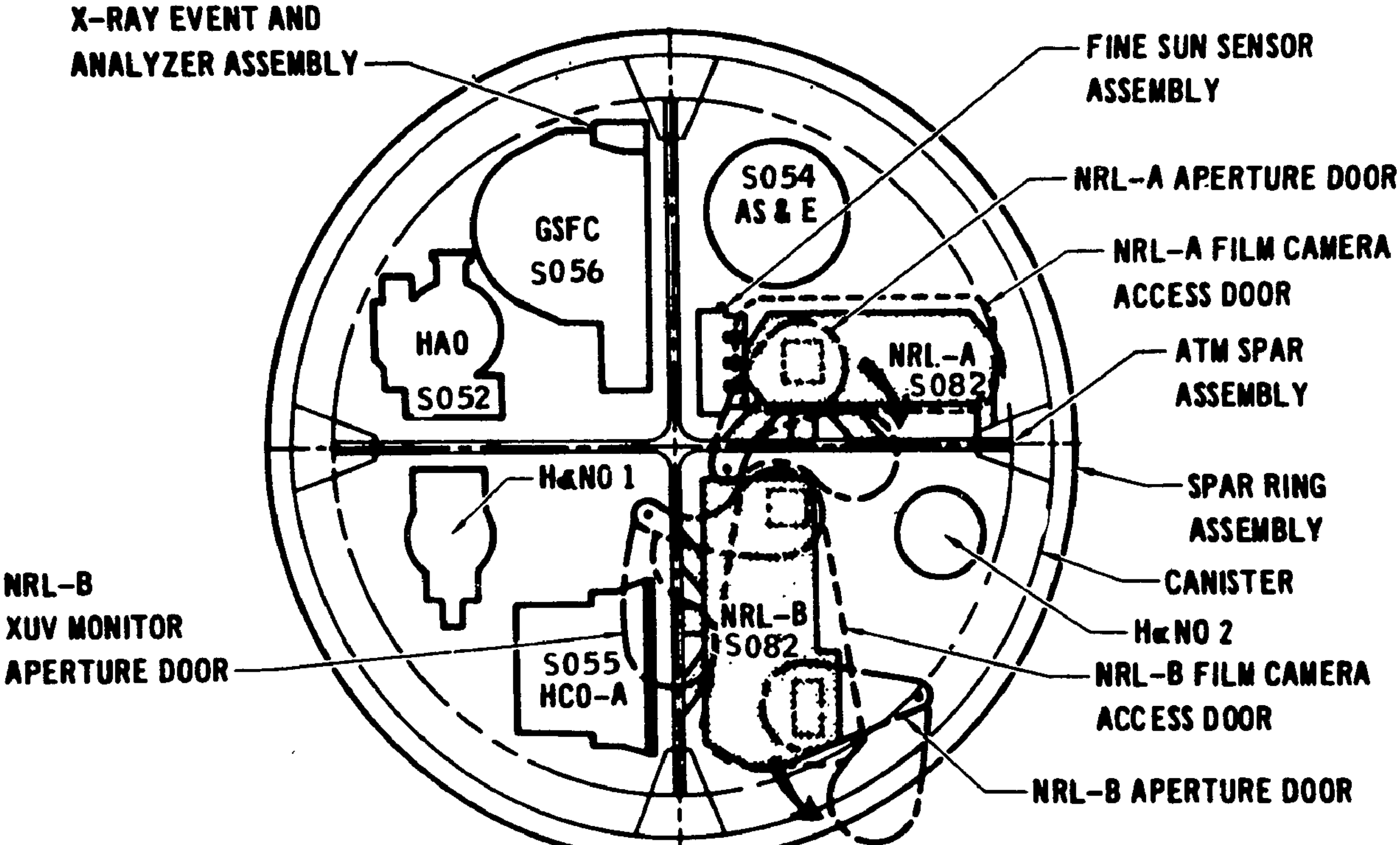


FIGURE 36 **ATM Spar, Sun End View**

The APCS is comprised of the Instrument Unit/Thruster Attitude Control Subsystem (IU/TACS), Control Moment Gyros Subsystem/Thruster Attitude Control Subsystem (CMGS/TACS) and Experiment Pointing Control System (EPCS).

The EPCS maintained fine attitude pointing and control about two axis for the ATM instrument package. The third axis (roll) was controlled from the C&D console. The ATM instrument package could be manually pointed to any desired location on the solar disk or its outer perimeter.

Vehicle attitude information was derived from strapdown reference computations in the ATM Digital Computer using rate gyro information, and, during orbital daytime only, Sun sensors. The ATMDC processed the sensor signals to generate the CMB gimbal rate commands. The astronaut had the capability of manually controlling the CMGS through his keyboard on the ATM C&D console.

Control Moment Gyros

Three double-gimbaled CMGS hardmounted at 90 degree angles to the ATM actuated the system. (A CMG is basically a spinning wheel that provides the forces required for vehicle control.)

The ATM (CMG) consisted of an induction-motor-drive constant-momentum rotor, gimbal supported to provide two degrees of freedom. Associated with each CMG was an Electronics Assembly for positioning the gimbals and controlling the gimbal rates, and an Inverter Assembly for providing power. Each CMG has an angular momentum storage capability of 2,300 foot-pound-seconds.

The EPCS provided fine pointing control and stability for the ATM experiments, further isolating them from any disturbance torques from the Skylab assembly. This system provided control to within 2.5 arc seconds for periods up to 15 minutes, utilizing fine pointing Sun sensors for attitude reference. The experiment package could be offset pointed within a ±24 arc min square centered on the solar disc. It could also be rotated to any desired roll orientation through ±120 degrees.

To help maintain stability and alignment for the scientific instruments, a thermal control loop was incorporated within the skin of the experiment canister to circulate liquid coolant. This active thermal control system was self contained within the canister. The water/methanol cooling fluid transfers heat absorbed from cold plates to radiators on the exterior side of the experiment canister, where it radiated into space. The active coolant systems maintained an average temperature within the canister of approximately 12°C (53°F). Each experiment also had its own thermal control heaters, designed to maintain its temperatures within about ±0.6°C (1°F).

As part of the ATM control and displays, two selectable video presentations were available to the astronaut conducting the experiments. Pictures of the Sun were displayed in various wavelengths from several of the solar instruments; thus a crewman onboard the spacecraft was able to assure proper identification and tracking of solar events of interest and point the instruments with a high degree of accuracy or spatial resolution (1 arc second corresponds to about 700 kilometers (434 statute miles) on the solar disk).

The ATM solar array consisted of four individual wing assemblies which were stowed in a folded configuration during launch and deployed in orbit at 90° to each other.

The solar cell panels were made up of a framework of rectangular aluminum tubing mounting solar cell modules. The four outboard panels of each wing mounted 20 modules. The inboard panel mounted 10 modules on the outboard portion of the panel.

The ATM was mounted on the ATM Deployment Assembly (DA) which provided in-orbit structural support between the ATM and the Fixed Airlock Shroud (FAS) and deployed the ATM upon reaching orbit.

Payload Shroud

The Payload Shroud (PS) was a smooth structure which surrounded and protected the ATM, MDA, AM, and associated hardware during the launch and climb-out phase of the mission. The principal requirement was to provide an aerodynamic and environmental protection cover for Skylab elements and structural support to the ATM during the prelaunch and launch phases. Once in orbit, the PS was split into four sections or quadrants by pyrotechnic devices and jettisoned. The four shroud sections were joined with "shear" rivets and latching link mechanisms.

The total PS was 6.5 meters (21.7 feet) in diameter at the aft end (interface locking ring), 16.8 meters (56 feet) long and weighed 11,794 kilograms (26,000 pounds).

Command Service Module

The Skylab Command and Service Module was basically the same CSM (J-type) used during the Apollo Program. Numerous modifications and certain deletions had been made to accommodate the unique mission requirements of the Skylab missions.

CSM 116, 117, and 118 were flown on SL-2, SL-3, and SL-4 respectively. CSM 119 was available as backup or rescue vehicle if it had been needed.

Major modifications included the addition of a 12-tank reaction control system (RCS) propellant storage module, with a total of 680 kilograms (1,500 pounds) of propellants to more than double the former RCS propellant capacity, expansion of the spacecraft's thermal control system, addition of a 50-gallon water tank to eliminate water dumps, addition of three 500-ampere-hour descent batteries, deletion of one of the vehicle's three fuel cells, and deletion of two of the four service propulsion system (SPS) propellant tanks and one of the two helium tanks.

Command Module

The Command Module (figure 37) transported three crewmen and between 453-680 kilograms (1,100-1,500 pounds) of stowed equipment to and from Skylab, served as the primary communications vehicle and command station for the SWS, provided backup attitude control, and had the capability of being reactivated after 56 days of semidormancy in space.

The CSM guidance and navigation system was powered down and the command module computer was maintained on standby during orbit activities.

At launch, the CSM cabin atmosphere contained 60 percent oxygen and 40 percent nitrogen. Lithium hydroxide (LiOH) cartridges were changed after 12 hours of use or if CM carbon dioxide partial pressure exceeded 5.5 mm mercury pressure.

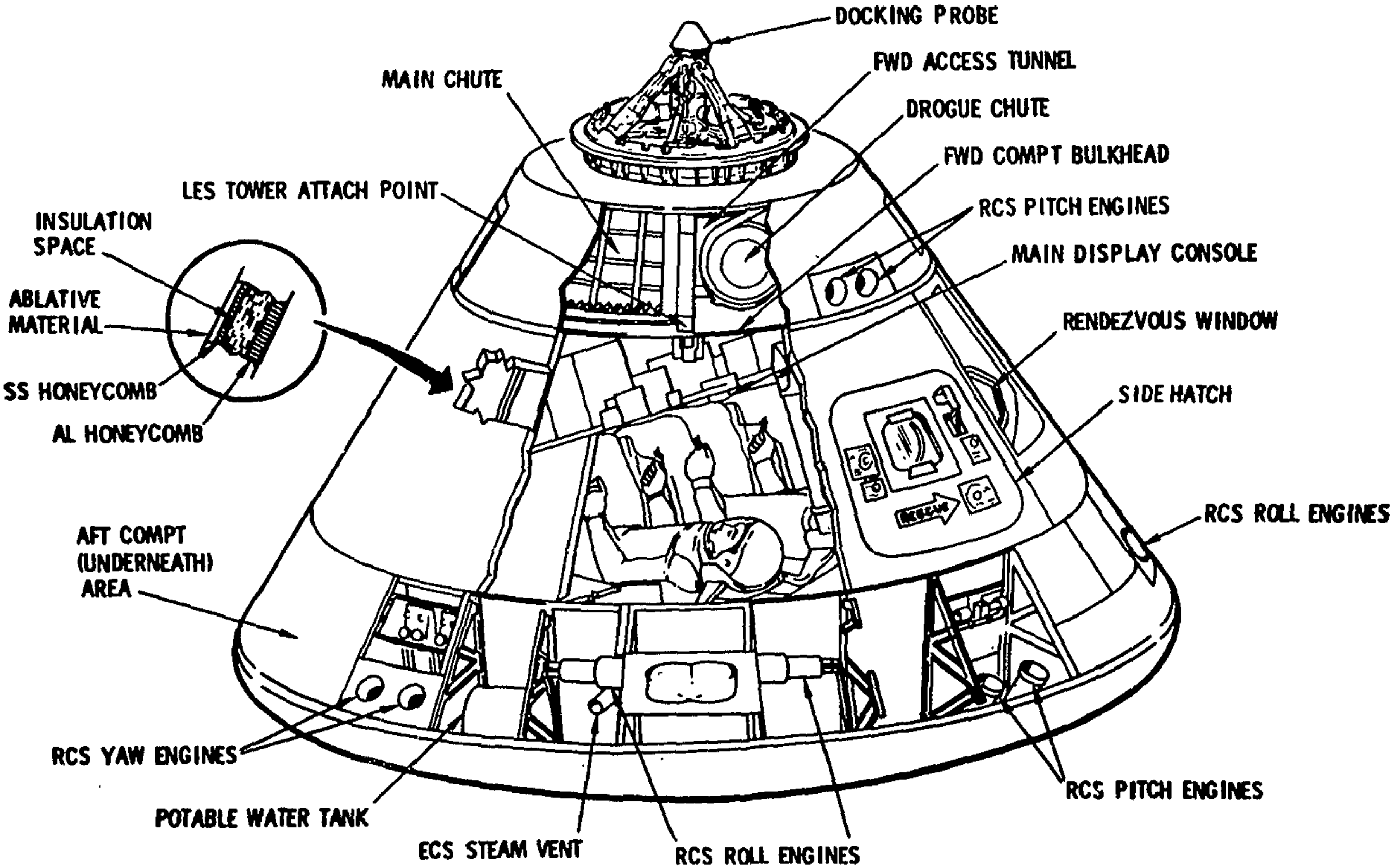


FIGURE 37 **Command Module**

LiOH cartridge replacements were stored in the MDA and deployed in the CM. The LiOH system was operative only during CSM use and during molecular sieve bakeout deactivation.

The CSM fuel cells remained on hydrogen-oxygen cryogenic supply for approximately 13 days or until the supply was depleted. Residual hydrogen was vented to space and excess oxygen was vented through the cluster or vented overboard.

Entry and post landing batteries (A and B) were turned on five minutes prior to an SPS burn and turned off immediately after completion of the burn. The batteries were charged immediately after docking.

The Spacecraft Lunar Module Adapter, or SLA, was a large truncated cone which connected the CSM and second stage of the launch vehicle. For Skylab flights SL-2, SL-3, and SL-4 the adapter contained only a stabilizing structure to brace the outer shell.

Service Module

The Service Module was a cylindrical structure which served as a storehouse of critical subsystems and supplies. It remained attached to the Command Module from launch until just before Earth atmosphere entry. Its main propulsion engine was used to perform rendezvous maneuvers and the deorbit burns for return to Earth.

Saturn V

Saturn V vehicle AS-513 was designated SL-1 for the first Skylab launch. The S-IC and S-II stages of the launch vehicle were essentially the same as those used in the lunar landing missions. From the S-II stage forward, the vehicle was considerably different. The Apollo launch vehicle had an S-IVB stage, IU, SLA, LM, SCM, and LES. On the SL-1, the S-IVB was replaced by the Orbital Workshop (OWS). Forward of the OWS was the IU, AM, MDA, and ATM; all except the IU were enclosed in the PS. The LES was not required since SL-1 was not manned. Total weight of the SL-1 launch vehicle and payload was approximately 2,822,300 kilograms (6,222,000 pounds). Height of the total assembly was 101.71 meters (333.7 feet). Payload capability was near 90,720 kilograms (200,000 pounds). The S-IC and S-II propulsive stages of the launch vehicle were each 10.06 meters (33 feet) in diameter. The S-IC was 42.06 meters (138 feet) long and the S-II was 24.84 meters (81.5 feet) long.

Several major changes were made to meet requirements of the Skylab mission. The boost acceleration limit was increased to 4.7 g for Skylab. (On Apollo missions the limit was set at 4 g because those vehicles were manned. Since the SL-1 mission was unmanned, the restriction on g-force was not as stringent.)

The S-IC engine cutoff sequence for Apollo missions was center engine first and then the outboard engines. On SL-1 the center engine was cut off first, followed by cutoff of two opposing outboard engines and then the remaining two outboard engines. The 1-2- cutoff sequence was programmed to gradually reduce slowdown instead of initiating it suddenly. Cutting off all four outboard engines at once would have subjected the ATM to a dynamic load that could have caused problems.

On Apollo missions, the terminal stage (last to provide propulsion) was the S-IVB; on SL-1 it was the S-II. Therefore, a number of changes had to be made to the S-II. First, provisions were made for S-II engines to be cut off by guidance signal instead of by propellant depletion. This enabled cutoff precisely at the desired velocity. Also, provisions were made to separate the S-II from the Skylab payload in such a manner as to preclude recontact.

The IU provided the initial payload attitude control signals and events-sequencing to enable systems activation and checkout functions. These included: jettison payload shroud; initiate ATM deployment; acquire solar inertial attitude; activate the Attitude and Pointing Control System (APCS); and transfer attitude control to the ATM.

Changing the launch azimuth from 72-100 degrees on Apollo missions to 40.88 degrees for Skylab made it mandatory to revise vehicle maneuvers at liftoff. On Apollo launches, the launch azimuth was slightly north of due east. A yaw maneuver caused the vehicle's boattail to move toward the launch tower in a direction slightly west of due north. This aimed the vehicle slightly east of south, causing it to move away from the tower as it rose. On the SL-1 launch, a yaw maneuver alone would move the boattail northwest and aim the vehicle southeast, which would not result in sufficient clearance of the tower for safety. Therefore, a pitch maneuver was combined with the yaw to cause the boattail to move directly northward toward the tower, aiming the rising vehicle southward away from the tower.

The Emergency Detection System (EDS) on Apollo launches was on a closed loop, providing abort capability and retention of telemetry of critical functions. On SL-1 the EDS was on an open loop which eliminated the abort feature by retained critical functions on telemetry. On SL-1, the only abort command possible was by the range safety officer. He could have destroyed the unmanned vehicle if it presented a hazard to inhabited areas.

Saturn IB

The SA-206, 207, and 208 launch vehicles which carried the three Skylab crews into orbit and rendezvous with the Skylab cluster were basic Saturn IB vehicles with modifications to update them to the SA-205 configuration. (SA-206, 207, and 208 were originally configured for unmanned flight.)

Each of the three Saturn IB vehicles consisted of the S-IB and S-IVB, (first and second propulsive stages, respectively) the instrument unit (IU) and the payload.

The SL-2 launch vehicle, SA-206, was made up of the S-IB-6, S-IVB-206, S-IU-206, and CSM-116. The SL-3 launch vehicle, SA-207, consisted of the S-IB-7, S-IVB-207, S-IU-207, and CSM-117. The SL-4 launch vehicle, SA-208, consisted of the S-IB-8, S-IVB-208, S-IU-208, and CSM 118.

Each launch vehicle with payload stacked was 68.3 meters (224 feet) tall and weighed about 589,680 kilograms (1,300,000 pounds). The payload capability for the launch vehicle was 16,012 kilograms (35,300 pounds) for SA-206, 16,507 kilograms (35,400 pounds) for SA-207, and 16,239 kilograms (35,800 pounds) for SA-208.

Each Saturn IB was launched from Launch Complex (LC) 39 at KSC. LC-39 was normally used for launching the larger Saturn V vehicle. The Saturn IB rested on a 39 meter (127 foot) tall pedestal on the launch platform. (The pedestal held the vehicle at the proper height above the platform to use existing tower swingarms with fueling, power and instrumentation facilties.)

Most of the changes made to the Saturn IB were a part of the continuing effort to improve the vehicle. Some changes, however, were necessary to support the Skylab Program. A number of changes eliminated single-point electrical failures and provided redundancy. Engine thrust was uprated to improve the payload capability. Other changes improved the vehicle's reliability by eliminating possible problems, such as leaks and corrosion. One change provided a means of dumping residual fuel through the J-2 engine of the second stage. Other changes added sensors to collect needed data.

Engine cutoff circuits in both propulsive stages were redesigned to eliminate inadvertent engine cutoff. Two vibration sensors and one pressure measurement device were added for evaluation of possible longitudinal oscillations ("Pogo") and load responses if such should occur in flight.

Each of the eight H-1 engines was uprated from 889,600 Newtons (200,000 pounds) to 911,840 Newtons (205,000 pounds) thrust to increase the payload capability. Total stage thrust was increased from 7,116,800 Newtons (1,600,000 pounds) to 7,294,720 Newtons (1,640,000 pounds).

The capability was added to deorbit the S-IVB/IU stages of SL-2, SL-3, and SL-4 by dumping residual propellants through the J-2 engine to alter the vehicle's trajectory. By controlling the vehicle's attitude and the time and duration of the dump, the S-IVB/IU was impacted in the ocean. The maneuver was commanded in real time after considering vehicle trajectory, condition, and capability. Sending the spent stage into the ocean eliminated the hazard of space debris impacting a populated land area.

APPENDIX II

Skylab Experiments

The Skylab experiment program consisted of more than 270 scientific and technical investigations representing virtually every field that has been recognized as being able to benefit from operations in near-earth orbit. The instruments, sensors and other equipment for conducting these experiments and investigations were located in various parts of Skylab, some inside and some outside.

The experiment program was developed through the joint cooperation of engineers and scientists from both foreign and dosmetic educational institutions, private industry, and Government agencies. Included were 19 experiments proposed by high school students. The 54 items of experiment hardware included available off-the-shelf equipment whenever practicable to reduce costs. On the other hand, sophisticated hardware not used before on manned spacecraft was developed when required to meet certain experiment objectives.

The major experiment areas were:

Life Sciences - 19 experiments to support some 28 investigations dealing with the effects on men and animals of long duration in the space environment.

Solar Physics - Nine solar instruments to provide unprecedented observations for 45 investigations of solar phenomena.

Earth Observations - Six remote sensing instruments to support more than 140 individual investigations for the study of the Earth from space.

Astrophysics - 14 instruments to make observations to support 24 studies of the solar system and beyond.

Material Science - The properties of orbital weightlessness were exploited to investigate the advantages of materials processing in space - 18 experiments.

Engineering and Technology - To advance the knowledge for design and operation of future space systems - 13 experiments.

Student Experiments - 19 investigations.

A basic set of biomedical data had been collected as a safety monitoring procedure on all the manned flights of the Mercury, Gemini, and Apollo programs. The parameters recorded have been heart and respiration rates, body temperatures, and blood pressure. These were supplemented by a variety of pre and postflight measurements of such factors as exercise capability, cardiovascular stress response, hematological-biomedical changes, immunology studies, and microbiological evaluations. In the Gemini program, medical experiments of limited scope were conducted in flight to investigate the time course of the changes which had been noticed on previous missions.

The following physiological effects of spaceflight on man have been observed: Loss of body weight; a small and inconsistent loss in bone calcium and muscle mass; and generally a reduction in orthostatic tolerance upon return to Earth.

These effects completely reversed themselves within a few days after return to Earth and showed no consistent relations to flight duration. However, some concern remained that continued effects in extended missions could significantly reduce man's effectiveness in space and increase the danger of re-adapting to the gravity conditions on Earth.

The Skylab biomedical program consisted of:

- The actual stay of nine men in space, with the associated operational medical monitoring and the observations of crew performance in a wide variety of scientific and operational tasks.

- The biology experiments designed to study fundamental biological processes affected by the space environment.

- The biotechnology experiments directed toward advancing the effectiveness of man-machine systems in space operations and improving the technology of space-borne bioinstrumentation.

Mineral Balance (M071)

The purpose of this experiment was to collect data for a predictive understanding of the effects of spaceflight on the muscle and skeletal systems by measuring the day-to-day gains or losses of pertinent biochemical constituents.

The data collected in support of M071 was: Daily body weight, accurate food intake (quantity and composition), accurate fluid intake, volume of 24-hour urine output, samples of pooled 24-hour urine output, determine the mass, process, and store all feces and vomitus, if any (all collected and processed inflight for return and postflight analysis) and preflight, inflight and postflight blood samples taken for analysis.

Urine was analyzed for calcium, phosphorus, magnesium, sodium, potassium, chlorine, nitrogen, urea, hydroxproline and creatinine. Feces were analyzed for calcium, sodium, phosphorus, magnesium, potassium and nitrogen. Blood was analyzed for calcium, phosphorus, magnesium, alkaline phosphotase, sodium, potassium, total protein, glucose, hydroxyproline, creatinine, chloride and electrophoretic pattern.

Principle investigator was G. D. Whedon, M.D., National Institutes of Health, and L. Lutnak, M.D., Cornell University.

Bio-Assay of Body Fluids (M073)

The purpose of this experiment was to assess the effect of space flight on endocrine-metabolic functions including fluid and electrolyte control mechanisms.

The data collected in support of M073 were: Daily body weight, accurate food intake (quantity and composition), accurate fluid intake, volume of a 24-hour urine output, samples of pooled 24-hour urine output (collected and processed inflight for return and postflight analysis), and preflight, inflight and postflight blood samples taken for analysis.

Urine was analyzed for sodium, potassium, aldosterone, epinephrine, antidiurectic hormones (ADH), urine osmolality, hydrocortisone, total body water and total and fractional Ketosteroids. Blood was analyzed for renin, sodium, potassium, chloride, plasma osmolality, extracellular fluid volume (ECF), parathyroid hormone, thyrocalcitonin, throxine, adrenocorticotropic hormone (ACTH), hydrocortisone and total body water.

Principal investigator was Dr. Carolyn S. Leach, Johnson Space Center.

Specimen Mass Measurement (M074)

The primary purpose of this experiment was to demonstrate the capability of accurately weighing 50 to 1,000 gm masses in a null gravity environment. The secondary purpose was to provide a means of accurately determining the mass of feces, vomitus and food residue generated in flight. These mass measurements provided data for M071 and M073 experiments.

The Specimen Mass Measurement Device was a device that utilized the inertial property of mass in lieu of a gravity field to determine mass. Basically, the SMMD consisted of a spring mounted tray. The oscillatory period of the spring was a function of the amount of mass on the tray. The spring's period was measured electro-optically, and this measurement was electronically converted to a direct mass read out onboard.

Principal investigator was Dr. William E. Thornton, Johnson Space Center, and coinvestigator was Col. John W. Ord, Medical Corps, USAF Hospital, Clark Air Force Base, Phillippine Islands.

Bone Mineral Measurement (M078)

The purpose of this experiment was to assess the effects of the space flight environment on the occurrence and degree of bone mineral changes.

The data collected are preflight and postflight gamma ray scans of the heel bone and right radius of the forearm. Comparison of these gamma ray scans give a comparison of bone density (a measure of bone calcification) before and after flight. The experiment was conducted preflight and postflight only.

Principal investigator was Dr. J. M. Vogel, U.S. Public Health Service, San Francisco, California, and coinvestigator was Dr. John R. Cameron, the University of Wisconsin Medical Center.

Lower Body Negative Pressure (M092)

The purpose of this experiment was to provide information concerning the time course of cardiovascular adaptation during flight, and to provide inflight data for predicting the degree of orthostatic intolerance and impairment of physical capacity to be expected upon return to Earth environment.

The data collected in support of M092 were blood pressure, heart rate, body temperature, vectorcardiogram, Lower Body Negative Pressure Device (LBNPD) pressure, leg volume changes, and body weight.

The LBNPD consisted of a cylinder which enclosed the lower half of the subject. A diaphragm formed an air seal around the subject's waist. Provisions were made to lower the pressure in the cylinder thus exposing the lower body to a series of negative pressures. This negative pressure simulated the effects of the normal hydrostatic pressure of the blood in the cardiovascular tree, or a person standing erect on a one-g field.

Two Leg Volume Plethysmographs (one for each leg) were required. (These devices were capacitance gauges for measuring the expansion of the legs on exposure to the LBNPD vacuum. The amount of expansion is a measure of the amount of blood pooling in the legs.)

The Blood Pressure Assembly consisted of a pressure cuff affixed around the upper arm, a microphone to pick up the Korotkoff's sounds, and signal conditioners. These interfaced with a programming unit to cycle the pressure cuff automatically, the electronic circuitry for blood pressure decisions and displays, and calibration circuitry in the Experiment Support System (ESS).

Principal investigator was Dr. Robert L. Johnson, Johnson Space Center, and coinvestigator was Col. John W. Ord, Medical Corps, Clark Air Force Base.

Vectorcardiogram (M093)

The purpose of this experiment was to measure the vector cardiographic (VCG) potentials of each astronaut during the preflight, inflight, and postflight periods so that flight-induced changes in heart function can be detected.

The VCG was also used to determine crewmen heart rates during the M092 and M171 experiments.

The data collected in support of M093 was a readable VCG taken at regular intervals throughout the mission while the crewmen were at rest and before, during, and after specific exercise periods.

The VCG system consisted of an eight-electrode input harness, a Frank Lead Network, calibration and timing circuits, and three ECG signal conditioner channels. The VCG system presented three normalized, amplified ECG signals and an analog heart rate signal to the spacecraft telemetry system. A bicycle ergometer (part of the M171 system) was used to provide a specific exercise profile with which to compare the VCG data.

Principal investigator was Dr. Newton W. Allebach, USN Aerospace Medical Institute, Pensacola, Florida, and coinvestigator was Dr. Raphael F. Smith, School of Medicine, Vanderbilt University.

Cytogenetic Studies of the Blood (M111)

The objectives of this experiment were to make preflight and postflight determinations of chromosone aberration frequencies in the peripheral blood leukocytes of the Skylab flight crewmen and to provide "in vitro" radiation dosimetry. Another objective was to acquire data that would add to the findings of other Skylab cytologic and metabolic experiments to determine the genetic consequences of long duration space travel on man.

Periodic blood samples were taken before and after the flight, beginning 1 month before and ending 3 weeks after recovery. The leukocytes were placed in a short terminal culture. During the first cycle mitotic activity in the "in vitro" cultures, standard chromosome preparations of the Leukocytes will be prepared.

Principal investigator was Dr. Lillian H. Lockhart of the University of Texas Medical Branch. Coinvestigator was P. Carolyn Gooch of Brown and Root-Northrop.

Man's Immunity - In Vitro Aspects (M112)

The objective of this experiment was to assay changes in humoral and cellular immunity as reflected by the concentrations of plasma and blood cell proteins, blastoid transformations and synthesis of ribonucleic (RNA) and desoxyribonucleic (DNA) acids by the lumphocytes.

The experiment obtained preflight baselines (21, 7, and 1 days before launch), indications of normal metabolism, from the crewmen and a ground control group composed of three men physically similar to the crewmen. Inflight blood samples were taken four times from each crewman during the SL-2 mission and eight times from each crewman during the SL-3 and SL-4 missions. Seven days and 21 days after recovery, samples were taken from each crewman. Information was compared with preflight baselines, inflight profiles and with data from the control group to detect any significant deviations.

Principal investigator was Dr. Stephen E. Ritzmann, and coinvestigator was Dr. William C. Levin, both of the University of Texas Medical Branch.

Blood Volume and Red Cell Life Span (M113)

The objective of this experiment was to determine the effect of earth orbital missions on the plasma volume and the red blood cell populations with particular attention paid to the changes in red cell mass, red cell destruction rate, red cell life span, and red cell production rate.

This experiment had four parts; in each, a different radioisotope tracer was injected into crewmen's veins and into a control group.

The site of red blood cell (RBC) production in the mature adult is the marrow of membranous bones (e.g., sternum and vertebrae) with the rate of production dependent on metabolic demands and the current red cell population. The rate of RBC production was measured quantitatively by injection of a known quantity of a radioactive iron tracer into crew members.

Since the rate of RBC production acts with RBC loss to increase or decrease the total RBC mass present at a given time, any changes in the rates of RBC production and destruction will be necessarily reflected in the red cell mass. Changes in red cell mass were measured and analyzed in the flight crew members by injection of radioactive chromium (in the form of sodium chromate) tagged red cells.

To determine the selective age dependent erthrocyte destruction and mean red cell life span, carbon-fourteen labelled glycine was injected into a superficial arm vein of each crew member and control subject.

Finally, plasma volume changes were measured by adding a known amount of radioiodinated human serum albumin to each crew member's blood.

Blood samples were frozen and returned to Earth for postflight analysis.

Blood samples of each crewman were taken preflight (21, 20, 14, 7, and 1 days before launch), inflight (four times for SL-2, eight times for SL-3), and postflight (recovery day 1, 3, 7, 14, and 21 days after recovery).

Principal investigator was Dr. Phillip C. Johnson, Jr., Baylor University College of Medicine.

Red Blood Cell Metabolism (M114)

The objective of this experiment was to determine if any metabolic and/or membrane changes occur in the human red blood cell as a result of exposure to the space flight environment.

This experiment assessed the influence of the space flight environment on the metabolic processes which support crewmen's erythrocytes. The experiment was designed to complement Experiment M113.

Blood samples of each crewman were taken preflight (21, 7, and 1 days before launch), inflight (four times during SL-2, eight times during SL-3), and postflight (recovery day 1 and 14 days after recovery).

Blood was analyzed for methemoglobin, glyceraldehyde-6-phosphate dehydrogenase, phophglyceric acid kinase, reduced gluthathione, adenosine triphosphate, glutathione reductase, lipid peroxide levels, acetylocholinestecase, phosphofructo-kinase-2, 3-diphosphoglycerate, and hexokinase.

BLood samples were frozen and returned to Earth for postflight analysis.

Principal investigator was Dr. Charles E. Mengel, University of Missouri School of Medicine.

Special Hemotologic Effect (M115)

The primary objective of this experiment was to examine critical physiochemical blood parameters relative to the maintenance of a stable state of equilibrium between certain blood elements and to evaluate the effects of spaceflight on these parameters. A secondary objective was to provide essential data on blood which assisted in interpreting other hematology/immunology experiments.

Blood studies made on Gemini and Apollo astronauts have shown that changes in red cell mass, blood constituents and in the fluid and electrolyte balance can be expected as a result of the space environment.

Blood samples of each crewman were taken preflight (21, 14, 7, and 1 day before launch), inflight (four times on SL-2, eight times on SL-3), and postflight (recovery day 1, 3, 7, 14, and 21 days after recovery).

Blood was analyzed for sodium, potassium, single cell hemoglobin, red blood cell hemoglobin, RNA, protein distribution, hemoglobin characterization, electrophoretic mobility, red blood cell age profile, red blood cell electrolyte distribution, membrane and cellular ultrastructure, acid and osmotic fragility, critical volume, volume distribution, red blood cell count, white blood cell count, differential white cell count, micro hematocrit, platelet count, hemoglobin, and reticulocyte count.

Blood samples were frozen and returned to Earth for postflight analysis.

Principal investigator was Dr. Stephen L. Kimsey, Johnson Space Center. Coinvestigator was Dr. Craig L. Fischer, Eisenhower Memorial Hospital.

Human Vestibular Function (M131)

The purpose of this experiment was threefold: To test the crew's susceptibility to motion sickness in the Skylab environment; to acquire data fundamental to an understanding of the functions of human gravity receptors in the prolonged absence of gravity; and to test for changes to the sensitivity of the semicircular canals.

The data collected in support of M131 were: Threshold perception of rotation; motion sickness symptoms caused by out-of-plane head motions while being rotated; and the ability of crewman to determine his orientation with respect to spacecraft reference points with visual cues. Data were collected before, during, and after flight.

The inflight equipment used for M131 included:

Rotating Little Chair (RLC) - This chair was a framed seating device which was convertible for operation in either rotating or tilt litter mode.

Drive Motor for Chair Rotation - This motor had the capability of rotating the seated subject within the limits of 1 to 30 rpm and with an accuracy of $\pm$ 1%.

Control Console - The console contained mode selector, speed selector, tachometer, indicators, timers, and other devices for control and a response matrix for coding a subject's response to the rotational tests.

Otolith Test Goggle - This device was used to measure the visual space orientation in two dimensions. It provided the visual target for the oculogyrol illusion test.

Custom Bite Boards - The bite boards were used to hold the otolith test goggle precisely and comfortably in position over the observer's eyes.

Reference Sphere and Magnetic Pointer/Readout Device - These devices were used for measuring spatial localization using nonvisual clues. A magnetic pointer was held against the sphere and moved by the subject to determine the subject's judgments of his orientation. The position was measured by the three-dimensional readout device.

Principal investigator was Dr. Ashton Graybiel, and coinvestigator was Dr. Earl Miller, both of Naval Aerospace Medical Research Laboratories, Pensacola, Florida.

Sleep Monitoring (M133)

The purpose of this experiment was to evaluate objectively the quantity and quality of inflight sleep through an analysis of electroencephalographic (EEG) and electro-oculographic (EOG) activity.

It had been demonstrated that disrupted patterns of sleep were associated with modifications in performance capabilities. Therefore, objective investigative data regarding sleep in the space environment is of practical significance in terms of learning more of man's capabilities and limitations in the performance of space missions.

The data collected in support of M133 were: Preflight baseline EEG and EOG data on a crewman for 3 consecutive nights of sleep; periodical inflight EEG and EOG data throughout a crewman's sleep period; and postflight sleep EEG's and EOG's on approximately 1, 3, and 5 days after recovery.

The M133 equipment consisted of a wholly self-contained device which recorded the EEG and EOG on magnetic tape and also provided telemetry data in near real time. Electrodes were incorporated into a fitted cap that crewmen wore during sleep periods to detect the EEG and EOG signals. The cap also fitted with accelerometers to detect head movement to keep this movement from influencing the sleep-stage determination systems.

The EEG and EOG tapes were returned at the conclusion of the mission for postflight analysis.

Principal investigator was Dr. J. D. Frost, Jr., Baylor School of Medicine, Houston, Texas.

Time and Motion Study (M151)

The purpose of M151 was to study the adaptation of man in prolonged periods of zero gravity by comparing, through use of time and motion determination, identical activities performed by astronauts during ground-based training and inflight.

The only inflight data required for this experiment was to have the crew photograph themselves as they performed flight-planned activities required of them during execution of the Skylab missions. Films made by the crewmen were returned and analyzed postflight. These data were compared to baseline data taken during crew training.

Flight-planned tasks selected for analysis satisfied the following functional objectives:

- To study the locomotion of crewmen as they translated in the zero gravity environment with and without "loads."

- To study the fine and gross motor activities of crewmen in performing operations with and without the use of restraints.

- To study crewmen performing tasks which required visual, tactile, auditory feedback or combinations thereof.

- To study IVA and EVA activities.

- To study repeated activities performed early, middle, and late in the missions which showed adaptation to the zero gravity environment.

Principal investigator was Joseph F. Kubis, Ph. D., of Fordham University, and coinvestigator was Edward J. McLaughlin, Ph. D., of NASA Office of Manned Space Flight.

Metabolic Activity (M171)

The primary purpose of this experiment was to determine if man's metabolic effectiveness in doing mechanical work was progressively altered by exposure to the space environment. The secondary purpose was to evaluate the bicycle ergometer as an exerciser for long duration missions.

The data collected in support of M171 were: ergometer workrate, ergometer rpm, oxygen uptake, carbon dioxide output, minute volume, vital capacity, respiratory quotient, heart rate, blood pressure, vectorcardiogram, body weight, body temperature, and Skylab environmental parameters.

A metabolic analyzer was used to measure oxygen uptake, carbon dioxide output, and minute volume. These determinations were made through the use of a spirometer and mass spectrometer.

The bicycle ergometer was used to provide a calibrated workload.

Principal investigator was E. L. Michel, and coinvestigator was Dr. J. A. Rummel, both of the Johnson Space Center.

Body Mass Measurement (M172)

The Body Mass Measurement experiment demonstrated body mass measurement in a null gravity environment, validated theoretical behavior of this method, and supported those medical experiments for which body mass measurements were a requirement.

The data collected in support of M172 were: Preflight calibration of BMMD And measurement of known masses up to 100 kilograms (220 pounds) three times during each Skylab mission. The BMMD was also used for daily determination of the crewmen's weight.

The self-contained instrument consisted of a spring/flexure pivot mounted chair, the method of operation being similar to that for the Small Mass Measurement (M074). A photo optical pickup was mounted beneath the chair to determine zero crossing, and its output was timed and converted to a direct mass readout.

Principal investigator was Dr. W. E. Thornton of the Johnson Space Center.

Effect of Zero G on Single Human Cells (S015)

The purpose of this experiment was to determine the effect of zero gravity on living human cells in a tissue culture. The data collected in support of S015 were: Time lapse cinematographic films of inflight tissue culture growth and crew logs. Also, the tissue cultures were returned for postflight analysis.

The flight hardware for Experiment S015 consisted of a microscope-camera assembly and a growth curve module subsystem, both enclosed in a single hermetically sealed package.

A separate specimen chamber for each microscope provided temperature controlled environments in which to grow the cell cultures. Each chamber had its own independent media exchange to provide fresh nutrients to the cultures twice each day.

Principal investigator was Dr. P. O. Montgomery, and coinvestigator was Dr. J. Paul, both Dallas (Texas) County Hospital; Dr. P. Kruse, Jr., Noble Foundation, and Dr. L. Hayflick, Stanford University.

Circadian Rhythm - Pocket Mice (S071)

The purpose of this experiment was to determine if the daily physiological rhythms of mammals were altered in space flight. If the rhythms are changed or affected, the indication would be that physiological rhythms are timed by some factor not found in space. Changed or affected rhythms alter the basic control of metabolism. It is important that normal biological rhythms in man be maintained for his well being and effectiveness during spaceflight. If normal physiological rhythms are maintained, the conclusion can be made that spaceflight does not impose biorhythm restriction and that man can work in space without degrading his performance due to bio-rhythm disturbance.

The experiment consisted of six pocket mice placed in a completely dark cage having 15°C (60°F) temperature, relative humidity of 60%, and an atmospheric pressure equivalent to sea level.

Principal investigator was Dr. Robert G. Lindberg of Northrop Corporate Laboratories.

(This experiment failed on launch and, therefore, no data were obtained.)

Circadian Rhythm - Vinegar Gnat (S072)

The purpose of this experiment was to determine if the daily emerging cycle of the vinegar gnat (drosophila) pupae was altered during space flight.

Extensive experiments have shown that even though gnats in the pupal stage develop at different rates depending on temperature, they will not emerge from the pupae as adult gnats until some kind of internal signal is given off.

This triggering signal is somehow timed to occur at an exactly fixed time delay after a flash of light, and it occurs at the same daily interval thereafter, regardless of the temperature.

The experiment was to have measured the emergence times of four groups at 20°C (68°F) to find out whether spaceflight conditions change the mechanism which kept the rhythm constant despite changes in temperatures.

Principal investigator was Colin S. Pittendrigh of Stanford University.

(This experiment also failed at launch and, thus, no data were obtained.)

Solar Physics

The Sun is one of the most widely studied objects in the sky but much about it remains a mystery. Such questions as the origin of solar flares, the development and decay of active regions, and the temperature characteristics of the corona remain. Until recently it was possible to observe solar emissions only at wavelengths which could penetrate the Earth's atmosphere--visible and radio emission. Vital ultraviolet and X-ray regions of the solar spectrum are cut off from earth-bound viewing. Also, the daytime atmospheric scattering of visible light causes the sky to be much brighter than the solar corona. Thus, rare solar eclipses are the only opportunities to view the extended solar corona.

The Sun is the ultimate source of all energy on the Earth, and all terrestrial life depends on it. The Sun is also the nearest star. An understanding of the stars depends on an understanding of the Sun. The Sun is an astrophysical laboratory close at hand. By using the Sun, studies can be made of atomic, nuclear and plasma physics, aerodynamics, hydrodynamics, and magneto-hydrodynamics.

A better understanding of the following solar physics problems was awaiting use of the instruments in space to study the Sun:

How is the corona heated?

What is the nature of the atmospheric structural detail?

What do coronal streamers look like in space?

What is the relationship between these streamers and surface features?

What are solar flares?

How do active regions evolve?

Several instruments studied a region of the solar atmosphere (chromosphere). This region is from about 800 to 9,650 kilometers (500 to 6,000 miles) above the Sun's surface. Temperature in this region increases from about 5,000 to 1,000,000°C. The much higher temperatures of the chromosphere give rise to the ultraviolet radiation. UV radiation was studied in terms of particular emission features at specified wavelengths. These studies revealed the types of atoms present in this region under various phases of solar activity and have shed light on the mechanism which supplies the heat to this region. Three different UV detector experiments are on the ATM, and an additional UV detector was aboard for operation through an airlock.

The solar corona begins about 9,650 kilometers (6,000 miles) above the surface and continues far into space. The density of matter in the corona is quite low, but temperatures vary from almost a million degrees in quiet regions to tens of millions of degrees in certain regions during solar flares. These high temperatures cause the ions and electrons in the corona to radiate X rays. X-ray telescopes on Skylab were equipped with cameras to photograph the X-ray corona of the Sun.

Because the corona is so large and hot, many free electrons are available to scatter the white visible light radiated from the surface of the Sun. This scattered light is very much weaker than the radiation from the solar surface. A coronagraph is an instrument capable of studying the faint corona without viewing the bright solar surface. Since the intensity of scattered light is a measure of the electron density in the corona, photographs take out to 4.8 kilometers (3,000,000 miles) from the surface provided the first look at the corona over an extended period.

Experiment S020, X-ray/UV Solar Photography, was one experiment planned to be conducted using an airlock in the sunlit side of the OWS. All other solar physics experiments were mounted in the ATM.

X-ray/Ultraviolet Solar Photography (S020)

The objective of S020 was to record on photographic film the detailed energy spectrum of X-ray and ultraviolet radiation from normal and explosive areas in the solar atmosphere.

The 10 to 200 angstrom region of the solar spectrum is rich in emission lines of highly ionized atoms. Many of these emission lines are weak and require instruments of high sensitivity for their observation. S020 took observations by taking advantage of the long exposure times and film return capability of the Skylab spacecraft.

The S020 experiment was planned for long exposure photography through the solar side scientific airlock. This airlock was used to deploy the parasol sun shield and was, therefore, not available for scientific data to the PI; mounting hardware was designed to attach the experiment externally during EVA to permit pictures of the Sun in that spectrum to be obtained. The hardware was flown up to the workshop by the third crew and was used during three EVA's during their mission.

Principal investigator was Dr. Richard Tousey, U.S. Naval Research Laboratory, Washington, DC.

White Light Coronagraph (S052)

The White Light Coronagraph was designed to obtain photographs of the solar corona out to 3 million miles (6 solar radii) in visible light. These photographs, taken twice daily or at rates up to one every 13 seconds during periods of high limb activity, provided new information related to the rapidly moving matter, sometimes travelling at relativistic speeds, which is transported outward from the Sun due to solar events occurring at the solar limb. Systematic changes, to the extent that the corona was apparent over several solar rotations, allowed correlations to be made with surface features as they moved into proper position on the limb of the Sun. (Earth-based coronagraphs are hampered because Earth sky brightness is much greater than the corona and prevents acquisition of detailed corona information).

The experiment was approximately 3 meters (10 feet) long, 0.46 meters (1.5 feet) in diameter, and weighed 142 kilograms (314 pounds). It included an externally mounted disk system to occult (block) the brilliant solar surface which allowed viewing of the faint corona radiation. The experiment data were presented on the TV system, which was displayed on the C&D video monitors or transmitted by telemetry to ground or recorded on film.

One loaded film camera, which contained 35mm film for approximately 8,000 data frames was placed in the experiment prior to launch, and three replacement film cameras were stored in the MDA. Film retrieval and replacement was accomplished by astronaut EVA from the center work station with exposed film being returned to Earth by CM for evaluation.

As part of the activities associated with the observation of the Comet Kohoutek, an additional film magazine was stowed in the Skylab 4 Command Module. This magazine was used during the last mission and doubled the scientific output from this experiment on that mission.

Dr. Robert MacQueen of the High Altitude Observatory, Boulder, Colorado, was principal investigator.

X-ray Spectrographic Telescope (S054)

The X-ray Spectrographic Telescope took sequential photographs of X-ray producing events (flares and active regions) for determining corona temperatures and energetic particle densities. This information was correlated with similar data from other experiments.

The X-ray telescope consisted of two concentric mirrors of highly polished metal alloy to intercept the X-radiation and focus it at grazing incidence. Filters of beryllium, aluminized mylar and other materials with varying thickness selected the X-ray wavelength band to be photographed. A transmission grating was used in conjunction with the filters to obtain information on the spectral features of the X-ray emission.

The telescope weighed more than 136 kilograms (300 pounds) and was 3 meters (10 feet) long and almost ½ meter (1.5 feet) in diameter.

A small 7.6 centimeter (3 inch) grazing incidence instrument placed in the unused central portion of the larger telescope was used to provide a "live" picture of the Sun in X rays for the astronaut to view. This aid complemented the H-alpha images in TV and assisted the astronauts in getting the best possible data from the ATM.

Dr. Riccardo Giacconi, American Science and Engineering Corporation, was the principal investigator.

UV Scanning Polychromator Spectroheliometer (S055)

The purpose of this experiment was to observe temporal changes in the ultraviolet (EUV) radiation emitted by several types of solar regions. The EUV region of the solar spectrum is generated in the chromosphere and lower corona. The instrument operated photoelectrically and required no film. All data were recorded electronically. The instrument was capable of accurately measuring the strength of certain emission features of elements with high time resolution in various stages of ionization. It observed seven emission lines in the wavelength region from 300 to 1,350 angstroms. Simultaneous observations of chromospheric and coronal layers of flares were obtained, and the energy radiated in selected emission lines in the EUV region was measured.

Radiation from the Sun entered the instrument and was reflected by a mirror which was movable along both axes. The mirror was adjusted to place the desired square segment of the solar surface on the spectrometer grating. The rest of the light was reflected back and out of the instrument. The radiation was broken up into its spectral components and the EUV portion was received by seven detectors. The eighth detector was a zero order position and, hence, saw light at all wavelengths. The zero order detector indicated whether or not the solar disk was being viewed.

The instrument was 3 meters (10 feet) long and 0.6 by 0.6 meters (2 by 2 feet) in cross section. It weighed 156.5 kilograms (345 pounds).

Dr. E. M. Reeves of Harvard College Observatory was principal investigator.

X-ray Event Analyzer/D-ray Telescope (S056)

The objective of the S056 experiment was to gather solar radiation data in the X-ray region of the solar spectrum which provided information regarding physical processes occurring within the solar atmosphere, with special emphasis on data of active solar phenomena such as solar flares. This information will lead to an increased knowledge of the influence of the Sun's magnetic field on flare development and a more definite understanding of the relationships between Sun spots and solar flare formation. The experiment consisted of two separate and independently operated instruments, the X-ray Event Analyzer (X-REA) and the X-ray Telescope (X-RT) which obtained complementary X-ray data.

The X-ray Event Analyzer provided spectral data (photon intensity as a function of wavelength) in 10 bands from 2 to 20 angstroms. These spectral data served two purposes: (1) Their real time in orbit display on the C&D console gave the astronaut solar X-ray and microwave flux information necessary for pointing and operating the X-RT; and (2) their analysis provided detailed flare temperature, density and chemical abundance information.

The X-RT recorded solar images in the form of X-ray filtergrams (images viewed in narrow wavelength intervals) in five band widths from 5 to 33 angstroms and one band width in visible light. The filtergrams provided temporal (time oriented) and spectral (position oriented) variations of the spectral data in flare regions.

The X-REA consisted of two gas filled proportional counters, pulse height analyzers, and associated electronics components. The proportional counters produced linear outputs proportional to the solar energy levels detected. The pulse height analyzer sorted the proportional counter outputs, with respect to amplitude, into six energy levels in one output channel and four energy levels in the other. These data were then transmitted via telemetry to the Earth and/or displayed on the counter or activity history plotter of the ATM Control and Display Console for real time in-oribt astronaut information display.

The X-RT consisted of a telescope using glancing incident optics to obtain solar images on photographic film. Film retrieval and replacement was accomplished by EVA with three replacement film canisters, each containing film for about 7,200 data frames, stored in the MDA. Exposed film canisters were returned to Earth in the CM for data evaluation. (A fourth canister was flown to the workshop on SL-4 for comet observation.)

Operation of the X-RT camera and the X-REA was by the astronaut at the ATM Control and Display Console. The level of X-RT operation depended upon solar activity with the astronaut selecting patrol mode with a quiet Sun or active modes with an active Sun which required more photographs per unit of time. The astronaut was capable of acquiring targets to photograph using experiment pointing control of the ATM canister which was provided from the C&D Console.

James E. Milligan of the Marshall Space Flight Center was principal investigator.

XUV Spectrograph/Spectroheliograph (S082)

These experiments sequentially photographed the Sun over long periods required for proper studies in selected ultraviolet wavelengths. Resulting pictures (spectroheliograms) showed specific emission features greatly enhanced over photographs of the solar disk in white light. Therefore, the Sun appears quite "blotchy" with much of the emission confined to active regions. The spectroheliograph ("A" instrument) covered the wavelength region from 150 to 650 angstroms (EUV regions). The spectrograph ("B" instrument) took data highly resolved into wavelengths in the middle and near ultraviolet region. This instrument could be pointed anywhere on the solar disk to obtain detailed emission characteristics of a region only 1,600 kilometers (1,000 miles) wide.

The astronaut took photographs of the Sun with the spectroheliograph. He selected the wavelength range to be studied and the exposure time. The "B" instrument was used to take spectra at various portions of the limb or solar disk. The astronauts selected the mode of operation and the wavelength region to be covered. The XUV monitor provided a display of 150-650 angstrom activity and gave an indication of XUV images being taken photographically by the "A" instrument.

The "B" instrument consisted of a mirror and entrance slit which selected portions of the solar disk or limb to be viewed. A set of two gratings spread the UV region from 970 to 3,940 angstroms onto photographic film. An XUV monitor allowed the Sun to be viewed by the astronauts on TV in the XUV regions. The instrument weighed 169 kilograms (373 pounds).

Dr. Richard Tousey of the Naval Research Laboratory was principal investigator.

H-Alpha Telescopes

The H-Alpha Telescopes provided the primary means for the boresight pointing of the ATM experiment package. There are two telescopes sensitive to the red hydrogen alpha lights of the Sun in the H-Alpha package. One was equipped with a beam splitter for simultaneous photographic and television pictures. The other telescope was operated in the TV mode only. Both telescopes were equipped with a Fabry-Perot filter to make precise observations at the desired wavelength. A zoom capability allowed specific portions of the solar disk to be viewed in detail. These telescopes took TV and photographic pictures of the solar disk showing flare activities as tremendously enlarged H-Alpha emission sources, which are the primary mode of classifying the size of a flare region.

The H-Alpha telescope was one of the "eyes" of the astronaut. Active regions were followed as they traversed the solar disk. When flares were observed, the amount of H-Alpha emission was correlated with emission intensities in other energy regions.

One telescope weighed 86 kilograms (190 pounds) and was 2.7 meters (9 feet) long and approximately 0.3 meters (1 foot) in diameter. The second telescope which was not used for photographic purposes was 1.5 meters (5 feet) long, 0.3 meters (1 foot) in diameter and weighed 50 kilograms (110 pounds).

Dr. E. M. Reeves of Harvard College Observatory was the principal investigator.

Earth Observations

Remote sensing of the Earth from orbital altitudes has the potential of yielding information which is of fundamental importance for effective use and conservation of natural resources in both underdeveloped and technologically advanced nations.

Photography from orbital altitudes in the visible and near-infrared spectral regions has already proven to be invaluable for standard synoptic mapping of geographic features over large areas. Systematic use of multispectral remote sensing techniques over an extensive wavelength region has the potential of greatly extending the scope of this capability to include mapping of terrestrial resources and land uses on a global scale. Resources amenable to study are: crop and forestry cover; health state of vegetation; types of soil; distribution of snow pack; surface or near-surface mineral deposits; sea-surface temperatures; and the location of likely feeding areas for fish. Comprehensive surveys of such resources will help cope with developing world-wide problems of such accelerating urgency as food supplies, mineral shortages, energy needs, environment pollution and expanding patterns of human settlements.

Many of the environmental features requiring study are in remote regions of the Earth and are highly variable in time. Space Systems can offer the following distinct advantages over conventional aircraft: a broad field of view afforded by the increased altitude; periodic coverage of the same area; and coverage of areas otherwise not easily accessible.

The earth resources program objectives are to gather natural and cultural resource data and to monitor environmental and ecological relationships. Major areas of application are agriculture, forestry, hydrology, geology, oceanography, geography, meteorology and ecology. Some of the specific applications in these areas are:

Agriculture/forestry: Improve planning and marketing with current crop census and yield estimates; increase yield by determining soil characteristics and optimizing water management; and reduce losses by early identification of disease, infestation, etc.

Oceanography: Improve fishing productivity by locating cold water upwellings, biologically rich areas, optimum thermal conditions; improve ship routing by measurement of sea state, detection of navigation hazards, and monitoring of sea ice; and improve development of continental shelves by mapping submarine topography and locating oil seeps.

Hydrology: Inventory of water sources for optimum water management; identify new sources of fresh water; monitor health and other characteristics of lakes; identify, monitor and evaluate pollution; and predict and assess flood damage.

Geology: Identify geologic features related to mineral resources such as faults, folds and later changes in rock beds; and monitor dynamic features such as volcanic eruptions, landslides and coastal and rivers dimentation changes.

Geography: Inventory and classify man's activities through production of thematic maps; and understand physical geography to improve rural and urban development.

Currently, earth resources data are being collected by ocean ships and buoys, sounding rockets, aircraft flights and spacecraft. Each method has advantages and disadvantages. In general, direct, or ground sensing, methods provide greater accuracy than remote sensing methods. Sensor resolution may be the limiting factor in remote sensing. However, much of the desired earth resources data can be provided satisfactorily with present sensors and those currently being developed.

The Skylab Earth Resources Experiment Program, (EREP) composed of six remote sensing systems, was designed as a spaceborne facility for use as a part of, and in support of, the already existing broad-base international studies on the techniques and application of earth remote sensing. These studies encompassed multispectral sensing at ground level, by aircraft, and by unmanned spacecraft in addition to Skylab.

The Skylab EREP provided additional and more precise data on spacecraft sensing capabilities, allowing a more thorough evaluation of sensor techniques and returned-data correlation and application. Also, the manned earth resources satellite offered unique features not presently possible with automated systems. These were the ability to evaluate test site conditions, to acquire and track uniform, small test sites off the ground track, and to vary the data acquisition activities as a system conditions warrant.

The EREP sensors could be operated individually as a group, depending on the scientific requirements and other factors such as weather and vehicle capability. Data were recorded on tape and film and returned to the Earth for processing.

Each EREP experiment consisted of the data collecting instrument and the necessary support hardware for equipment mounting and stowage. The experiments were centrally controlled from the EREP control and display panel. EREP data were recorded on magnetic tape by the tape recorder. These data were supplemented by voice annotation and MDA housekeeping data.

The EREP hardware was located on the interior and exterior of the MDA. External doors were opened on the S190, S191 and S192 experiments to permit optical viewing of the Earth's surface.

Principal investigators numbering more than 100 from the United States and 40 from other nations were selected for earth observation experiments.

Data from EREP was correlated with information acquired from aircraft and ground observations and sensors on the NASA Earth Resources Technology Satellite. More than 850 scientists submitted proposals in April-June 1971, for investigations using LANDSAT and EREP data.

Multispectral Photography Facility (S190)

S190 had been designed to photograph regions of the Earth's surface, including oceans, in a range of wavelengths from near infrared through the visible. The facility was in two parts: The Multispectral Photographic Camera (S190A), six channel 70 mm cameras that simultaneously photographed the same area, each viewing a different wavelength; and the Earth Terrain Camera (S190B), a single lens camera.

The S190A experiment used a six-channel, high-precision 70 mm camera system. The matched distortion and focal length camera array contained forward motion compensation to correct for spacecraft motion. The six-inch focal length lenses had a field of view of 21.1 degrees across flats providing a square surface coverage of about 169 kilograms (88 nautical miles) from the expected 435 kilogram (235 nautical mile) altitude. The system was designed for the following wavelength/film combinations:

.5 - .6	Micrometers	Pan-XB&W
.6 - .7	"	Pan-XB&W
.7 - .8	"	IR B&W
.8 - .9	"	IR B&W
.5 - .88	"	IR Color
.4 - .7	"	HI RES Color

The spectral regions designated were selected to separate the visible and photographic infrared spectrum into the bands that were expected to be most useful for multispectral analysis of earth surface features. Further spectral refinements were made by using different filter combinations.

The S190B portion utilized a single 18-inch focal length lens with 5-inch film. Its field of view of 14.2 degrees across flats provided square surface coverage of about 112 kilograms (59 nautical miles) from orbit. This camera was designed to use high resolution color film and was operated from the OWS SAL window.

The camera compensated for spacecraft forward motion through programmed camera rotation. Shuttle speeds were selectable at 5, 7, and 10 milliseconds with a curtain velocity of 110 inches per second.

Areas of Earth surface photographed were of particular interest to EREP investigators. Before each pass the crew received ground update for settings, number of exposures, etc.

Infrared Spectrometer (S191)

The primary goal of Experiment S191 was to make an evaluation of the applicability and usefulness of sensing earth resources from orbital altitudes in the visible through near-infrared and in the far-infrared spectral regions. Another specific goal was to assess the value of real-time identificaiton of ground sites by an astronaut.

The S192 instrument had 13 spectral bands from 0.4 to 12.5 micrometers in the visible, near infrared and thermal infrared regions. The system gathered quantitative high spatial-resolution line-scan imagery data on radiation reflected and emitted by selected ground sites in the U.S. and other parts of the world.

The motion of the sensor is a circular scan with a radius of 41.8 kilometers (22.6 nautical miles). Data of ground scenes were recorded as the scan swept a track 75 kilometers

(37 nautical miles) wide in front of the spacecraft, yielding a 260-foot resolution at an altitude of 435 kilometers (235 nautical miles). The S192 optical mechanical scanner utilized a 30 cm (12 inch) reflecting telescope with a rotating mirror. The telescope and mirror were mounted outside the MDA.

The data were recorded on the EREP tape recorder. Since the high data rate of S192 was not compatible with the standard recording speed of the recorder, the speed was increased 60 inches per second during operation of the scanner.

Microwave Radiometer/Scatterometer/Altimeter (S193)

The objectives of the experiment were the near simultaneous measurement of the radar differential back-scattering cross section and the passive microwave thermal emission of the land and ocean on a global scale and to provide engineering data for use in designing space radar altimeters.

The S193 data was useful in studying varying ocean surfaces, wear conditions, sea and lake ice, snow cover, seasonal vegetational changes, flooding, rainfall and soil types. The sensor generally operated over ocean and ground areas where ground truth data were available; however, additional targets of opportunity, such as hurricanes and storms, were viewed if the opportunity arose.

The S193 incorporated a radiometer, scatterometer and radar altimeter, all operating at the same frequency of 13.9 gigahertz (GHz). The equipment shared a common gimballed antenna mounted on the outside of the MDA. The scatterometer measured the back-scattering coefficient of ocean and terrain as a function of incidence angle ranging from 0 to 52 degrees. The radiometer was a passive sensor which measured the brightness temperature, from a cell on the Earth's surface, as a function of incidence angle from the surface.

The S193 ground coverage was 48 degrees forward and 48 degrees to either side of the spacecraft ground track.

All data were recorded on magnetic tape on one digitized channel.

L-Band Microwave Radiometer (S194)

The experiment objective was to supplement experiment S193 in measuring brightness temperature of the Earth's surface along the spacecraft track, which provided ocean surface features, meteorology winds and Earth surface features.

The S194 experiment was a passive microwave sensor utilizing a fixed planar array antenna. S194 recorded the brightness temperature of the Earth in the L-band range with a digital output giving an absolute antenna temperature to an accuracy of one degree Kelvin. The system utilized a built-in calibration scheme that sampled known sources.

All data were recorded on magnetic tapes. The data output was at 200 bits per second.

Astrophysics

Until recently, progress in astronomy has been made by theoretical and observational advances using instruments associated with ground based optical telescopes. Skylab experiments identified advantages and disadvantages of man-attended space observations and obtained information needed for planning future, more advanced instruments. Most of the observations performed were of a type not possible from the surface of Earth because of the absorbing and light scattering effects of the atmosphere surrounding Earth.

Nuclear Emulsion (S009)

The objective of this experiment was to record the cosmic ray flux incidence outside the Earth's atmosphere, more specifically, the relative abundance of high energy primary heavy nuclei.

Theories of nucleogensis predict the relative abundance of nuclei that would be produced in the thermonuclear reactions occurring in possible sources such as neutron stars. It is, therefore, of great interest to study the relative abundance of the nuclei reaching the Earth. To obtain as accurate a measure as possible of the relative abundance of various nuclei in the primary cosmic ray flux, nuclear emulsions must be carried into space.

The Skylab nuclear emulsion experiment provided a long exposure to determine the abundance of the rarer heavy nuclei.

The instrument consisted of two adjacent stacks of nuclear emulsion strips. This emusion differed from regular photographic emulsions being considerably thicker and containing a much higher density of grain material to improve the detection of tracks left by charged particles. The stacks were hinged together like a book and contained several layers of different emulsion types.

The motor which opened and closed the "book" failed during the first mission and the data was uninterpretable. A new unit was fabricated and resupplied on SL-4 and normal performance was restored.

The emulsion stacks were mounted inside the Skylab Multiple Docking Adapter, separated from space by a thin section of the spacecraft wall. During exposure, the "book" was open, allowing high energy particles which had passed through the wall to enter the front surface of both emulsion stacks.

The exposed emulsion was returned to the Earth and peeled apart in thin strips which were numbered, developed and scanned for tracks. By measuring the variations in thickness and direction of the tracks and tracing their entire path through the strips, the energy and charge of the cosmic rays can be determined.

The relative abundances of various nuclei observed from the primary cosmic radiation provide crucial information from which one can learn something about the physical conditions where the nuclei were formed, the time that was elapsed since they were formed, and the nature of their interactions with interstellar material in transit.

Dr. Maurice M. Shapiro, Naval Research Laboratory was the principal investigator.

Ultraviolet Stellar Astronomy (S019)

Experiment S019 was designed to take UV photographs of large areas of the Milky Way in which young, hot stars were abundant. About 50 star fields, each 4 by 5 degrees in area, were photographed during each Skulab mission, two to three exposures on each field. Exposure times were 30, 90, and 270 seconds, depending on the brightness of the stars photographed.

The S019 experiment consisted of a 6-inch reflecting telescope and a movable mirror. The telescope was operated through the scientific airlock in the OWS. The rotating mirror was extended through the SAL by the extension mechanism to allow the telescope line of sight to be pointed over a large area of the sky. The telescope was operated manually by the astronaut.

The telescope was capable of recording ultraviolet radiation down to a wavelength of 1,350 angstroms. Its main objective was to study the differences from star to star in the several strong spectrum lines known to exist in the 1,350 and 2,000 angstrom region of the spectrum.

Some of these lines are formed by the atmosphere of the star while other lines are formed by the interstellar gas between Earth and the stars. One special advantage of the telescope was its ability to photograph a 4 by 5 degree region of the sky and to record the spectra of all the stars in that region on one photograph.

The principal investigator was Dr. Karl G. Henize, a scientist-astronaut of the Johnson Space Center.

UV Airglow Horizon Photography (S063)

The Ultraviolet Airglow Horizon Photography was a photographic experiment with two separate experiment assemblies. One experiment assembly performed ozone photography; the other assembly performed twilight airglow photography.

The behavior of ozone is an important factor in the thermal balance of the atmosphere. The amount of absorption can be determined by taking two series of simultaneous photographs. One series, using a 35mm camera with ultraviolet filters, recorded the varying amounts of absorption of ultraviolet illuminations, indicating varying densities of ozone. The other series, using a second 35mm camera without UV filters, was aimed at the same target but obtained color photographs of atmospheric and ground features such as water, mountains and clouds.

The UV camera was mounted at the antisolar SAL and the color camera in the Wardroom window.

The twilight airglow experiment photographed the glow occurring in the upper atmosphere caused by chemical reactions in the ozone, oxygen and other gases when they are stimulated by the Sun's radiation. The upper atmosphere was photographed at twilight against the dark sky of space.

Principal investigator was Dr. Donald M. Parker, Naval Research Laboratory, Washington, DC.

Gegenschein/Zodiacal Light (S073)

The purpose of this experiment was to measure the brightness and polarization of the visible background of the sky as seen from the Skylab above the Earth's atmosphere.

Previous photographs and light level readings taken from the ground, rockets and satellites have not been sufficiently accurate to distinguish between models of the sources contributing to the faint visible background light of the sky outside the atmosphere. Handheld photographs, taken from Gemini spacecraft, of the Gegenschein, or antisolar enhancement, have established that it is extraterrestrial in orgin rather than a phenomenon occurring in the Earth's atmosphere. An Apollo lunar orbit experiment attempted to photograph the Gegenschein from the dark side of the lunar orbit to determine by triangulation whether or not it is due to a "zero phase" enhancement of sunlight scattered off the interplanetary medium or a cloud of dust maintained in the gravitational null point 1,609,000 kilometers (one million miles) from the Earth, opposite the Sun. The Skylab study was to be a complete survey of the sky from above the variable interference of visible airglow emission and atmospheric extinction.

There was no dedicated hardware for this experiment. The T027 photometer and 16mm operational data acquisition camera were used.

By comparing the amount of light at different colors and polarizations with the spectrum of the Sun one can indirectly obtain information about the sizes, shapes, composition and numbers of the dust particles traveling in interplanetary space which reflect the sunlight and produce the zodiacal light. In addition, the variation of the brightness relative to the direction of the Sun and the ecliptic plane will enable the interplanetary contribution to background light level to be distinguished from the interstellar background and any contribution from a hypothetical dust cloud associated with the Earth and Moon.

During the first mission, this experiment was operated for 14 hours and 37 minutes. An anomaly occurred during Skylab which resulted in the jettisoning of the photometer. (All scientific airlock experiments were designed so they could be jettisoned if any anomaly occurred which prevented their being retracted back into the workshop. S073 experienced a failure in the pointing mechanism and was jettisoned in order to free the SAL for use by other experiments.) The crew later rigged the hardware of the coronograph contamination measurement experiment (T025) and the 35 mm camera from the UV airglow horizon photography experiment (S063) and took seven exposures of the gegenschein. During the last mission, 96 additional photographs were taken.

Dr. J. L. Weinberg, Dudley Observatory, Albany, New York, was the principal investigator.

Particle Collection (S149)

The purpose of the S149 Particle Collection experiment was to study the nature and distribution of interplanetary dust by exposing specially prepared surfaces to space. Impacts of cosmic dust at high speeds produce impact craters and in some cases a portion of the profile remained at the impact site. The controlled, exposed surface was also examined to determine the rate of surface contamination of the Skylab environment. The S149 instrument consisted of gold covered smooth plates 15 centimeters (six inches) square and layers of film mounted inside resealable cassettes.

Sets of four plates were exposed for 72-hour periods during the manned missions and also during the two unmanned storage periods. After being exposed to the space environment, the first set of cassettes (four) were returned to Earth for analysis.

This experiment also helped to better define the hazard to space travel posed by dust particle erosion of critical optical surfaces and windows.

The experiment hardware was to be positioned by deployment of the T027 extension device through the Scientific Airlock.

Of course, the solar scientific airlock could not be used. The S149 was deployed during EVA on the third mission.

Principal investigator for S149 was Dr. Curtis L. Hemenway of Dudley Observatory.

Galactic X-ray Mapping (S150)

The objective of this experiment was to conduct a survey of the sky for faint X-ray sources.

X-radiation has been observed from more than 40 stellar sources over the past 10 years. Most of these studies have been conducted in the energy region from 1-10 KeV using rockets with a viewing time of only 3 minutes. Satellites such as SAS-A, launched December 1970, have completed the survey of stellar sources in the 1-10 KeV region. The Skylab experiment provided sky survey in the 0.2-12 KeV energy range.

The instrument consisted of a set of proportional counters which covered the spectral region from .2 to 12 KeV. It was physically mounted on the launch vehicle. Accordingly, the life time of the experiment was to be limited to 4-5 hours. During this time detectors with a 20° field of view were to determine the location of X-ray sources to within 20 arc minutes.

In flight, a failure occurred which caused the pressure around the proportional counters to decay and the high voltage power supply turned itself off after 103 minutes of operation.

Dr. William Kraushaar, University of Wisconsin, was the principal investigator.

Ultraviolet Panorama (S183)

The objective of this experiment was to measure ultraviolet brightness of a large number of stars.

Rocket experiments have obtained high resolution spectra of individual bright stars and the OAO-A2 telescope has obtained images of many star fields in four spectral bands.

The Skylab experiments provided a photographic survey in three bands with fine spatial and photometric resolution of a number of star fields previously unavailable.

The instrument, a spectrographic assembly used the same movable mirror as S019. Total weight was about 175 pounds. The spectrographic assembly was mounted in the antisolar airlock in the wall of the Skylab with the movable mirror extended outward to permit viewing in different directions.

The assembly included a grating spectrograph which collected the ultraviolet light from the spectrum of the stars in the field of view into 600 A wide bands centered at 1800 A and 3100 A. Stars as faint as 7th magnitude were recorded with 7 arc minutes of angular resolution over a 7 by 9 degree field of view. It also included a small Schmidt camera which recorded the field of view in a 600 A wide band of UV radiation centered at 2500 A. angular resolution over a 7 by 9 degree field of view.

The photographs were returned to Earth for processing. From the film images, the amount of light emitted by stars in the three ultraviolet bands was determined. These values were compared with theoretical ultraviolet spectra and the spectra of brighter stars obtained by OAO and the S019 experiment to determine average ultraviolet colors or differences between stars of the same type. In addition, the variation with wavelength of observation of distant stars due to interstellar dust were used to study the distribution and composition of this dust. The overall average ultraviolet color of a group of stars such as a cluster or a galaxy were compared with the visible color of unexpected discrepancies.

The high temperature experienced in the workshop was thought to have damaged the film for this experiment and a new carousel was launched in the first command module. During the first mission several malfunctions occurred and the carousel jammed. The film was returned to Earth and upon development, the quality was not as good as expected. An intensive failure analysis was made both in France and the United States and outgassing of the gold coating of the plastic film holders was pinpointed as the cause of the poor film quality. A new carousel was designed, built and tested and launched on SL-4.

All in all, this experiment was a highly complex mechanical device and it experienced many problems (jamming, broken glass, improper indexing) and the crew was able to repair most problems.

Dr. Georges Courtes, Director of the Laboratoire d'Astronamie Spatiale du CRNS, Marseille, France, was the principal investigator.

Trans-Uranic Cosmic Rays (S228)

The objective of this experiment was to provide a detailed knowledge of the relative abundances of nuclei with Z (atomic map number) greater than 26 in the cosmic radiation, specifically to observe and identify as many transuranic nuclei as possible. This experiment observed and helped determine upper limits on the flux or super heavy cosmic rays with Z greater than 110, and determined simultaneously the energy spectrum of cosmic rays with Z=26, Z 85, from about 1,500 to 1,500 MeV/nucleon.

The experiment utilized plastic (Lexan) detectors mounted in the OWS and exposed to cosmic radiation. These cosmic rays penetrated the detector packages streaking the plastic sheets within. Subsequent to return to Earth these plastic sheets were chemically etched and the cosmic ray tracks were measured with an optical microscope. With this technique, both the atomic number and energy of each particle can be determined.

An additional detector module was launched with the third crew to collect data on cosmic rays which did not have to penetrate the workshop walls. It was attached to a clipboard on a handrail during the first EVA of the mission and retrieved on the last. Also, one module was left in the docking adapter by the last crew for the collection of very long exposure in the event Skylab is revisited in the future.

Dr. P. Buford Price of the University of California, Berkeley Campus, was the principal investigator.

Magnetospheric Particle Composition (S230)

The objective of S230 was to measure the abundances of heavy, rare ions in the Earth's magnetosphere, principally the isotopes of the noble gases, and to compare these to the abundance ratios previously measured in the solar wind composition experiment used in the Apollo program. Analysis of experiment results helped to determine the origin of magnetospheric particles through careful study of the isotopes.

The experiment consisted of sheets of collecting foil of aluminum, aluminum oxide and platinum mounted on the ATM Deployment Assembly truss. Each piece of foil, a rectangle of about 35 by 48 centimeters (14 by 19 inches) was mounted on a flexible backing material and formed into a cuff that was wrapped around one of two spools on the DA truss. Two cuffs were used per spool with one cuff being covered by the other.

Two cuffs from one spool were retrieved during the first and third EVA of SL-3, and two cuffs from the other spool were retrieved during the first and second EVA of SL-4. The cuffs were stored in an envelope in the OWS food freezer until returned to Earth for analysis.

Coinvestigators are Dr. Don Lind, astronaut, at the Johnson Space Center, and Dr. Johannes Geiss, University of Bern, Switzerland.

Materials Science and Manufacturing in Space

The condition of weightlessness in orbital flight makes it possible to conduct operations in materials processing that could not be done easily on Earth, if at all. Melting and mixing without the contaminating effects of containers, suppression of convection and buoyance in liquids and molten material, control of voids, and the ability to use electrostatic and magnetic forces otherwise masked by gravitation open the way to new knowledge of material properties and ultimately to valuable new products for use on Earth. These potential products range from composite structural materials with highly specialized physical properties to large highly perfect crystals with valuable electrical and optical properties to new vaccines that could not be produced by conventional means on Earth.

The progress of Space Shuttle planning has raised the prospect that vehicle capabilities sufficient to support large-scale experiment programs and limited commercial manufacturing operations will be made available. Practical experience developing the materials for Skylab has already proved of great value in concept planning of an improved and enlarged facility for the Space Shuttle program. Evaluation of Skylab results will help engineers finalize the design of Shuttle equipment.

Materials Processing Facility (M512)

The objectives of the experiment to be performed in the M512 facility were to demonstrate and evaluate the merits of molten metal phenomena for manufacturing in a space enviroment, to gain experience in molten metal characteristics in space for future application of construction, assembly, and maintenance outside the Earth enviroment, and for the manufacture and retrieval of valuable products for use on Earth.

The facility provided a basic apparatus and a common spacecraft interface for a group of metallic and non-metallic materials experiments and test and demonstrated a system approximating the "facility approach" projected for future space experimentation, where common hardware will be used to perform multiple experiments.

The M512 facility demonstrated in space the feasibility of joining metallic materials by applying heat through an electron beam and an exothermic source, respectively. The experimental hardware was also utilized as a common facility for materials processing experiments.

The M512 facility, hard mounted in the MDA, consisted of a vacuum work chamber with associated mechanical and electrical controls, an electron beam subsystem and a control and display panel. The vacuum chamber was a 40-centimeter (16.25-inch) sphere with a hinged hatch for access. It was connected to the space enviroment by a 10-centimeter (4-inch) diameter line containing two butterfly poppet valves. The electron beam subsystem was mounted to the chamber so that the beam traversed the sphere along a diameter parallel to the plane of the hatch closure. The chamber wall contained a cylindrical well accommodating the small electric furnaces used for the M518 and M555 experiments. Auxiliary provisions included ports for a floodlight and the 16mm data acquisition camera, a bleed line, a repressurization line and a port for a vacuum cleaner. A subsystem was also provided for spraying water into the chamber during some runs of the M479 experiment for quenching.

The electron beam operated nominally at 20 kV and 80 mA and was provided with focusing and deflection coils that could be operated from the control panel.

The control panel had controls and displays for all of the experiments to be performed in the facility, including a gauge for the vacuum chamber voltage and current meter for the electron beam and a thermocouple temperature indicator.

Data from the experiments were samples, those parts of the apparatus that were returned, motion picture records of the two electron beam experiments and M479, plus comments by the operating crewmen. The returned samples are being studied in comparison with control samples produced on Earth.

The experiments conducted using the M512 facility, the objectives of each, and the pricipal investigators were:

Metals Melting (M551)

The objectives of Experiment M551 were to:

- Study the behavior of molten metals in microgravity.

- Characterize the structures formed in metals melted and rapidly solified in zero gravity.

- Test means of joining and cutting metals by electron beam welding in zero gravity.

Richard Poorman of the Marshall Space Flight Center was the principal investigator.

Exothermic Brazing (M552)

The objectives of Experiment M552 were to:

- Test and demonstrate a method of brazing components in space repair and maintenance operations.

- Study surface wetting and capillary flow effects in weightless molten metals.

J. R. Williams of the Marshall Space Flight Center was principal investigator.

Sphere Forming (M553)

The objective of the experiment was to demonstrate the effects of zero gravity on fundamental solidification phenomena. In particular, high purity nickel, a Ni-12% Sn alloy, Ni-1% Ag alloy, and Ni-30% Cu alloy, were melted on stings and resolidified in both the free flowing and captive conditions.

These materials were to permit study of the effects of low-gravity solidification phenomena which could apply equally to the majority of the more complex alloys and solidification procedures which could be of commercial importance. Because of time limitations during SL-2 only 7 of the 14 samples were completed.

E. A. Hasemeyer of the Marshall Space Flight Center was principal investigator.

Single Crystal Growth

The objective of this experiment was to grow single crystals of gallium arsenide from solution. Unfortunately, this experiment could not be flown because of the volume demands of the SL-2.

Experiment M479 - Zero Gravity Flammability

The objective of Experiment M479 was to ignite various materials in a five psia oxygen/nitrogen mixture to determine:

- Extent of surface flame propagation and flashover to adjacent materials.

- Rates of surface and bulk flame propagation under zero convection.

- Self extinguishment.

- Extinguishment by vacuum and water spray.

The combustion chambers and controls for this experiment were provided by Experiment M512. Individual flammability tests lasted from a minimum of 10 seconds to a maximum of 4 minutes. Each test was photographed in its entirety so that combustion rates could be determined by post-flight analysis.

Principal investigator was J. H. Kimzey of the Johnson Space Center.

Multipurpose Electric Furnace (M518)

The Multipurpose Electric Furnace system provided a means of performing experiments on solidification, crystal growth and other processes involving phase changes in materials. The furnace system was used to perform experiments involving phase changes at elevated temperatures in systems comprising selected combinations of solid, liquid and vapor phases. Because of the near zero gravity aboard Skylab, the liquid and vapor phases were expected to be essentially quiescent and phases of different density had little or no tendency to separate.

The system consisted of three main parts: the furnace, designed to interface with the M512 Materials Processing Facility; a programmable electronic temperature controller which controlled the temperature levels in the furnace; and experiment cartridges which contained the sample materials. The furnace had three specimen cavities so that three material samples were processed in a single run. The furnace was constructed to provide three different temperature zones along the length of each sample cavity as follows:

- A constant temperature hot zone at the end of the sample cavity where temperatures up to 1,000 degrees C (1832 degrees F) were reached.

- A gradient zone next to the hot zone where temperature gradients ranging from 20 degrees C (63 degrees F) to 200 degrees C (392 degrees F) per centimeter were established in the samples.

- A cool zone in which heat conducted along the samples was rejected by radiation to a conducting path that carries the heat out of the system.

Each sample of material was enclosed in a cartridge in which the actual temperature distribution applied to the sample was controlled by the thermal design of the cartridge.

The control package provided active control of the furnace temperature. It was set to a specific temperature within the furnace's capability by the astronaut. Two timing circuits in the controller enabled the astronaut to program the soak time spent at the set temperature and the cooling rate of the furnace at the end of the soak period. Active temperature control continued during programmed cooling.

Once the specimens were installed in the furnace and the system activated by the astronaut, the system operated automatically except for complete system shutdown. The material cartridges were returned to Earth for examination.

The experiment equipment was comprised of the furnace, control package and 33 cartridges (11 experiment sets), cables to interconnect the system and to connect the system to power and data outlets, two cartridge containers, a tube of thermal grease and a cartridge extraction tool.

The 11 experiments used the Multipurpose Electric Furnace, the objectives and principal investigators were:

Vapor Growth of II-VI Compounds (M556)

To determine the degree of improvement that can be obtained in the perfection and chemical homogeneity of crystals grown by chemical vapor transport under weightless conditions in space. Dr. Harry Wiedemeier, Rensselaer Polytechnic Institute, Troy, New York, was principal investigator.

Immiscible Alloy Compositions (M557)

To determine the effects of near-zero gravity on the processing of materials compositions which normally segregate on Earth. J. O. Reger, TRW Systems Group, Redondo Beach, California, was principal investigator.

Radioactive Tracer Diffusion (M558)

To measure self-diffusion and impurity diffusion effects in liquid metals in spaceflight and characterize the disturbing effects, if any, due to spacecraft acceleration. Dr. Anthony O. Ukanwa, Marshall Space Flight Center, was principal investigator.

Microsegregation in Germanium (M559)

To determine the degrees of microsegregation of doping impurities in germanium caused by convectionless directional solidification under conditions of weightlessness. Dr. Francois A. Padavani, Texas Instrument Corporation, Dallas, was principal investigator.

Growth of Spherical Crystals (M560)

To grow doped germanium crystals of high chemical homogeneity and structural perfection and study their resulting physical properties in comparison with theoretical values for ideal crystals, Dr. Hans Walter, University of Alabama, Huntsville, was principal investigator.

Whisker-Reinforced Composites (M561)

To produce void-free samples of silver reinforced with oriented silicon carbide whiskers. Dr. Tomoyoski Kawada, National Research Institute for Metals, Tokyo, was principal investigator.

Indium Antimonide Crystals (M562)

To produce doped semiconductor crystals of high chemical homogeneity and structural perfection and to evaluate the influence of weightlessness in attaining these properties. Dr. Harry C. Gatos and Dr. August F. Witt, Massachusetts Institute of Technology, Cambridge, Massachusetts, were coinvestigators.

Mixed III-V Crystal Growth (M563)

To determine how weightlessness affects directional solidification of binary semiconductor alloys and, if single crystals are obtained, to determine how their semiconducting properties depend on alloy composition. Dr. William R. Wilcox, University of Southern California, Los Angeles, was principal investigator.

Metal and Halide Eutectics (M564)

To produce highly continuous controlled structures in samples of the fiber-like sodium fluoride-sodium chloride and plate-like bismuth-cadmium and lead-tin eutectics, and to measure their physical properties. Dr. Alfred S. Yue, University of California, Los Angeles, was principal investigator.

Silver Grids Melted in Space (M565)

To determine how pore sizes and pore shapes change in grids of fine silver wires when they are melted and re-solidified in space. Dr. A Derutherre, Catholic University of Belgium, Reverlee, Belgium, was principal investigator.

Copper-Aluminum Eutectic (M566)

To determine the effects of weightlessness on the formation of lamellar structure in eutectic alloys when directionally solidified. E. A. Hasemeyer, Marshall Space Flight Center, was principal investigator.

Engineering and Technology Experiments

The Engineering and Technology experiments provided data which is important in the development of future space systems for exploration and the conduct of scientific experimentation.

A number of the experiments were particularly oriented toward the interaction of man with his new zero-gravity environment. In this category were:

- Habitability and Crew Quarters, M487
- Astronaut Maneuvering Equiptment, M509
- Crew Activities/Maintenance, M516
- Manual Navigation Sightings, T002
- Crew/Vehicle Disturbance, T013
- Foot-Controlled Maneuvering Unit, T020

The Astronaut Maneuvering experiments (M509 and T020) closely allied. They investigated several different techniques for use by man for extravehicular activity (EVA). In the Skylab program, these maneuvering units were operated inside the OWS working volume.

Several experiments were designed to study the spacecraft environment, both natural and induced:

- Radiation in Spacecraft, D008
- Thermal Control Coatings, D024
- Thermal Control Coatings, M415
- Inflight Aerosol Analysis, T003
- Coronagraph Contamination Measurement, T025
- ATM Contamination Measurements, T027

The two thermal control coating experiments were complementary. The M415 experiment investigated the effect of the launch environment-Earth's atmosphere, retrorockets, etc. - on spacecraft surfaces. The D024 experiment investigated the long-term effects of the space environment, particularly sunlight, on spacecraft surfaces.

Radiation in Spacecraft (D008)

The purpose of Experiment D008 was to test advanced radiation, instruments and techniques for determining the radiation effects on man and to provide correlative data for radiation hazard prediction methods for long duration manned spaceflight mission planning.

The D008 experiment was composed of a movable tissue equivalent dosimeter, a linear energy transfer spectrometer, and five passive dosimeters. The passive dosimeters integrated the does received during the entire mission.

D008 was flown aboard SL-2. The experiment hardware remained in the CM for the course of the mission. No crew participation was required.

Principal investigator for the D008 experiment was Capt. Andrew D. Grimm, and coinvestigator was Joseph F. Janni, both of Kirtland Air Force Base, New Mexico.

Thermal Control Coatings (D024)

This experiment consisted of exposing material samples to the space environment and had the following objectives:

- Determine the effects of near-Earth space environments on selected experimental thermal control coatings which have been extensively investigated in the laboratory.

- Correlate the effects of the space environment on these coatings with measured effects of ground-based simulated space environments.

- Gain new understanding of the mechanisms of degradation of thermal control coatings caused by actual space radiation.

The experiment was a companion to Experiment M415, which determined the effects of the launch environments on thermal control coatings.

Experiment D024 provided the first opportunity to examine in detail samples that were chemically or physically unaltered since retrieval from space.

The experiment package consisted of four panels, two of which contained 36 thermal control coating samples. The samples were 2.54-cm (1-inch) diameter discs coated with various selected thermal control coatings. The other pair of panels contained strips of polymetric plastic five mils thick. The panels were square plates, about 17 centimeters ($6\frac{1}{2}$ inches) on a side and 0.6 centimeters ($\frac{1}{2}$ inch) thick. Each had a flexible handle to prevent contamination of the samples while handling.

Panels were attached with snap fastners to the AM truss assembly. Here they received no cluster shadowing in the solar inertial attitude held during most of the mission. Protective covers were removed from the panels 24 hours before launch. Protected by the payload shroud during launch, the samples should not have been affected by the launch environment.

Dr. William L. Lehn of the Air Force Materials Laboratory, Wright Patterson Air Force Base, was principal investigator.

Thermal Control Coatings (M415)

The objective of Experiment M415 was to determine the degradation effects of prelaunch, launch and space environments on the thermal absorption and emission characteristics of various coatings commonly used for passive thermal control.

The principal elements of this experiment consisted of two panels, each containing 12 thermal sensors arranged in four rows of three. Three different thermal control coating samples were mounted on the sensors in each row. All of the coating samples were thermally isolated from surrounding structures. Unlike Experiment D024, detailed spectral reflection measurements could not be made since the coatings were not retrieved. Thermal properties were measured by temperature sensors and the data were telemetered to the ground.

Eugene C. McKannan, Marshall Space Flight Center, was principal investigator.

Habitability/Crew Quarters (M487)

Throughout the three manned visits to the Skylab, flight crews were asked to evaluate everyday spacecraft-type activities such as sleeping, eating and the ease or difficulty of getting around. The crew documented with film and tape-recorded comments the habitability features of the workshop as part of Experiment M487, the objectives of which were to provide data useful in the design of future manned spacecraft.

Habitability features such as architecture, environmental elements and communications techniques affect everyday spacecraft activities and crew performance. Objective and subjective data were obtained on OWS environment, internal architecture, adequacy of mobility aids and restraints, food and water, garments and personal accounterments, personal hygiene, housekeeping, internal communications, and subjective data on the adequacy of the off-duty activity provisions.

Instruments, including a measuring tape, portable thermometers, surface temperature digital thermometer, sound meter and frequency analyzer, velometer and force gauge were provided for the experiment.

Principal investigator was Caldwell C. Johnson, Jr., of the Johnson Space Center.

Astronaut Maneuvering Equipment (M509)

The objectives of this experiment were to: demonstrate Astronaut Maneuvering Unit flying qualities and piloting capability; test and evaluate system response; and relate the data and experience gained to ground-based analysis, future AMU design requirements, and projected EVA capabilities.

The astronaut maneuvering equipment consisted of two jet-powered AMU's, a back-mounted hand controlled unit called the automatically stabilized maneuvering unit (ASMU or backpack) and handheld maneuvering unit (HHMU).

The ASMU had a rechargeable/replaceable high pressure nitrogen propellant tank and battery. Control moment gyro and reaction jet stabilization modes were provided. A third mode allowed the pilot to fire the reaction jets directly through the hand controllers. The ASMU provided propellant and instrumentation for evaluation of the HHMU mode.

The ASMU was maneuvered by 14 thrusters located in various positions on the backpack. The thrusters were controlled by two hand-controllers mounted on arms extending from the backpack. The left hand controlled translation forward, backward, up, down, and sideways; and the right hand, using an aircraft-type handgrip, controlled rotation in any direction.

The HHMU was a handgrip unit with a pair of thrusters that pulled the astronaut forward, a single thruster that pushed him backwards, and thruster controls.

Skylab crew members flew the units in a shirt sleeve and pressure suit mode inside the forward dome of the workshop.

The observer operated the cameras, cued the pilot on test operations procedures and analyzed and described the test progress over the voice communication system. Comments made by the pilot and observer during and immediately after each experiment run (varying from 50 to 80 minutes duration) were taped and dumped to tracking stations at the scheduled intervals.

Principal investigator for M509 was Major C. E. Whitsett, Jr., assigned to the Air Force Space Transportation System Office at the Johnson Space Center.

Crew Activities/Maintenance (M516)

This experiment investigated crew performance in zero gravity, long duration missions, primarily through observations of normal Skylab tasks. It was related closely to M151 and M487. The experiment called for:

- Systematic documentation of man's performance during prolonged weightless spaceflight.

- Acquisition and evaluation of inflight maintenance data.

- Evaluation of data relative to design criteria for Skylab and future missions.

- Evaluation and report of findings in terms useful to future manned mission planners.

Performance data were gathered in the areas of manual dexterity, locomotion, mass handling and transfer, and maintenance.

M516 was handled in the following phases:

Preflight - Crew performance data acquired during preflight simulations and training sessions to be used to establish baseline data for comparison with data acquired inflight.

Inflight - M516 used film coverage provided by various other experiments and operational activities which related to crew performance activities.

Postflight - The crewmen provided subjective and technical comments during debriefing regarding crew performance activities.

Principal investigator was R. L. Bond of the Johnson Space Center.

Manual Navigation Sightings (T002)

The objective of this experiment was to investigate the effects of the spaceflight environment (including long mission time) on the navigator's ability to take space navigation measurements through a spacecraft window using handheld instruments.

Previous data obtained with the use of simulators, aircraft, and the Gemini spacecraft had already demonstrated that man, in a space environment, could make accurate navigation measurements using simple handheld instruments. This, together with already developed techniques for reducing the data to a position determination, meant that a technique is available for man to navigate in space using simple instruments and without a computer. The intent of this experiment was to determine whether long mission duration appreciably affects the capability of man to obtain accurate measurements.

The equipment for this experiment consisted of two handheld instruments, a sextant and a stadimeter. The sextant measured the angles between two stars, and between single stars and the edge of the Moon. The stadimeter, also an optical device, determined spacecraft altitude by measuring the apparent curvature of the horizon.

Data returned was logbook entries of the sextant and stadimeter readings, supplemented by crew comments on the voice tape recorder.

Robert J. Randle, Ames Research Center, and Major Stanley Powers, USAF, were coinvestigators.

In-Flight Experiment Aerosol Analysis (T003)

The objective of this experiment was to measure the size, concentration and composition of particles in the atmosphere inside the Skylab as a function of time and location.

An aerosol analyzer had been designed for Experiment T003 which was capable of separating particulates into three size ranges, accumulating the total particles in the three size intervals and displaying the results immediately to the astronaut. The instrument also contained a particulate collection system so that postflight analysis could be used to ascertain the shape and composition of the individual particles.

The instrument was a multi-channel, battery operated particle counter capable of sorting aerosol particles into three size groups: 1 to 3 microns, 3 to 9 microns, and 9 to 100 microns.

The instrument was handheld by an astronaut at the desired point of measurement. Representative locations throughout the spacecraft were tested.

Dr. William Z. Leavitt, Department of Transportation, was principal investigator.

Crew/Vehicle Disturbances (T013)

The objective of this experiment was to measure the effects of various crew motions on the dynamics of manned spacecraft, specifically the torques, forces, and vehicle motions produced by the astronaut's body motions; to verify information obtained from ground simulation programs; and to determine the effects of astronaut motion on the attitude and control of the vehicle.

Experiment T013 was designed to provide system designers with accurate models of crew motion disturbances.

Body motion of the astronaut was measured by the Limb Motion Sensing System (LIMS) which is a skeletal structure incorporated into a suit, with pivots at the major body joints. Each pivot was monitored by a linear potentiometer which provided a continuous measurement of body limb position as the subject astronaut performed the assigned task. Onboard motion picture photography, using two 16mm Data Acquisition Cameras, was used concurrently with the LIMS.

A Force Measuring System (FMS) consisting of two Force Measuring Units (FMUs) was used to measure the forces and moments applied to the OWS structure during the assigned task, which included soaring between the FMUs.

The measurement data of the LIMS and FMS were processed and telemetered to the ground along with real-time transmission of the applicable ATM Pointing Control System data.

Bruce A. Conway, Langley Reseach Center, was principal investigator.

Foot-Controlled Maneuvering Unit (T020)

This experiment evaluated an astronaut maneuvering device that did not require use of the astronaut's hands. Both the ASMU (Automatically Stabilized Maneuvering Unit) and the HHMU (Handheld Maneuvering Unit) used in Experiment

M509 required the astronaut to use his hands to control the unit. The foot-controlled maneuvering unit (FCMU) was a foot-operated propulsion device that was straddled by the operator as if riding a bicycle. The unit was propelled by high pressure nitrogen contained in the detachable propellant tank used in the M509 experiment.

Donald E. Hewes, Langley Research Center, was the principal investigator.

Coronograph Contamination Measurements (T025)

The primary objective of Experiment T025 was to visually and photographically observe and record the amount of light scattered by particles from thruster firings and waste dumps. One purpose of T025 was to determine the extent and nature of the induced contaminant and to assess its effect on other optical experiments on the spacecraft. Another objective was to look through the Earth's upper atmosphere to determine the type and amount of particulate matter.

The T025 experiment hardware consisted of a modified 35mm Nikon camera attached to a coronagraph which was to be fitted into the solar Scientific Airlock.

Since the solar SAL was used for the parasol thermal shield, a special bracket had to be devised to attach the experiment outside the workshop so it could be used during extravehicular activities. A special occulting disc was also needed. The needed equipment was flown to the workshop on SL-4, the last manned visit. (This experiment was also used to record data from the Comet Kohoutek).

The discs occulted the solar disk, and the SWS was oriented so that only scattered light from particulate matter was recorded on the photographic film.

Principal investigator for this experiment was Dr. Mayo Greenberg of Dudley Observatory. Coinvestigator was George Bonner of the Johnson Space Center.

Contamination Measurements (T027)

This experiment consisted of two separate pieces of hardware, T027 Sample Array and the T027/S073 Photometer System, each with its own objectives. The Universal Extension Mechanism, part of the Photometer System was also used to deploy the portable TV and Experiment S149 through the SAL. Photometer system hardware was also to be used to meet the objectives of Experiment S073.

T027 Sample Array

The basic objective of the T027 Sample Array experiment was to obtain controlled data on the degradation effects of contaminants associated with Skylab on the optical properties of various windows, mirrors and diffraction gratings. A secondary objective was to obtain near-real-time data on contamination rates during sample exposure by use of Quartz Crystal Microbalances.

Window contamination on Gemini and Appollo flights have interfered with star sightings and lunar surface photography experiments. Sources of contaminant depositions have been found to be thruster firings and molecular evaporations from various materials on the spacecraft.

The Sample Array System was to expose optical samples to the space environment for controlled periods. The Sample Array was deployed outside the spacecraft on a boom. The total of 248 samples of different types were to be exposed. The samples consisted of window materials, mirrors, gratings and other optical surfaces suitable for various wavelength regions.

Since the solar SAL was unavailable, the anti-solar SAL was used and abnormal temperatures were encountered. Also, because of the workshop meteroid shield incident, the experiment could not be deployed until in the mission and, as a result, was outgassing throughout its operation. At the end of the first mission the instrument was returned for analysis and it was found to have failed and no good data were recorded.

T027 Photometer System

The objective of the T027 Photometer System was to measure the brightness and polarization of the scattered sunlight from the solar illumination of the particulate contaminant cloud surrounding Skylab. Variations of the contaminant cloud with respect to time and location were also to be measured.

The Photometer System measured three parameters which fully characterize the radiation from the skyglow and from the Skylab corona; i.e., brightness of the total and of the polarized components, and orientation of the plane of polarization. Measurements pertaining to the skyglow (zodiacal light, Gegenschein, starlight, F-region airglow) are best performed on the dark side.

The photoelectric photometer was deployed through the Scientific Airlock (SAL) by means of the Universal Extension Mechanism. The Photometer Head was mounted on a gimballed system at the end of the mechanism to permit scanning in elevation and azimuth through limits of 0 to 112.5 degrees and 0 to 354 degrees respectively.

The photometer head contained an optical train with a polarizing disk, ten selectable filters, a field of view system and a photomultiplier tube to sense and analyze the integrated light entering the system. A radioactive calibration source was provided to allow automatic system calibration.

During the second manned mission the photometer was installed and, using the universal extension system, deployed. (The photometer had been used on the first manned mission for 11 scans of the sky). At the completion of the run a malfunction occurred which made it impossible to retract the experiment. It was necessary to jettison the photometer and the universal extension system in order to free up the airlock for other experiments. (Jettisoning of the experiments was designed into the SAL to insure that the equipment would have maximum usage).

The loss of the photometer affected not only the T027 experiment, but also the S073 experiment. Loss of the extension system affected S149 and the use of the universal television. Later schemes were improvised using T025 and S063 hardware as well as S073 data such that the principal investigators did receive some useful data.

The principal investigator was Dr. Joseph A. Muscari, of Martin Marietta Aerospace.

Comet Kohoutek (1973f)

A major effort was made during the last manned mission to view the Comet Kohoutek from Skylab. The fact that the space station was in orbit during the time of the perehelion passage of the comet and the wide array of scientific instruments Skylab carried, offered scientists an opportunity which was unparalleled. Since the comet was discovered early in its passage, there was ample time to develop a comprehensive and coordinated viewing plan.

The National Aeronautics and Space Administration observation plan included, not only Skylab instruments, but also balloons, rockets, ground observatory and unmanned satellite instruments. The observation frequencies ranged from X-ray to microwave. The observation by the Skylab astronauts were the only viewings that could be made at perihelion.

Existing Experiments:

Ultraviolet Stellar Astronomy S019 - To assist in the determination of the composition of the comet and to study the astrophysical processes which occur in the comet as a function or time.

Ultraviolet Airglow Horizon Photography S063 - To study the spatial and temporal variation in the selected atomic and molecular constituents and the degree of linear polarization of the coma and tail.

Gegenschein and Zodiacal Light S073 - To study the distribution of comet particles.

Coronagraph Contamination Measurements T025 - To study particulate production rates and spatial distribution and to study the production and distribution of hydroxol, cyanide, sodium, ammonia, and carbon monoxide molecular components of the coma and tail.

White Light Coronagraph S052 - To study the structural density and its evolution with time and to study the tail mass changes near perihelion passage.

X-ray Spectrograph S054 - To study the mass density of medium weight elements such as carbon, nitrogen and oxygen.

Ultraviolet Scanning Polychromator Spectroheliometer S055A - To study the radiance of the hydrogen halo.

X-ray Telescope S056 - To study the soft X-ray fluorescence of materials.

Extreme Ultraviolet Spectroheliograph S082A - To study the chemical composition and the ratio of helium to hydrogen.

Spectrograph and Extreme Ultraviolet Monitor S082A - To study the metallic, diamotic, and polytomic emission lines for unique data on the chemical composition.

New Hardware

Far Ultraviolet Electronographic Camera S201 - S201 was flown on Apollo 16 and the backup unit was modified to fit the Scientific Airlock of Skylab. The articulated mirror system was used to aim the instrument at the comet. The camera was mounted in a vacuum tight aluminum cannister (along with the camera high voltage power supply and electronics). The cannister was mounted on the SAL and opened to vacuum. Light entered the forward end and passed through a transparent collector plate. A 5-inch spherical mirror focussed the light on a potassium bromide photo cathode. The resulting photoelectrons were accelerated by a -20 KV potential on the cathode and focussed by a magnetic field on a 35mm NTB-3 film at the near end. Two corrector plates were automatically interchanged: lithium floride for the 1,050 to 1,600 angstrom bandpass and calcium floride for 1,250 to 1,600 bandpass.

Each activation caused 11 exposures at 1, 2, 5, 6, and 15 seconds through the lithium floride plate and 3, 10, 30, and 107 seconds through the calcium floride plate (three frames were wasted during corrector plate change).

The objectives were to study the far ultraviolet emission of the comet with special emphasis on examining the hydrogen halo.

The principal investigator for S201 was Dr. Thornton Page of the Naval Research Laboratory.

Kohoutek Photometric Photography S-233

S-233 was a somewhat ad-lib operation using an operational 35mm Nikon camera with a 55mm lens. Pictures were taken from various windows with the handheld camera. Since time exposures of 60 to 8,180 seconds were required, the crew had to make extensive use of improvised mounting surfaces (i.e., tape, cardboards, etc.) to steady the equipment. The principal investigator was Dr. Charles Lundquist of the Marshall Space Flight Center.

Student Experiments

In October 1971 NASA and the National Science Teachers Association announced a national competition for student (grades 9 through 12) proposals for an experiment for Skylab. NSTA administered the competition in cooperation with the NASA Educational Program Division and Skylab Program Office. More than 3,400 proposals were received, evaluated and judged by the NSTA. Of these 3,400 proposals, 301 were selected as regional winners and 25 national winners were announced in March 1972. Of these 25 national winners, 11 were selected for development of hardware for Skylab, eight others used existing hardware, and six could not be accommodated as proposed because of Skylab performance requirements or schedule constraints.

Four of the six that could not be accommodated were provided data from existing Skylab experiments which either were similar to the student's proposal or satisfied an alternate interest of the student. The remaining two were associated with NASA researches in areas closely related to their proposed subject of interest.

All student experiments were handled in a manner very similar to the mainline Skylab experiments with the student investigator assuming the role of principal investigator under the guidance and with the assistance of a science advisor from the Marshall Space Flight Center. Consulting science advisors were assigned from the Johnson Space Center in Houston.

The 25 students and experiments selected for participation in the Skylab Program were:

Joe B. Zmolek, Oshkosh, Wisconsin
"Atmospheric Heat Absorption" - ED 11
Lourdes High School, William L. Behring, Teacher/Sponsor

Experiment was to determine the attenuation, due to the Earth's atmosphere, of radiant energy in the visible and near IR regions over both densely populated and sparsely populated sections of the Earth.

Troy A Crites, Kent, Washington
"Volcanic Study" - ED 12
Kent Junior High School, Richard C. Putnam, Teacher/Sponsor

Experiment was to determine the feasibility of predicting volcanic activity based on remotely sensed thermal infrared surveys.

Alison Hopfield, Princeton, New Jersey
"Libration Clouds" - ED 21
Princeton Day School, Normal Sperling, Teacher/Sponsor

Experiment was to observe the two zero-force regions in the Earth-Moon system where it is expected that small space particles will accumulate.

Daniel C. Bochsler, Silverton, Oregon
"Objects Within Mercury's Orbit" - ED 22
Silverton Union High School, John P. Daily, Teacher/Sponsor

Experiment was to identify a planetary body (or any other identifiable object) which may orbit the Sun at a radius substantially less that that of Mercury's orbit.

John C. Hamilton, Aiea, Hawaii
"UV from Quasars" - ED 23
Aiea High School, James A. Fuchigami, Teacher/Sponsor

Selected photographs obtained by ultraviolet stellar astronomy equipment were analyzed.

Joe W. Reihs, Baton Rouge, Louisiana
"X-Ray Steller Classes" - ED 24
Tara High School, Helen W. Boyd, Teacher/Sponsor

Experiment was to make observation of celestial regions in X-ray wavelengths in an attempt to relate X-ray emissions to other spectral characteristics of observed stars.

Jeanne L. Leventhal, Berkeley, California
"X-Rays From Jupiter" - ED 25
Berkeley High School, Harry E. Choulett, Teacher/Sponsor

To detect X-rays from the planet Jupiter and establish the correlation of X-ray emission with solar activity and decametric radio emission.

Neal W. Shannon, Atlanta, Georgia
"UV from Pulsars" - ED 26
Fernbank Science Center, Dr. Paul H. Knappenberger, Teacher/Sponsor

To attempt to measure the radiation from known Pulsars in the UV spectral region to determine whether or not the UV data correlates with known existing Pulsar Spectral data.

Robert L. Staehle, Rochester, New York
"Bacteria and Spores" - ED 31
Harley School, Alan H. Soanes, Teacher/Sponsor

To assess the differences in survival, growth and mutations of bacteria when compared with similar group of Earth enviroment spores.

Todd A. Meister, Jackson Heights, New York
"In Vitro Immunology" - ED 32
Bronx High School of Science, Vincent G. Galasso, Teacher/Sponsor

To determine the extent to which the absence of gravity affects the in vitro demonstration of the immune-response mechanism.

Kathy L. Jackson, Houston, Texas
"Motor Sensory Performance" - ED 41
Clear Creek High School, Mary K. Kimzey, Teacher/Sponsor

To measure the changes in fine, manipulative capabilities of a crew member due to extended exposure to the Skylab environment.

Judith S. Miles, Lexington, Massachusetts
"Web Formation" - ED 52
Lexington High School, J. Michael Conley, Teacher/Sponsor

To observe the web-building process and the detailed structure of the web of the common cross spider (Araneus diadematus) in a normal environment and in a Skylab environment.

Joel G. Wordekemper, West Point, Nebraska
"Plant Growth" - ED 61
Central Catholic High School, Lois M. Schaaf, Teacher/Sponsor

Donald W. Schlack, Downey, California
"Plant Phototropism" - ED 62
Downey High School, Jean C. Beaton, Teacher/Sponsor

These two experiments were combined into a single joint experiment whose objectives were:

To determine the differences in root and stem growth and orientation of rice seeds in specimens grown in zero gravity and on Earth under similar environmental conditions.

To determine whether light can be used as a substitute for gravity and on Earth under similar environmental conditions.

To determine whether light can be used as a substitute for gravity in causing the roots and stems of rice seeds to grow in the appropriate direction in zero gravity, and to determine the minimum light level required.

Cheryl A. Peltz, Littleton, Colorado
"Cytoplasmic Streaming" - ED 63
Arapahoe High School, Gordon B. Scheele, Teacher/Sponsor

To perform microscopic observation of leaf cells of elodea plants in zero gravity to determine if there is any difference between the intracellular cytoplasm motion compared with cytoplasmic motion of similar leaf cells on Earth.

Roger G. Johnston, St. Paul, Minnesota
"Capillary Study" - ED 72
Ramsey High School, Theodore E. Molitor, Teacher/Sponsor

To determine if the zero gravity environment induces changes in the characteristics of capillary and wicking action from the familiar Earth-gravity characteristics.

Vincent W. Converse, Rockford, Illinois
"Mass Measurement" - ED 74
Harlem High School, Mary J. Trumbauer, Teacher/Sponsor

To demonstrate the principle of the existing Skylab specimen mass and body mass measurement devices, utilizing the classical spring-mass mechanical oscillator.

Terry C. Quist, San Antonio, Texas
"Neutron Analysis" - ED 76
Thomas Jefferson High School, Michael Stewart, Teacher/Sponsor

To record impacts of low energy neutrons. The detectors mounted on the inboard faces of water tanks will be able to discriminate between neutrons in four energy spectra.

W. Brian Dunlap, Youngstown, Ohio
"Liquid Motion in Zero G" - ED 78
Austintown Fitch High School, Paul J. Pallante, Teacher/Sponsor

To observe and photograph the motion of a liquid-gas interface (gas bubble surrounded by a liquid) subjected to an impulsive force.

The following six student experiments could not be accommodated in the Skylab Program as proposed. The student, his experiment as proposed, the reasons for its not being included directly in the Skylab Program, and the alternatives are listed below.

Keith Stein, Westbury, New York
"Microorganisms in Varying 'G'"
W. Tresper Clarke High School, Dennis Unger, Teacher/Sponsor

To subject numerous different species of bacteria, ciliated cells, and other microorganisms to a complex regime of varying levels of gravitational forces.

The development of a centrifuge qualified for manned spaceflight could not be accomplished in the limited time available. Data on microorganisms in zero "G" from the Skylab Microbiology Detailed Test Objective were provided.

Kent M. Brandt, Grand Blanc, Michigan
"Chick Embryology"
Grand Blanc Senior High School, Charles E. Martell III, Teacher/Sponsor

This experiment involved the launching of a number of fertile chicken eggs, incubating the eggs in orbit. At stated intervals the development of one or more eggs was to be terminated and the egg preserved. At least one egg would have been carried to full term and, hopefully, hatched. The embryonic eggs and the live chick were to be returned.

It was concluded that the hardware involved placed too great a demand in terms of weight, volume, and crew time to enable launching in the Command Module. He was associated with Dr. John Lindberg, the principal investigator for S071--Circadian Rhythm--Pocket Mice.

Keith McGee, Garland, Texas
"Colloidal State"
South Garland High School, Ann Patterson, Teacher/Sponsor

To determine the effect of zero-g environment on a series of colloidal suspensions, solutions and gels, as well as electrophoretic processes.

The successful performance of this experiment would require a highly stable platform. The normal vibration levels in Skylab, together with the required attitude changes and maneuvers, precluded achieving the required stability.

He was associated with the NASA researchers who were involved in the Apollo 14 and 16 electrophoresis demonstrations.

Kirk M. Sherhart, Berkley, Michigan
"Powder Flow"
Berkley High School, Helen Politzer, Teacher/Sponsor

To study the parameters involved in achieving the flow of powdered or granulated materials as opposed to liquids.

Detailed studies revealed that significant development problems existed that precluded production of hardware within the allowable time.

He was affiliated with the NASA researchers on material flow in zero gravity environment.

Gregory A. Merkel, Springfield,
"Brownian Motion"
Wilbraham and Monson Academy, Solon Economou, Teacher/Sponsor

To investigate the effect of zero gravity on the Brownian progression of a solute through its solvent. This experiment required a highly stable platform for time periods of up to a month. The Skylab was not capable of providing the required degree of stability.

He has indicated a strong interest in the field of astronomy. Thus, he was affiliated with Dr. Karl Henize, the principal investigator for S019--UV Stellar Astronomy.

James E. Healy, Bayport, New York
"Universal Gravity"
St. Anthony's High school, Dr. Paul E. Mottl, Teacher/Sponsor

To measure the mass attraction force (universal gravity) using a space qualified Cavendish balance.

The forces being measured were found to be at least three orders of magnitude less than the forces induced by the Skylab motions and, thus, were incapable of measurement.

He exhibited an interest in the effect of crew motion on the attitude stability of the Skylab. Thus, he was affiliated with Bruce Conway, the principal investigator on T013.

References

1. "MSFC Skylab Mission Report - Saturn Workshop", by the Skylab Project Office, MSFC, Huntsville, Alabama, NASA TM X-64814, October 1974

2. "Skylab Mission Report, First Visit", Johnson Space Center, Houston, Texas, NASA Report JSC-08414, August 1973

3. "Skylab Mission Report, Second Visit", Johnson Space Center, Houston, Texas, NASA Report JSC-08662, January 1974

4. "Skylab Mission Report, Third Visit", Johnson Space Center, Houston, Texas, NASA Report JSC 08963, July 1974

5. "Skylab Mission Report, Supplement 3, Flight Crew Contributions to the Skylab Mission", Johnson Space Center, Houston, Texas, NASA Report JSC-08963, July 1974

6. "Saturn V Launch Vehicle Evaluation Report", Marshall Space Flight Center, Huntsville, Alabama, NASA Report MPR-SAT-FE-73-4, August 1973

7. "Skylab 1 Post Launch Report", Kennedy Space Center, NASA Report RCS 76-000-00048, June 1973

8. "Flares Observed by the NRL/ARM Spectrograph and Spectroheliogram During the Skylab Missions", Sherrer, V. E. and Tousey, R. 1975, Proc. International Conf. on 'X-rays in Space', Vol II, 986, Univ. of Calgary

9. "Skylab 4 Visual Observations Project Report", J. L. Kaltenbach, W. B. Lenoir, M. C. McEwen, R. A. Weitenhagen, V. R. Wilmarth, Johnson Space Center, Report JSC-09053, NASA Report TM X-58142, Houston, Texas, June 1974

10. "Instrumented Personal Exercise During Long-Duration Space Flight", C. F. Sawin, J. A. Rummel, E. L. Michel, Journal of Aviation, Space and Environmental Medicine, Vol. 46 No. 4 p394-400, April 1975, Washington, D. C.

11. "NASA Investigation Board Report on the Initial Flight Anomalies of Skylab 1 on May 14, 1973", by Bruce T. Lundin, et al, Lewis Research Center, Cleveland, Ohio, July 1973

12. "Lessons Learned on the Skylab Program", by the Skylab Project Office, Marshall Space Flight Center, Huntsville, Alabama, NASA Report, February 22, 1974

13. "Lessons Learned on the Skylab Program", by the Skylab Program Office, Office of Manned Space Flight, NASA Headquarters, Washington, D. C., March 11, 1974

14. "Lessons Learned on the Skylab Program", by the Skylab Project Office, Kennedy Space Center, Florida, April 1, 1974

15. "Lessons Learned on the Skylab Program", by the Saturn Program Office, Marshall Space Flight Center, Huntsville, Alabama, February 22, 1974

16. "Lessons Learned on the Skylab Program", by the Skylab Project Office, Johnson Space Center, Houston, Texas, July 18, 1974

17. "Skylab News Reference", Office of Public Affairs, National Aeronautics and Space Administration, Washington, D. C., March 1973

18. "Proceedings of the Skylab Life Sciences Symposium", Johnson Space Center, Aug. 27-29, 1974, NASA Report, JSC-09275, TM X-48154 Volumes I and II, Houston, Texas, November 1974

19. "Proceedings of the Third Space Processing Symposium", Marshall Space Flight Center, April 30 - May 1, 1974, NASA Report, Huntsville, Alabama

20. "Proceedings of the Comet Kohutek Workshop", Edited by Gilmer A. Gary, Marshall Space Flight Center, June 13-14, 1974, NASA SP-355, Huntsville, Alabama, 1975

21. "Proceedings of the NASA Earth Resources Symposium", Johnson Space Center, June 8-12, 1975, To be published, Houston, Texas, 1976

22. "AIAA/AGU Conference on Science Experiments on Skylab", Marshall Space Flight Center, October 30 - November 1, 1974, To be published, Huntsville, Alabama, 1976

23. "Skylab Illustrated Chronology", Historical Staff, Management Services Office, Marshall Space Flight Center, NASA Report MHR 9A&PS-MS-H, Huntsville, Alabama, May 1, 1973

24. "Skylab Preliminary Chronology", Historical Staff, National Aeronautics and Space Admin., Compiled by Roland Newkirk, Report HHN-130, Washington, D. C., May 1973

25. "Apollo Applications Test Requirements", Apollo Applications Office Test Directorate, Office of Manned Space Flight, NASA, Washington, D. C. Report NHB 8080.3 October 1967, amended August 1972

Bibliography

1. "Skylab - Program Description," National Aeronautics and Space Administration (NASA), Washington, DC, October 1971, (U.S. Government Printing Office Stock No. 3300-0411)

2. "Astronautics and Aeronautics, 1971, Chronology of Science, Technology, and Policy," NASA, Washington, DC, 1972

3. "Astronautics and Aeronautics, 1972, Chronology of Science, Technology, and Policy," NASA, Washington, DC, 1974

4. "Astronautics and Aeronautics, 1973, Chronology of Science, Technology, and Policy," NASA, Washington, DC, 1975

5. "The Skylab Orbital Laboratory," William C. Schneider and William D. Green, Jr., Advances in Space Science and Technology, Academic Press, New York and London, 1972

6. "The Skylab Experiment Program," William C. Schneider and William D. Green, Jr., Advances in Space Science and Technology, Academic Press, New York and London, 1972

7. "Skylab Experiments," NASA, Office of Manned Space Flight, Washington, DC, August 1972

8. "Skylab - Pioneer Space Station," William G. Holder and William D. Siuru, Jr., Rand McNally, Chicago, 1974

9. "Skylab Earth Resources Data Catalog," NASA, Lyndon B. Johnson Space Center, Houston, Texas, 1974

10. "Skylab - A Manned Scientific Space Laboratory," a paper presented at the XXIInd International Astronautical Congress, Brussels, Belgium, by Leland F. Belew, NASA, George C. Marshall Space Flight Center, Huntsville, Alabama, September 1971

11. "The Quiet Sun," Edward G. Gibson, NASA, Manned Spacecraft Center, Houston, Texas, 1973

12. "Skylab Report: Man's Role in Space Research" by Owen K. Garriott, Science, Vol. 186, pp. 219-226, October 18, 1974

13. "Far-Out Comet Watching," by Stephen P. Maran, Sky Reporter, Natural History, October 1974

14. "Comet Kohoutek," a workshop held at the Marshall Space Flight Center, NASA SP-355, NASA, Washington, DC, 1975

15. "Observing Earth from Skylab," NASA Facts NF56/1-75, NASA, Washington, DC, 1975

16. "Skylab Preliminary Chronology," compiled by Roland Newkirk, Historical Office, NASA, Washington, DC, May 1973

17. "Skylab Illustrated Chronology," by David S. Akens, Historical Staff, George C. Marshall Space Flight Center, Huntsville, Alabama, MHR 9, May 1973

18. "Skylab - A Guidebook," by Leland F. Belew and Ernst Stuhlinger, EP 107, U.S. Government Printing Office, Washington, DC, 1973

19. "Skylab," by William C. Schneider, Yearbook of Science and Technology, 1975, McGraw Hill, New York, 1975

20. "The Skylab Results," edited by William C. Schneider and Thomas E. Hanes, Advances in Astronautical Sciences, Vol. 31, Part 1 and 2, American Astronautical Society, Tarzana, California, 1975

21. "Skylab and Pioneer Report," edited by Phillip H. Bolger and Paul B. Richards, Science and Technology Series, Vol. 36, American Astronautical Society, Tarzana, California, 1975

22. "Skylab Science Experiment," edited by George W. Morganthaler and G. E. Simonson, Science and Technology Series, Vol. 38, American Astronautical Society, Tarzana, California, 1975

23. "Skylab: An Experimental Space Station," by William C. Schneider, Scienza and Tecnica 73, Mondadori Publishing Co., Milan, Italy, 1973

24. "Saving Skylab," by William C. Schneider and William D. Green, Jr., Technology Review, Vol. 76, No. 3, Massachusetts Institute of Technology, Cambridge, Massachusetts, January 1974

25. "Technical Evaluation of Space Vehicles and Orbital Platforms," by William C. Schneider, XVIII International Congress on Transports and Communications, October 14, 1970, Genoa, Italy

26. "Skylab Status Report," by William C. Schneider, AIAA 7th Annual Meeting, Houston, Texas, October 1970

27. "The Impact of the Apollo Applications Program on Space Station Engineering," by William C. Schneider and William D. Green, Jr., Symposium on Space Stations, NASA, Langley Research Center, Langley Field, Virginia, February 1969

28. "The Impact of Apollo Applications on Space Station Engineering," by William C. Schneider and William D. Green, Jr., American Astronautical Society/Operations Research Society Joint National Meeting, Denver, Colorado, 1969

29. "Skylab Profiles," by John H. Disher, William D. Green, Jr., and Leland F. Belew, American Institute of Aeronautics and Astronautics, June 1971

30. "Skylab and its Solar Astronomy Experiments," by William C. Schneider, American Association for the Advancement of Sciences Annual Meeting, Philadelphia, Pennsylvania, 1971

31. "Early Results from Skylab I," unsigned, Journal of the American Aeronautics and Astronautics, September 1973

32. "Skylab II: Seeing the Sun in a Different Light," AIAA, Astronautics and Aeronautics, February 1974

33. "Skylab, Outpost on the Frontier of Space," By Thomas Y. Canby, National Geographic, October 1974 (also condensed in Reader's Digest, March 1975)

34. "Skylab Looks at Earth," by Thomas Y. Canby, National Geographic, October 1974

35. "The Sun as Never Seen Before," by Edward G. Gibson, National Geographic, October 1974