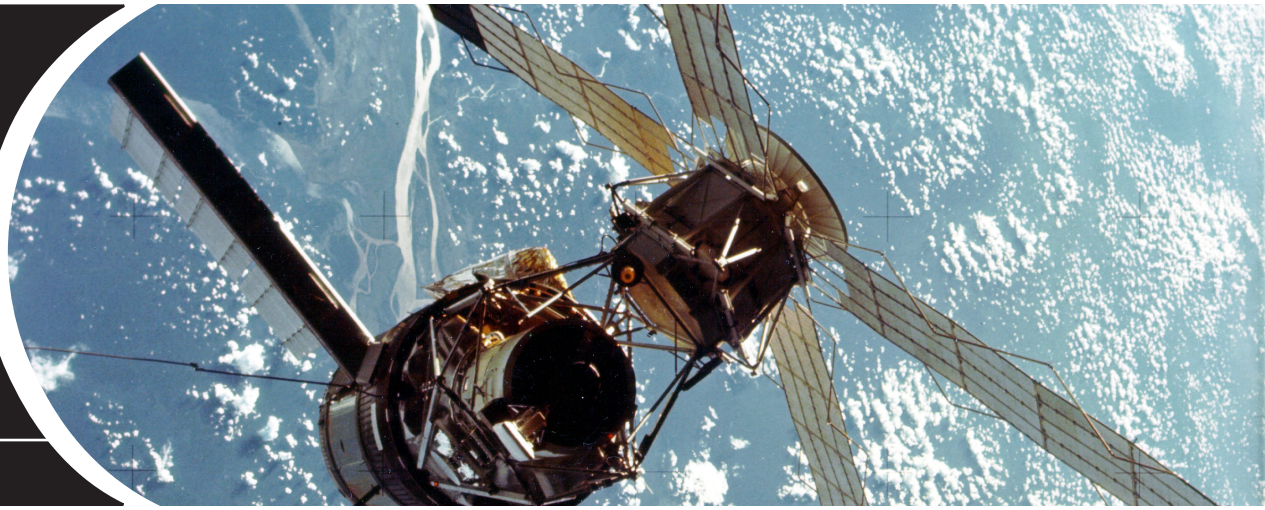
National Aeronautics and Space Administration



NASA SAFETY CENTER

SYSTEM FAILURE CASE STUDY

December 2014 *Volume 7 Issue 6*

Down, But Not Out

The Near-Loss and Recovery of America's First Space Station

PROXIMATE CAUSE

- Loss of the meteoroid shield destroyed SAS-2 and blocked deployment of SAS-1

UNDERLYING ISSUES

- Internal pressurization of auxiliary tunnel forced forward end of meteoroid shield away from the shell of the workshop
- Depiction of the meteoroid shield as an integral structural component during design phase permeated development and testing

AFTERMATH

- Recommendations from the Investigation Board
- Skylab was returned to a functional state after Skylab 2 mission repairs

May 14, 1973, Skylab soared into low Earth orbit from Kennedy Space Center (KSC) on a modified Saturn V (S-V) rocket. Whereas the launch of Skylab 1 was unmanned, Skylab 2, planned for launch the following day on May 15, would deliver a three-man crew to the station. However, once Skylab was in orbit and controllers initiated start-up procedures, it became apparent that the vehicle suffered damage during launch. Skylab 2 was postponed for 10 days. During those dire days, Skylab engineers scrambled to understand what went wrong and what they would do to fix it.

Background

Skylab's Mission

Skylab, the United States' first space station, was a program of unparalleled scientific scope—both as an orbital scientific laboratory and an off-world home for humanity. Skylab missions had several distinct focuses, including Earth resources observations, Sun and star studies, weightlessness studies, and Zero-G material processing.

Design and Planning

Skylab's largest element was its orbital workshop, a 48- by 22-foot cylindrical container that weighed nearly 78,000 pounds. The basic structure of the workshop was an upper S-IVB stage of the S-IB and S-V rockets—the workhorses of the Apollo program. The workshop had no engines, save for attitude control thrusters. It was modified internally to provide a large laboratory and living quarters for the crew.

Originally, designers planned for a "Wet Workshop" concept, where the specially constructed workshop was to be launched full of propellant as a "Wet" propulsive stage. Once empty of propellants and in orbit, the workshop would be purged and then filled with a life-supporting atmosphere. This design premise was based on the program using an S-IB launch vehicle.

A major design change was made July 22, 1969, 6 days after the Apollo 11 lunar landing. As a result of the successful lunar landing, S-V launch vehicles became available to the Skylab program. It was no longer necessary to launch the workshop as a propulsive stage. Engineers equipped the workshop for immediate occupancy while on the ground under the "Dry Workshop" design initiative.

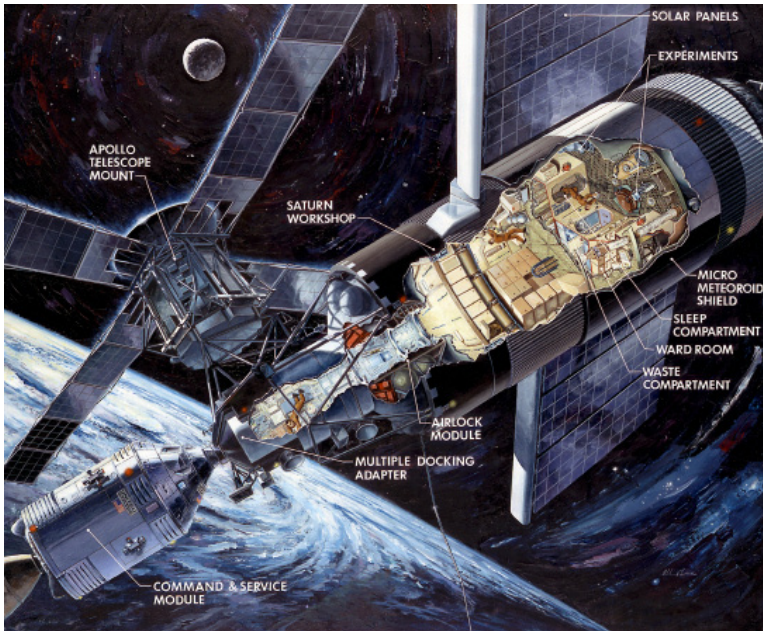


Figure 1. An artist's cutaway rendition of Skylab as it was intended (with both Solar Array Systems (SASs). Source: NASA

The nominal Skylab mission called for the launch of the unmanned S-V vehicle and workshop payload SL-1 into a near circular orbit. About 24 hours after the first launch, the manned Skylab 2 launch would occur using a command service module atop a SI-B vehicle. After rendezvous and docking, the crew would enter and activate the workshop.

Power and Protection

During the design stages of Skylab, Marshall Space Flight Center (MSFC) requested descriptions of "systems feasible as protection against probable meteoroids." This major concern of protecting the station from micrometeorite impacts resulted in a large, flexible external meteoroid shield that was added to cover the workshop. According to design criteria, the shield was to be a "structurally integrated part… capable of withstanding the dynamic forces imposed during the orbital workshop mission." In addition to providing meteoroid protection, the shield also served as a thermal barrier. Patterns of reflective and non-reflective paints covered all external surfaces of the shield in a carefully tailored design to control heat gains and losses.

For power, Skylab relied on a Solar Array System (SAS) that consisted of two large, three-section solar cell assemblies. Additionally, a third solar array was incorporated into the design of the observatory telescope. During launch, the assemblies were stored accordion-style inside beams that lay flat against the workshop and secured by tie-downs.

As Skylab 1 ascended through the atmosphere, seals attached to the SAS perimeter pressed against the meteoroid shield to keep it tight against the workshop. Once in orbit, the SAS assemblies were designed to deploy out 90 degrees from the workshop wall. After the ordnance release was fired, torsion rods and swing links would deploy the meteoroid shield out 5 inches from the workshop wall.

What Happened

Initial Flight Anomalies

Approximately 63 seconds into the flight of Skylab 1, numerous measurements indicated an early deployment and loss of the meteoroid shield and unlatch of the SAS-2 assembly. This occurred approximately at an altitude of 28,600 feet and velocity of Mach 1. Controllers also recorded abnormal meteoroid shield temperatures. At 190 seconds, the interstage second plane failed to separate. Sufficient thrust margin existed to achieve desired orbit.

Ten minutes after launch, the workshop stage separated from the launch vehicle. Eight seconds later, the workshop entered its nearly circular orbit above Earth and initiated a deployment and activation sequence. A shield protecting the refrigeration system radiator was jettisoned, and the workshop was maneuvered so the radiator was facing away from the Sun. Controllers activated the refrigeration system and then jettisoned the payload shroud. Fortunately, the four solar arrays of Skylab's solar telescope observatory deployed according to procedure. Skylab was then maneuvered to a "solar inertial" attitude, where the SAS and solar observatory would always face the Sun (Skylab did not roll like the Apollo craft, but remained in one position so that experiments could be conducted properly). Power from these arrays allowed controllers to operate the station at a minimum level.

The next event was deployment of the SAS and meteoroid shield. However, as Skylab went out of contact with ground tracking stations for the first time, controllers had not received the deployment signal from the shield or SAS. When Skylab came back into contact 15 minutes later, controllers still waited for the signal. As temperature readings rose, engineers concluded that the 63-second signal anomaly was a likely indicator that the meteoroid shield was lost.

The gold foil that coated the workshop exterior was designed to maintain the required balance of absorption and emission of heat between the meteoroid shield and workshop. Gold foil is highly absorbent to solar energy and possesses a very low heat loss rate. With the shield lost and the gold surface of the workshop exposed to the Sun, temperatures in the workshop rose over 200° F higher than it had been designed to withstand.

Proximate Cause

After reviewing evaluated telemetry data, the NASA Investigation Board reported that the most probable cause of the flight anomaly was the breakup and loss of the meteoroid shield as a result of aerodynamic loads unaccounted for in Skylab's design. The breakup

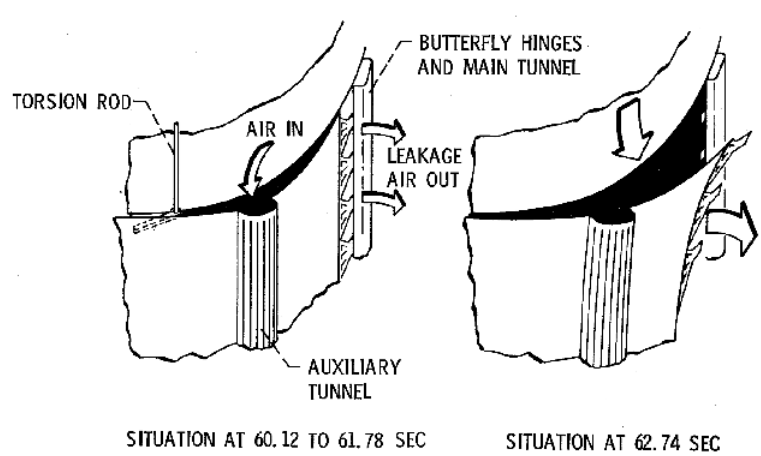


Figure 2. Possible meteoroid shield motion from 60.12 to 62.74 seconds. Source: NASA

of the shield broke the tie-downs securing solar array SAS-2 to the workshop. SAS-2 was completely lost 593 seconds into the flight when the exhaust plume of the S-II stage retro-rockets impacted the partially deployed array. Debris from the meteoroid shield also damaged the S-II interstage adapter ordnance system, preventing separation. Data later in the flight indicated the SAS-1 wing did not fully deploy.

Underlying Issues

Of the several possible failure modes of the meteoroid shield, the most probable was that the internal pressurization of the auxiliary tunnel forced the forward end of the shield away from the shell of the workshop and into the supersonic air stream. The pressurization of the auxiliary tunnel resulted from the admission of high-pressure air into the tunnel through several openings in the aft end (i.e., an imperfect fit of the tunnel with the aft fairing, an open boot seal between the tunnel and tank surface, and open stringers on the aft skirt under the tunnel). The venting analysis for the auxiliary tunnel was predicated on a completely sealed aft end; the openings in the tunnel resulted from a failure of communication among aerodynamics, structural design, and manufacturing personnel.

Despite 6 years of design, review, and testing, the project team failed to recognize the shield's design deficiency because they presumed the shield would be tight to the tank and structurally integrated as set forth in the design criteria. The shield system proved to be difficult to rig and obtain a close fit as designed. Handling such a large, lightweight structure required the coordinated action of a large group of technicians, and considerable adjustments to the assembly of the various panels were necessary to obtain a snug fit between the shield and workshop wall. Because of the difficulty of rigging the shield tight to the tank, engineers at KSC wrote Discrepancy Report DR 180. The report mapped the area of gaps between the shield and workshop and cited the Material Review Board's (MRB's) disposition to "use as is." Since the flight differential pressure was substantially higher than 8 psi, Skylab engineers believed the contact area during flight would be higher than 95 percent. The meteoroid shield was formally accepted as satisfactory for flight on January 10, 1973. No further adjustments to it were made prior to flight.

The shield's design deficiencies and the failure to communicate the critical nature of proper shield venting are attributed to an absence of sound engineering judgment and alert engineering leadership concerning the shield system over a considerable period of time.

The board found no evidence to suspect the design, development, and testing of the meteoroid shield was compromised by schedule or funding limitations. Aerodynamic, vibration, acoustic, and flutter tests were omitted from test specifications: a choice predicated on the "tight to the tank" design requirement and philosophy. The overarching management system used for Skylab was essentially the same as used for the Apollo program—and was fully operational for Skylab. No inconsistencies or conflicts were found in management records. What may have affected the oversight of the aerodynamic loads was the view that the shield was a structural component, rather than a complex system involving several distinct technical disciplines.

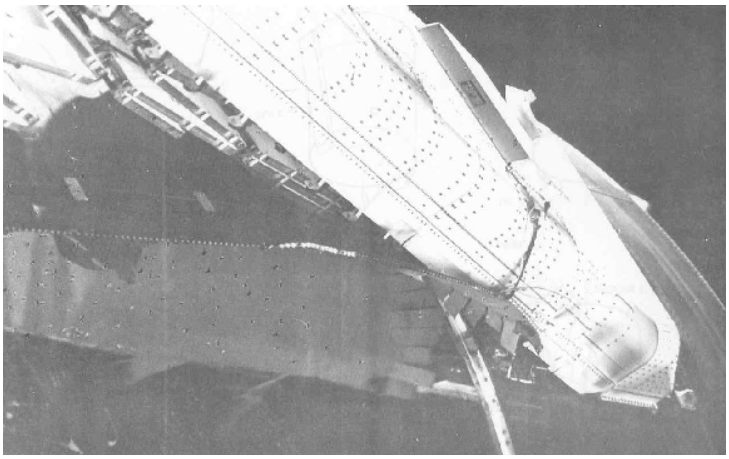


Figure 3. Photograph from orbit showing longitudinal aluminum angle bent over the SAS-1 wing. This angle was later cut, releasing SAS-1 for full deployment. Source: NASA

Aftermath

Damage Assessment and Planning

Skylab 2, scheduled for the following day, was postponed for 10 days to allow time for engineers to analyze the problem and possible solutions. While Apollo 11 was the apex of high stress missions for operators, Skylab 2 proved to be the equivalent for engineers.

Without the meteoroid shield to act as a sunshade, ground controllers maneuvered the space station to reduce the effect of the Sun's rays. In doing so, they had to balance thermal relief while also placing the working solar array of the observatory in a position where it could maintain effectiveness. After placing the workshop at a 45-degree angle from the Sun, solar power was decreased to 2800 watts (barely meeting attitude control and communication system requirements) and the interior temperature of Skylab stabilized around 130° F. Skylab's large gyroscopes (the first to be used on a spacecraft to control attitude and precision instrument pointing) played a pivotal role in maintaining the emergency positions for the station.

To preserve the workshop, engineers investigated several possible thermal barriers including thermal coatings, plastic shades, and fabric awnings. Engineers finally decided on a parasol variation of the fabric awning device as the primary choice (as it would not require astronauts to venture outside Skylab) and a two-pole awning as a backup or supplementary shield. Engineers also worked fervently to develop tools for the astronauts to use during Extra-Vehicular Activities (EVAs) to free debris from the damaged SAS-1 array. Finally, the other great concern was that Skylab's polyurethane foam insulation might have decomposed under the intense heat, creating a lethal environment inside the workshop.

Skylab 2

Skylab 2 launched on a Saturn IB rocket on May 25, 1973 from KSC, carrying a three-man crew to the damaged station. The crew took with them several solar shades and a variety of tools and cutters designed to free the jammed solar array. Eight hours later, as Skylab 2 closed the distance, the crew filmed and described Skylab's condition, confirming SAS-1 as partially deployed and SAS-2 as missing. The Skylab 2 crew attempted orbital repair to unpin SAS-1 but initial attempts failed.

The crew went so far as to perform a stand-up EVA, where one crew member tried tugging at the array with a 10-foot hooked pole while standing in the airlock recess with legs held by another crew member. This daring maneuver consumed a significant amount of maneuvering fuel from both the Skylab station and Skylab 2 vehicle. The crew experienced significant difficulty in docking with the Skylab station. After eight failed docking attempts, they successfully docked, ending their first day in orbit after 22 hours elapsed mission time.

The next day, on May 26, the crew entered Skylab and tested for noxious and toxic gases. The atmosphere proved safe for occupancy; and although the temperature was 126° F, the humidity was low enough for the crew to work for periods of 5 hours at a time. The crew deployed a parasol solar shade through an airlock in the side of the workshop. The 22- by 24-foot parasol composed of nylon, Mylar, and aluminum reflected enough solar energy to lower workshop temperatures. This allowed ground controllers to reposition Skylab at an attitude that immediately increased station power.

Two weeks later, on June 7, in attempts to relieve the overworked observatory solar array batteries, the crew assembled a 25-foot-long aluminum pole with a cable cutter tool on the end to sever the debris pinning the SAS-1 assembly. They had prepared for this repair by practicing in the Neutral Buoyancy Simulator at MSFC. Without power from the array, the second and third Skylab missions would have been unable to perform their main experiments, and the station's critical battery system would have been seriously degraded. With effort, the crew was able to fully deploy the SAS-1 assembly, increasing station power from 4000 to 7000 watts, assuring that Skylab would be able to carry out its scientific mission. During this EVA, the repair activities caused astronauts on the EVA to be flung far out from the station repeatedly, only to be saved by their safety tethers. For nearly a month, the crew made further repairs to the workshop, conducted medical experiments, gathered solar and Earth science data, and performed a total of 392 hours of experiments. The Skylab 2 astronauts spent 28 days in space, which doubled the previous U.S. record. Skylab 2 set a record for human spaceflight duration and proved that human beings, properly trained and equipped, could carry out complex and difficult repairs in space.

Relevance to NASA

Complex, multidisciplinary systems such as Skylab's meteoroid shield should have a designated project engineer who is responsible for all aspects of analysis, design, fabrication, test and assembly. The board found no evidence that the design deficiencies of the meteoroid shield were the result of, or masked by, the management systems used for Skylab. On the contrary, the rigor and detail of the systems area were a doubtless necessity for a program of Skylab's magnitude.

Concurrently, the investigation board emphasized that management must always be alert to the potential hazards of its systems and take care that an attention to rigor and detail does not inject an undue emphasis on formalism, documentation, and visibility. According to the board, such an emphasis could submerge intuitive thought processes of engineers or analysts.

Achieving a cross-fertilization and engineers' experience in analysis, design, test, or operations will always be important. Positive steps must always be taken to assure that engineers become familiar with actual hardware, develop an intuitive understanding of computer-developed results, and make productive use of flight data in the learning process. The role of chief engineer also can be a major asset to an engineering organization. The chief engineer can spend the majority of their time reviewing the subtle integration of all elements of a given system, free of administrative and managerial duties. Moreover, with regard to Skylab, the board suggested simplifying the design if a backup orbital workshop or similar spacecraft was to be flown, for example, omitting the shield and coating the workshop for thermal control, and relying on the workshop tank walls for meteoroid protection. (It is now known that meteoroid flux levels are considerably lower than those used in original Skylab calculations.)

Furthermore, the board offered suggestions for future management teams concerning engineering. Deployable structures that must move, or involve other mechanisms or devices, should not be considered a structural piece with responsibility placed on a structures organization. Managers must continuously strive to counteract the natural tendency of engineers to believe that a drawing is the real world. Firsthand experience with how hardware behaves and can fail is essential to design engineers.

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