The Initial Flight Anomalies of Skylab 1

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By the NASA Investigation Board

At approximately 63 seconds into the flight of Skylab 1 on May 14, 1973, an anomaly occurred which resulted in the complete loss of the meteoroid shield around the orbital workshop. This was followed by the loss of one of the two solar array systems on the workshop and a failure of the interstage adapter to separate from the S-II stage of the Saturn V launch vehicle. The investigation reported herein identified the most probable cause of this flight anomaly to be the breakup and loss of the meteoroid shield due to aerodynamic loads that were not accounted for in its design. The breakup of the meteoroid shield, in turn, broke the tie downs that secured one of the solar array systems to the workshop. Complete loss of this solar array system occurred at 593 seconds when the exhaust plume of the S-II stage retro-rockets impacted the partially deployed solar array system. Falling debris from the meteoroid shield also damaged the S-II interstage adapter ordnance system in such a manner as to preclude separation.

Of several possible failure modes of the meteoroid shield that were identified, the most probable in this particular flight was internal pressurization of its auxiliary tunnel which acted to force the forward end of the meteoroid shield away from the shell of the workshop and into the supersonic air stream. The pressurization of the auxiliary tunnel was due to the existence of several openings in the aft region of the tunnel. Another possible failure mode was the separation of the leading edge of the meteoroid shield from the shell of the workshop (particularly in the region of the folded ordnance panel) of sufficient extent to admit ram air pressures under the shield.

The venting analysis for the auxiliary tunnel was predicated on a completely sealed aft end; the openings in the tunnel thus resulted from a failure of communications among aerodynamics, structural design, and manufacturing personnel. The failure to recognize the design deficiencies of the meteoroid shield through six years of analysis, design and test was due, in part, to a presumption that the shield would be "tight to the tank" and "structurally integral with the S-IVB tank" as set forth in the design criteria. In practice, the meteoroid shield was a large, flexible, limp system that proved difficult to rig to the tank and to obtain the close fit that was presumed by the design. These design deficiencies of the meteoroid shield, as well as the failure to communicate within the project the critical nature of its proper venting, must therefore be attributed to an absence of sound engineering judgment and alert engineering leadership concerning this particular system over a considerable period of time.

The overall management system used for Skylab was essentially the the same as that developed in the Apollo program. This system was fully operational for Skylab; no conflicts or inconsistencies were found in the records of the management reviews. Nonetheless, the significance of the aerodynamic loads on the meteoroid shield during launch were not revealed by the extensive review process. Possibly contributing to this oversight was the basic view of the meteoroid shield as a piece of structure, rather than as a complex system involving several different technical disciplines. Complex, multidisciplinary systems such as the 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 were masked by, the content and processes of the management systems that were used for Skylab. On the contrary, the rigor, detail, and thoroughness of the systems are doubtless necessary for a program of this magnitude. At the same time, as a cautionary note for the future, it is emphasized that management must always be alert to the potential hazards of its systems and take care that an attention to rigor, detail and thoroughness does not inject an undue emphasis on formalism, documentation, and visibility in detail. Such an emphasis can submerge the concerned individual and depress the role of the intuitive engineer or analyst. It will always be of importance to achieve a cross-fertilization and broadened experience of engineers in analysis, design, test or operations. 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 this learning process. The experienced chief engineer, who can spend most of the time in a subtle integration of all elements of the system under purview, free of administrative and managerial duties, can also be a major asset to an engineering organization.

THE SKYLAB PROGRAM

Skylab missions have several distinct goals: to conduct Earth resources observations, advance scientific knowledge of the sun and stars, study the effects of weightlessness on living organisms, particularly human, and study and understand methods for the processing of materials in the absence of gravity. The Skylab mission utilizes the astronaut as an engineer and as a research scientist, and provides an opportunity for assessing potential human capabilities for future space missions.

Skylab uses the knowledge, experience and technical systems developed during the Apollo program along with specialized equipment necessary to meet the program objectives.

Figure 1 shows the Skylab in orbit. Its largest element is the orbital workshop, a cylindrical container 48 feet long and 22 feet in diameter weighing some 78,000 pounds. The basic structure of the orbital workshop is the upper stage, or S-IVB stage, of the S-IB and S-V rockets which served as the Apollo program launch vehicle. The orbital workshop has no engines, except attitude control thrusters, and has been modified internally to provide a large orbiting space laboratory and living quarters for the crew. The Skylab 1 (SL-1) space vehicle included a payload consisting of four major units—orbital workshop, airlock module, multiple docking adapter, Apollo telescope mount—and a two-stage Saturn-V (S-IC and S-II) launch vehicle as depicted in Figure 2. To provide meteoroid protection and thermal control, an external meteoroid shield was added to cover the orbital workshop habitable volume. A solar array system (SAS) was attached to the orbital workshop to provide electrical power.

The original concept called for a "wet workshop." In this concept, a specially constructed S-IVB stage was to be launched "wet" as a propulsive stage on the S-IB launch system filled with propellants. The empty hydrogen tank would then be purged and filled with a life-supporting atmosphere. A major redirection of Skylab was made on July 22, 1969, six 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. Consequently, it became feasible to completely equip the S-IVB on the ground for immediate occupancy and use by a crew after it was in orbit. Thus it would not carry fuel and earned the name of "dry workshop."

The nominal Skylab mission called for the launch of the unmanned S-V vehicle and workshop payload SL-1 into a near-circular (235 nautical miles) orbit inclined 50 degrees to the equator. About 24 hours after the first launch, the manned Skylab 2 (SL-2) launch would take place using a command service module payload atop the S-IB vehicle. After the command service module rendezvous and docking with the orbiting cluster, the crew enters and activates the workshop; Skylab is then ready for its first operational period of 28 days. At the end of this period, the crew returns to Earth with the command service module, and the Skylab continues in an unmanned quiescent mode for some 60 days. The second three-person crew is launched with a second S-IB, this time for a second 56-day period in orbit after which they will return to Earth. The total Skylab mission activities cover a period of roughly eight months, with about 140 days of manned operation.

THE FLIGHT OF SKYLAB 1

Skylab 1 was launched at 1730:00 (range time, R=0) on May 14, 1973, from Complex 39 A, Kennedy Space Center. At this time, the Cape Kennedy launch area was experiencing cloudy conditions with warm temperatures and gentle surface winds. Total sky cover consisted of scattered cumulus at 2,400 feet, scattered stratocumulus at 5,000 feet, broken altocumulus at 12,000 feet, and cirrus at 23,000 feet. During ascent, the vehicle passed through the cloud layers but no lightning was observed in the area. Upper area wind conditions were being compared to

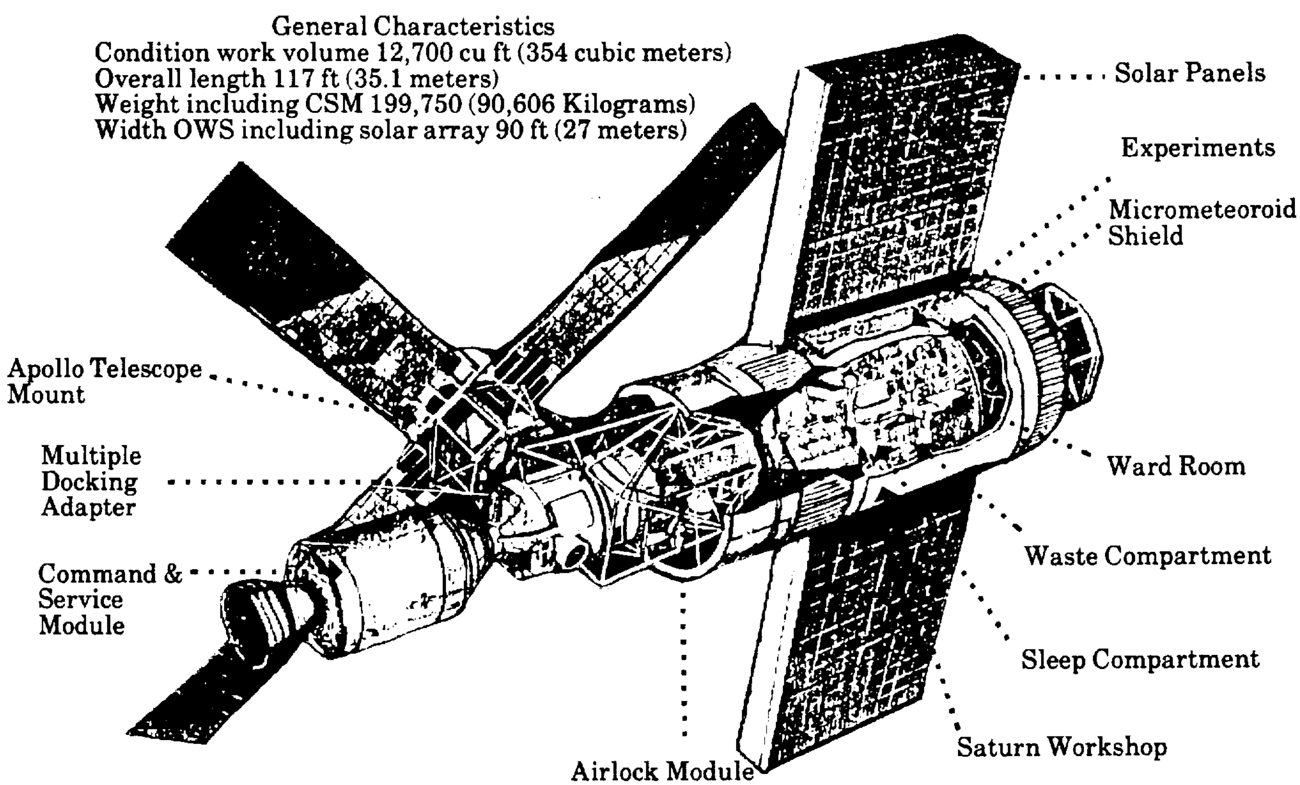

Figure 1 Skylab Cluster

PS Payload Shroud
Diameter 6.6 meters (21.7 feet)
Length 16.8 meters
Weight 11,794 kilograms (26,000 lbs.)

ATM Apollo Telescope Mount
Wi Width 3.3 meters
Length 4.4 meters
Weight 11.181 kilograms (24,650 lbs.)

MDA Multiple Docking Adapter
Diameter 3 meters (1o feet)
Length 5.2 meters (17.3 feet)
Weight 6,260 kilograms (13,800 lbs.)

AM Airlock Module
Diameter STS 3 meters (10 feet)
Diameter FAS 6.6 meters (21.7feet)
Length 5.3 meters (17.5 feet)
Weight 22,226 kilograms (49,000 lbs.)

IU Instrument Unit
Diameter 6.6 meters (21.7 feet)
Length 0.9 meter (3 feet)
Weight 2,064 kilograms (4,550 lbs.)

OWS Orbital Workshop
Diameter 6.6 meters (21.7 feet)
Length 14.6 meters (48.5 feet)
Weight 35,380 kilograms (78,000 lbs.)

S-II Second Stage
Diameter 10 meters (33 feet)
Length 24.8 meters (81.5 feet)
Weight 488,074 kilograms (1,076,000 lbs.) fueled
35,403 kilograms (78,050 lbs.) dry
Engines J-2 (5)
Propellants: Liquid Oxygen 333,837 liters (88,200 gallons)
Liquid Hydrogen 1,030,655 liters (272,300 gallons)
Thrust 5,150,000 Newtons (1,150,000 lbs.)
Interstage Approx. 5,171 kilograms (11,400) lbs.)

S-IC First Stage
Diameter 10 meters (33 feet)
Length 42 meters (138 feet)
Weight 2,245,320 kilograms (4,950,000 lbs.) fueled
130,410 kilograms (287,500 lbs.) dry
Engines F-1 (5)
Propellants: Liquid Oxygen 1,318,315 liters (348,300 gallons)
RP-1 (Kerosene) 814,910 liters (215,300 gallons)
Thrust 31,356,856 Newtons (7,723,726 lbs.)

Figure 2 SL-1 vehicle

most other Saturn-V flights. The flight environment was quite favorable.

The automatic countdown proceeded normally with Guidance Reference Release occurring at R-17.0 seconds and orbit insertion occurring at R+599.0 seconds. The orbital workshop solar array deployment was commanded on time; however, real-time data indicated that the system did not deploy fully.

The solar array system (SAS) on the orbital workshop consists of two large beams enclosing three major sections of solar cell assemblies within each. During ascent, the sections are folded like an accordion inside the beams which in turn are stowed against the workshop. The meteoroid shield is a lightweight structure wrapped around the converted S-IVB stage orbital workshop and is exposed to the flight environment. The two hinged solar array system wings are secured to the orbital workshop by tie downs above and below the meteoroid shield. Seals attached to the solar array system perimeter actually press against the shield to form an airtight cavity prior to launch. Once in orbit, the solar array system beams are first deployed out 90 degrees. The meteoroid shield is deployed later to a distance of about five inches from the orbital workshop wall. After the ordnance release is fired, meteoroid shield deployment is effected by torsion rods and swing links spaced around the structure fore and aft. The rods are torqued prior to launch and simply unwind in orbit to move the meteoroid shield away from the tank, Detection of pertinent conditions associated with the meteoroid shield and solar array system is afforded by measuring various parameters by telemetered instrumentation.

When the orbital workshop solar array system was commanded to deploy, telemetered data indicated that events did not occur as planned. The flight data was analyzed by flight operations personnel to reveal the possible source of the problem. At about R+60 seconds, the S-II telemetry reflected power increased slightly. At about 63 seconds, numerous measurements indicated the apparent early deployment and loss of the meteoroid shield. At this time, the vehicle was at about 28,600 feet altitude and at a velocity of about Mach 1.

At this time, vehicle dynamic measurements such as vibration, acceleration, attitude error, and acoustics indicated strong disturbances. Measurements which are normally relatively static at this time, such as torsion rod strain gauges, tension strap breakwires, temperatures, and solar array system position indicators, indicated a loss of the meteoroid shield and unlatch of the SAS-2 wing. Further preliminary evaluation revealed abnormal vehicle accelerations, vibrations, and solar array system temperature and voltage anomalies at about R+593 seconds. Temperature data loss and sudden voltage drops indicated that the SAS-2 wing was separated from the orbital workshop at this time. Other data later in the flight indicated the SAS-1 wing did not fully deploy when commanded to do so. Although not apparently associated with the 63-second and 593-second anomalies, the S-II stage range safety receiver signal strengths showed several drops throughout the flight beginning at about R+260 seconds.

63-Second Anomaly: Loss of Meteroid Shield

The Investigation Board evaluated the telemetry data in order to explain the various anomalies that occurred on Skylab 1. The first anomalous indication was an increase in S-II telemetry reflected power from a steady 1.5 W beginning at R+59.80 seconds. At this time the telemetry forward power remained steady at 58.13 W. By 61.04 seconds, the reflected power had reached 1.75 W, and by 80.38 seconds, the reflected power had stabilized at about 2.0 W. This abnormal increase in power might be indicative of a vehicle physical configuration change which altered the antenna ground plane characteristic.

Shortly after the telemetry reflected power increase, the meteoroid shield torsion rod 7 forward (measurement G7036) indicated a slight change toward the deployed condition. This occurred at R+60.12 seconds, and at 61.78 seconds the vehicle roll rate decreased slightly from a normal value of 1.1 degrees per second clockwise looking forward. The next torsion rod 7 forward sample at about 62.52 seconds revealed a further relaxation. The increase in telemetry reflected power and the movement of torsion rod 7 forward tend to indicate meteoroid shield lifting between positions I and II.

Between R+62.75 and 63.31 seconds, several vehicle dynamic measurements indicated a significant disturbance. A sensor on the orbital workshop film vault showed an abnormal vibration at 62.75 seconds followed by disturbances sensed by X and Y accelerometer pickups in the instrument unit, the pitch, yaw, and longitudinal accelerometers, and the pitch, yaw, and roll rate gyros. At 62.78 seconds, the roll rate gyro sensed a sudden clockwise roll rate resulting in a peak amplitude of 3.0 degrees per second clockwise 62.94 seconds. A sensor at the instrument unit upper mounting showed a maximum peak-to-peak shock of 17.2 g's at 63.17 seconds. In addition, the S-II engine actuators experienced pressure fluctuations caused by vehicle movement against the inertia of the non-thrusting engine nozzles.

The data indicate that the most probable sequence of meteoroid shield failure was initial structural failure of the meteoroid shield between the SAS-2 wing and the main tunnel (between positions I and II). The initial failure propagation from this area appears likely since the wardroom window thermocouple indication (C7013) remained normal at 62.94 seconds after SAS-2 indicated unlatched at 62.90 seconds and after the K7010 and K7011 tension strap measurements failed.

593-SECOND ANOMALY

As a consequence of the meteoroid shield failure at approximately 63 seconds, the SAS-2 wing was unlatched and partially deployed as evidenced by minor variations in the main solar array system electrical voltages and SAS-2 temperatures. Full deployment was prevented due to the aerodynamic forces and accelerations during the remainder of powered flight.

At the completion of the S-II phase of flight, the four 35,000-pound thrust retrorockets fired for approximately two seconds commencing at R+591.10 seconds followed by spacecraft separation at 591.2 seconds. The effect of retro-rocket plume impingement was observed almost immediately on the SAS-2 temperature and on vehicle body rates.

At 593.4 seconds the wing imparted momentum to the vehicle, probably by hitting and breaking the 90 degree fully deployed stops, and at 593.9 imparted a final kick as it tore completely free at the hinge link. In-orbit photographs show clearly the hinge separation plane and the various wires which were torn loose at the interface.

INTERSTAGE SECOND PLANE SEPARATION ANOMALY

Post-flight analysis revealed unexpectedly high temperatures and pressures in the S-II engine compartment following ignition and continued high after interstage separation command. The unusually high temperatures from S-II ignition and until the S-II interstage separation signal are considered by Marshall Space Flight Center (MSFC) to be caused by a change in the engine heat shield skirts introduced on this flight, and therefore do not indicate a problem. However, the increasing temperatures after the time of normal S-II interstage separation are indicative of an abnormal condition. More detailed investigation based on performance evaluation and axial acceleration time history revealed that the interstage had not been jettisoned; however, due to the vehicle performance characteristics and performance margin, the desired orbit was achieved.

Data analysis confirms that the primary ordnance command was properly issued at R + 189.9 seconds. The backup command was issued 100 milliseconds later but the exploding bridge wire circuit discharge was characteristic of an open circuit consistent with separation of the interstage disconnect by a minimum of 0.25 inch.

The linear shaped charge is mounted circumferentially around the S-II interstage. When fired by the primary command, the charge cuts the tension straps (in the direction of position II to position I) allowing the skirt to drop away. Normal propagation time of the linear shaped charge is approximately four milliseconds. Assuming a failure to propagate completely around the structure, analyses were made by appropriate contractor and government personnel to determine what area must remain intact in order to retain the skirt and what area must have been cut to allow rotation of the skirt sufficient to disconnect the connector panel. The various analyses isolate the region of failure to an arc extending from approximately $\Theta = 100$ degrees to as much as $\Theta = 200$ degrees.

This ordnance installation was different from prior Saturn flights. Previously, a single fire command from the instrumentation unit was issued which simultaneously detonated the linear shaped charge from both ends allowing the charge to propagate from both directions. On this flight, in an attempt to provide redundant firing commands, the detonators at each end of the linear shaped charge were separately connected to two command channels spaced 100 milliseconds apart due to the characteristics of the airborne equipment. As a result of the partial cutting of the interstage, it rotated sufficiently to separate the electrical connector prior to issuing the backup command.

A review of the history of manufacturing, acceptance, checkout, qualification and flight environment revealed no basic cause for failure. The most probable cause is secondary damage as a result of the meteoroid shield failure, attributed to falling debris as evidenced by the various shock and acoustic disturbances occurring in the 63-second time period.

The redundant mode of ordnance operation of all prior Saturn flights in which both ends of the linear shaped charge are fired at once from a single command would probably have prevented the failure, depending on the extent of damage experienced by the linear shaped charge.

FORWARD INTERSTAGE INTERNAL PRESSURE ANOMALY

Flight data indicated a deviation of the S-II forward interstage pressure from analytical values commencing at approximately 63 seconds. Inasmuch as the deviation from the analytical curve of the internal pressure versus time appeared to be coincident with the meteoroid shield failure, it was postulated that a portion of the shield had punctured the forward interstage. On this basis, it was possible to correlate the flight data with either an assumed 2.0 square foot hole in the conical section or an assumed 0.75 square foot hole in the cylindrical section.

RANGE SAFETY RECEIVER ANOMALY

During the S-II portion of the flight, the signal strength indications from both range safety receivers showed drops in level. From liftoff through R + 259 seconds, both receivers maintained relatively stable values above range requirements. At R + 259.57 seconds, receiver 2 signal strength began to drop and between this time and 522.1 seconds, both receivers indicated various degrees of signal strength shift. These signal strength shifts dropped below the 12 db safety margins required by Air Force Eastern

Test Range Manual 127-1. At R+327.81 seconds the receiver 2 signal strength dropped briefly below its threshold sensitivity. At this instant this receiver probably would not have responded to any range safety commands. Receiver 1 was, however, capable of receiving commands. At R+521.16, receiver 2 strength again dropped briefly to its threshold sensitivity. None of these drops could be correlated to ground system performance.

Analysis indicates that the most probable cause of the S-II receiver signal strength dropout was a variable phase shift within the vehicle's hybrid coupler due to the changing aspect angle produced by the moving vehicle and the fixed transmitting site. Because the decrease in receiver signal strength occurred with only one receiver at a time, range safety commands could have been received continuously throughout power flight. During two of these drops, however, the planned redundancy of range safety receivers was not available.

During this investigation, it was revealed that the Wallops Island and Bermuda ground stations did not continuously record ground transmitter power levels. The Board considers that such continuous recordings would be of value.

THE METEOROID SHIELD DESIGN

Although fairly simple in concept, the meteoroid shield had to provide such a variety of functions that it was, in fact, a quite complicated device. It was, foremost, a very lightly built cylindrical structure 270 inches in diameter (in the deployed condition) by 265 inches long.

In brief, the meteoroid shield is formed of a set of sixteen curved sheets of 2014 T6 aluminum panels, 0.025 inches thick, assembled at flanges and other fittings to form the cylinder shown. The forward and aft ends were reinforced with curved 7075 T6 angles.

Various special details were included in the assembly in order to hold it in place, deploy it in orbit, and provide access to the orbital workshop interior during prelaunch activities. The principal means of holding the shield in place in orbit (and to a lesser extent during powered flight) was a set of tension straps under the main tunnel. These straps were bonded to the orbital workshop wall and fitted with a hinge on each end to take the butterfly hinge that attaches to the adjacent meteoroid shield panel. These butterfly hinges were designed to rotate so as to lie against the sides of the main tunnel which enclosed the tension straps and various cable runs on the orbital workshop.

Clockwise from the tension straps and butterfly hinge, the next special feature is the auxiliary tunnel. This tunnel extends in an arch between panels of the thin meteoroid shield. The 28 titanium frames of this tunnel provide a very springy section in the relatively rigid hoop provided by the rest of the shield. The auxiliary tunnel also encloses a smaller tunnel covering the wiring for the thruster attitude control system. Farther around, in position I, there are two curved rectangular smaller panels, included to provide access to the orbital workshop.

Between positions I and IV, the two halves of the meteoroid shield overlap and are joined by a series of 14 trunnion bolts and straps. These trunnion bolts were used to adjust the tension with which the shield was held against the orbital workshop. Adjusting the bolts in the trunnion assemblies was a major aspect in positioning and tightening the meteoroid shield against the orbital workshop (rigging).

In order to provide the extra 30 inches of perimeter required when the meteoroid shield was deployed, a foldout panel assembly is included in the panel adjacent to the trunnions. The only remaining distinctive features of the meteoroid shield are the panels located over the scientific airlock and wardroom window at position III. The meteoroid shield is completed at the butterfly hinges and tension straps at position I.

Deployment Provisions

The deployment of the 265-inch-long meteoroid shield was accomplished by providing two folding panel sections on each side of a contained explosive pyrotechnic chain which extended axially for the full length of the shield except for short end reinforcements. When the ordnance strip is fired and separates the fold-over panel, the segments are released and the shield is deployed. After release of this folded panel, a number of swing arms are used to displace the shield away from the orbital workshop wall and hold it there. A rotational force is applied to these swing arms by a total of sixteen torsion rods suitably spaced around the ends of the meteoroid shield. When the meteoroid shield is stowed for launch, there is a larger twist in the torsion rods than after deployment. The links on one side of the ordnance chain swing in a direction opposite to those on the other side. The butterfly hinges on each side of the main tunnel permit the radial displacement of the shield at the location of the tension straps.

The meteoroid shield should therefore be regarded as a very limp system, which depends on being stretched tight around the orbital workshop to withstand the aerodynamic, vibratory, flutter and thrust loads at launch. After deployment, it needs very little strength to serve its primary objective as a meteoroid shield.

The Auxiliary Tunnel

The auxiliary tunnel extends from the forward skirt, down the full length of the meteoroid shield shield, and below the meteoroid shield by about 57 inches. Venting of this tunnel was provided through an outlet of 10 square inches under the corrugations of the tunnel cover at the aft end of the forward fairing. The tunnel was intended to be sealed at the aft end by a rubber boot assembly in both the stowed and deployed position. Note that the tunnel is displaced some 5 or 6 inches circumferentially upon deployment of the shield.

The main structural members of the auxiliary tunnel are titanium, arch-shaped, frame springs. These frames provide the structural tie between two meteoroid shield panels and provide both regulation of the pre-loading of the meteoroid shield to the orbital workshop and act as a flexible relief for diametrical changes resulting from thermal and pressure changes of the orbital workshop.

The tunnel also serves to protect the thrust attitude control system cables located in a small channel-shaped cover permanently attached to the orbital workshop. A segmented and corrugated outer skin form an aerodynamic fairing for the complete system and seals between forward and aft fairings.

Thermal Control

Although the primary purpose of the meteoroid shield is that of providing protection of the orbital workshop from meteoroids, it also plays a significant role in the thermal control system. Much of the overall thermal design was accomplished passively by painting the outer surfaces of the meteoroid shield black except for a large white cross-shaped pattern on the Earth side during flight. The entire surface of the orbital workshop wall was covered with gold foil. The overall choice of finishes biased the thermal design toward the cold side, it being easier to vernier control by heating rather than cooling.

Friction between the Meteoroid Shield and Orbital Workshop Wall

To provide a uniform tension throughout the meteoroid shield upon assembly and rigging for flight, and to permit transfer of the trunnion bolt tension into the frames of the auxiliary tunnel, it was necessary to minimize friction between the shield and the external surface of the orbital workshop. This was accomplished by applying a Teflon coating to the entire inner surface of the meteoroid shield assembly. Special care was also taken to assure that all fastening rivets be either flush with or below the Teflon surface of the shield. In addition to considerations of friction, the elimination of rivet head protrusions was important in not damaging the rather delicate gold surface used to provide the proper emissivity of the outer orbital workshop wall surfaces as mentioned above. This was a vapor-deposited gold surface applied to a Kapton backing and bonded to the outer workshop wall with an adhesive.

Panel Details

The sixteen panels comprising the meteoroid shield were formed of 0.025 inch thick aluminum stock fitted with doublers and angles to permit their assembly. In each of these panel joints, 96 holes of 1/8-inch diameter were drilled to vent any air trapped under the meteoroid shield skin. The special panel joint is required next to the SAS-1 wing because of the unavailability of sufficiently wide panel stock for the panel under SAS-1. It was a strap of metal of this special joint that became embedded in the SAS-1 cover and prevented automatic deployment of SAS-1 in orbit. It is, perhaps, of passing interest to note the longer length of exposed bolts in this particular joint.

Around the top of the panels is located an angle and a neoprene rubber rain or weather seal. This seal was not intended to be an aerodynamic seal and could not be expected

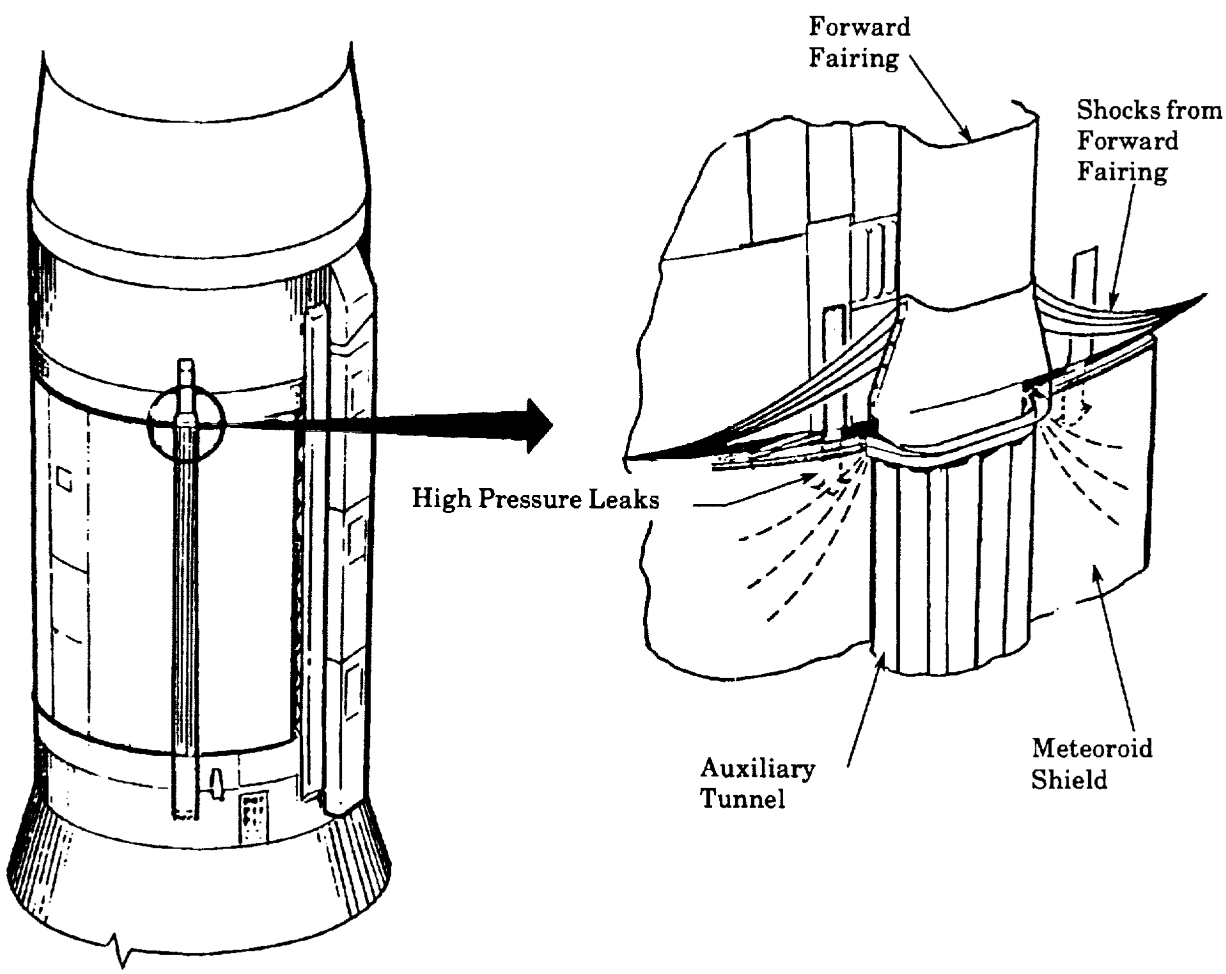

Figure 3 Compressibility waves from the forward auxiliary tunnel fairing

to accommodate significant relative deflections between the orbital workshop and meteoroid shield surfaces. To provide meteoroid protection at the two ends of the meteoroid shield, small strips of thin stainless steel "fingers" were squeezed down between the orbital workshop and the meteoroid shield when stowed. The thrust load of the shield, which weighs some 1200 pounds, is transferred to the forward flange of the aft skirt through a group of twelve thrust blocks.

SUMMARY AND RECOMMENDATIONS

The preceding analysis and discussion of possible failure modes of the meteoroid shield have identified at least two ways that it could fail in flight. Although the most probable cause of the present failure was the lifting of the shield from the orbital workshop tank by excessive pressures in the auxiliary tunnel, other failure modes could have occurred in other regions of flight or under more severe flight environments that were encountered by Skylab 1.

Among these other modes of potential failure, which could combine in various ways under varying conditions of flight, are excessive pressures under the forward edge of the shield, or inadequate venting of the folded ordnance panel. The inherently light spring force of the auxiliary tunnel frames, the crushing loads on these frames in flight, the inherent longitudinal flexibility of the shield assembly, the forces applied by the swing links to deploy the shield, the possible breathing of the shield panels as cavities are vented, the noncylindrical nature of the underlying pressurized tank, and the uncertain tension loads applied to the shield in rigging for flight all contribute to a lack of rigidity of the shield and a weakness of its structural integrity with the underlying tank structure.

A simple and straightforward solution to these inherent problems of the present shield design is therefore not likely. A fundamentally different design concept seems in order. One solution is, of course, to simply omit the meteoroid shield, suitably coat the orbital workshop for thermal control and accept the meteoroid protection afforded by the orbital workshop tank walls. Although the Board has not conducted an analysis, meteoroid flux levels are now known to be considerably lower than those used in the original calculations. A new analysis, based on these flux levels, may show acceptable protection.

Should some additional meteoroid protection be required, the Board is attracted to the concept of a fixed, nondeployable shield. Although the inherent weight advantages of a separable bumper are not available in this approach, the mission of Skylab could probably be satisfied in this manner. One concept would be to bond an additional layer of metal skin to the surface of the tank with a layer of nonventing foam between the orbital workshop tank and the external skin. The problem being statistical in nature, the entire shell of the orbital workshop would not have to be covered.

POSTULATED SEQUENCE OF THE MOST PROBABLE FAILURE MODE

The availability of flight data from the instrumentation on the meteoroid shield and the vehicle disturbances, the design features of the meteoroid shield, the solar array system photographs taken in orbit, descriptions by the astronauts, and other information permit the following postulation of the probable sequence of events associated with the meteoroid shield failure.

In Figure 4, sketches and details of salient events are correlated to the roll rate data around the 63 second anomaly period. The events are designated on the figures by times which are consistent with the available data.

60.12 Seconds - Meteoroid shield liftoff and local inflation in the vicinity of the auxiliary tunnel was indicated by a small shift in position of the torsion rod on the forward edge just to the left of the tunnel.

61.78 Seconds - Air entered the forward fairing opening, raised the pressure under the shield and high mass flows escaped through the adjacent holes in the butterfly hinge. This flow produced reactive force causing a gradual decrease in roll rate between 61.78 seconds and 62.74 seconds.

62.74 to 62.79 Seconds - Burst pressure under the auxiliary tunnel and adjacent meteoroid shield caused a large tangential load on the forward section of the butterfly hinge, causing the whole hinge to unzip. Fly around inspection indicated that the failure of the butterfly hinge occurred at the hinge line adjacent to the main tunnel.

The butterfly hinge was now completely broken. Aerodynamic drag on the meteoroid shield including the bulky auxiliary tunnel produced tension in the shield and pulled on the vehicle so as to roll it in the direction shown, that is, opposite to that noted earlier. The large area and mass of this metal flag induced a more rapid change in roll rate than the earlier jetting through the butterfly hinge. This process terminated as the meteoroid shield started to wrap around and lift the SAS-2 wing.

62.79 to 62.90 Seconds - During this interval the shield was wrapping around the SAS-2 wing producing a negative roll torque in the vehicle. At about 62.85 seconds the SAS-2 tie-downs were broken.

62.90 Seconds - Upon release of the SAS-2, the tension in the shield was transferred to the trunnions, causing failure of the trunnion straps. Upon separation of this section of the shield, the negative roll torque ended.

62.90 to 62.95 Seconds - In this interval, the remaining section of the meteoroid shield began unwinding, introducing a large positive roll torque.

63.17 Seconds - A large shock was detected by the instrument unit upper mounting ring vibration sensor due to the impact of the separated section of the meteoroid shield upon the conical adapter between the orbital workshop and the SAS-1 stage.

63.7 Seconds - The meteoroid shield continued to unwind and whip until 63.7 seconds when it reached SAS-1 wing. As the meteoroid shield began to wrap around the SAS-1 wing, a negative roll torque resulted. The meteoroid shield then ripped apart from top to bottom at the longitudinal joint adjacent to SAS-1, pulling a portion of the joint assembly over the SAS-1 wing as the meteoroid shield section departed. From this point on the vehicle showed normal response to its roll control system.

Possible Impact of Costs and Schedules on the Meteoroid Shield

The origin of Skylab in late 1966—as an extension of the use of Apollo hardware for experiments in Earth orbit—imposed an initial environment of limited funding and strong schedule pressures on the program. Skylab, then designated the Apollo Applications Program (AAP), was to fit in among the Apollo flights under schedules imposed by the mainline Apollo program. Funding was provided out of the Apollo program and thus the needs of Skylab competed with those of the higher priority Apollo program.

The situation changed in mid-1969 when Skylab became a major line item in its own right and was to use a Saturn-V launch vehicle with a dedicated, dry, orbital workshop. From that point on, increased funding and new flight schedules were established for Skylab. Nonetheless, the original concept of the meteoroid shield was retained when the orbital workshop changed from Saturn-IB propulsion stage to a dry workshop launched by a Saturn-V. The Board was therefore interested in determining the extent, if any, that either the initial limitation of funds and time, or any subsequent limitations, determined the design or thoroughness of development of the meteoroid shield. This inquiry was limited to the possible effect of funding and schedule of the meteoroid shield as designed and flown on Skylab 1 and did not consider whether meteoroid protection could have or should have been provided in some other way had the program not evolved as it did.

In the Board's review of the evolution of the meteoroid shield from initial design concept, through testing and development, to final assembly for flight, particular attention was devoted to any impacts arising from limitation of funds or time. Extensive discussions were also held with management personnel of MDAC-W, MSFC, JSC, and NASA Headquarters on this matter. In no instance could the Board find any evidence that the design or testing of the meteoroid shield was

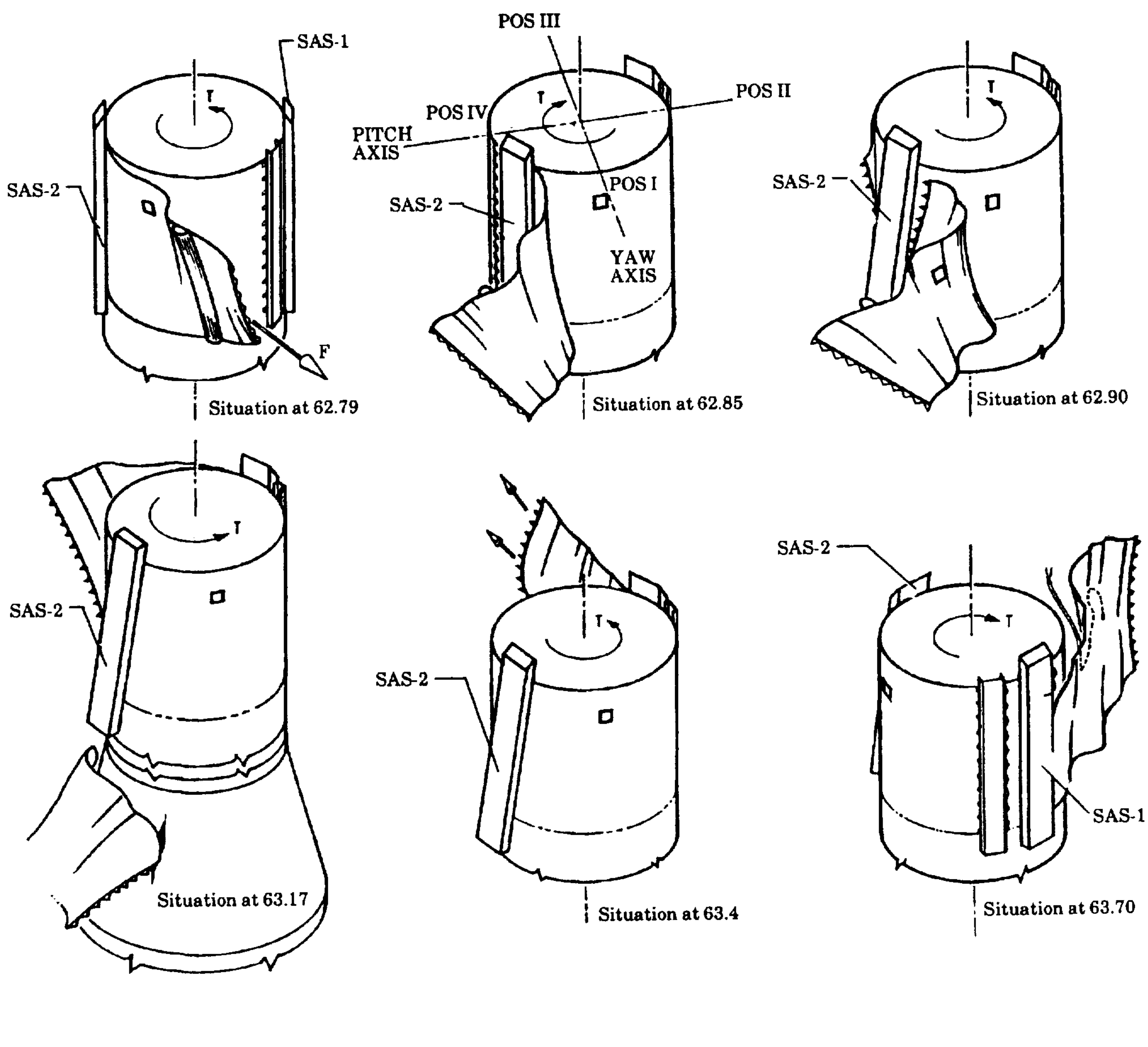

Figure 4 — Postulated Sequence Failure Mode

compromised by lack of funds or time. Program personnel, both government and contractor, had full confidence in the basic concept of the meteoroid shield and thus saw no need to alter the design when the change to a dry, Saturn-V launched orbital workshop occurred. Given the concept that the shield was to be maintained tight to the orbital workshop tank, and thus structurally integrated with the well-established S-IVB structure, the emphasis of testing given to ordnance reliability and shield deployment was considered proper. Neither the records of Skylab nor the memories of key personnel revealed any tests or analyses of the meteoroid shield that were considered desirable at the time and which were precluded by lack of funds or time.

THE SKYLAB MANAGEMENT SYSTEM

The management system utilized for the Skylab program was derived directly from that which had been developed and used in the Apollo program. As such, it included a series of formal reviews and certifications at progressive points in the program life cycle that are intended to provide visibility to contractor and NASA management on program status, problems and their resolution. The selected review points and their primary purpose are set forth in Skylab Program Directive No. 11A, which is summarized as follows:

Preliminary Requirements Review (PRR). "To verify by formal review the suitability of the conceptual configuration and to establish the requirements and action necessary to achieve a design baseline."

Preliminary Design Review (PDR). "To verify by formal review the suitability of the baseline design of the Contract End Item."

Critical Design Review (CDR). "To verify by formal review the suitability of the design of a Contract End Item when the design is essentially complete."

Configuration Inspection (CI). "To certify that the configuration for the Contract End Item as being offered for delivery is in conformance with the baseline established at the CDR."

Certification of Flight Worthiness (COFW). "To certify that each flight stage module and experiment is a complete and qualified item of hardware prior to shipment."

Design Certification Review (DCR). "To examine the design of the total mission complex for proof of design and development maturity."

Flight Readiness Review (FRR). "A consolidated review of the hardware, operational and support elements to assess their readiness to begin the mission."

The primary thrust of these key program milestones is thus a formal review and certification of equipment design or program status; the primary purpose being served is to provide visibility into these matters to senior NASA and contractor program management. As noted in the Skylab Program Directive, the organization and conduct of the review is a major responsibility of a senior program or management official. For each review, specific objectives are to be satisfied, in conformance with preestablished criteria and supported by specified documentation. The reviews are thus highly structured and formal in nature, with a major emphasis on design details, status of various items and thoroughness of documentation. Several hundred specialists, subsystem engineers and schedule managers are generally in attendance.

The material presented in these reviews is, of course, developed over a period of time in many lower-level reviews and in monthly progress reports dealing with various systems and subsystems. In addition, several other major reviews peculiar to Skylab were conducted, including the following:

- Cluster System Review of December 1967
- Mathew's Subsystem Review Team of August 1970-July 1971

- Critical Mechanisms Review of March 1971
- Systems Operations Compatibility Assessment Review of October 1971-June 1972
- Structural/Mechanical Subsystem Reviews of July 1971-May 1972
- Hardware Integrity Review of March 1973
- MSFC Center Director's Program Reviews

There was thus no shortage of reviews. In order to determine the consideration given to the meteoroid shield throughout the program, the Board examined the minutes, presentation material, action items, and closeout of data of each of these reviews and progress reports. In every case, complete records and documentation were available for inspection. In no case did the Board uncover any conflict or inconsistency in the record. All reviews appeared to be in complete conformance to Program Directive 11A and were attended by personnel appropriate to the subject matter under consideration. The system was fully operational.

And yet, a major omission occurred throughout this process—consideration of aerodynamic loads on the meteoroid shield during the launch phase of the mission. Throughout this six year period of progressive reviews and certifications the principal attention devoted to the meteoroid shield was that of achieving a satisfactory deployment in orbit and containment of the ordnance used to initiate the deployment. As noted in the preceding section on possible failure modes, design attention was also given to the strength of the hinges, trunnion straps and bolts, to the crushing pressures on the frames of the auxiliary tunnel, to flutter and to the venting of both the auxiliary tunnel and the several panels of the shield. But never did the matter of aerodynamic loads on the shield or aeroelastic interactions between the shield and its external pressure environment during launch receive the attention and understanding during the design and review process which in retrospect it deserved.

This omission, serious as it was, is not surprising. From the beginning, a basic design concept and requirement was that the shield be tight to the tank. As clearly stated in much of the early documentation, the meteoroid shield was to be structurally integral with the S-IVB tank—a piece of structure that was well proven in many previous flights. The auxiliary tunnel frames, the controlled torque on the trunnion bolts and the rigging procedure itself were all specifically intended to keep the shield tight against the tank. The question of whether the shield would stay there under the dynamics of flight through the atmosphere was simply not considered in any coordinated manner—at least insofar as the Board could determine by this concentrated investigation.

Possibly contributing to this oversight was the basic view of the meteoroid shield as a piece of structure. Organizationally, responsibility for the meteoroid shield at MDAC-W was established to develop it as one of the several structural subsystems, along with such items as spacecraft structure and penetrations, pressure vessels, scientific airlocks, protective covers and finishes. Neither the government, (MSFC), or the contractor, (MDAC-W), had a full-time subsystem engineer assigned to the meteoroid shield. While it is recognized that one cannot have a full-time engineer on every piece of equipment, it is nonetheless possible that the complex interactions and integration of aerodynamics, structure, rigging procedures, ordnance, deployment mechanisms, and thermal requirements of the meteoroid shield would have been enhanced by such an arrangement. Clearly, a serious failure of communications among aerodynamics, structures, manufacturing and assembly personnel, and a breakdown of a systems engineering approach to the shield, existed over a considerable period of time. Further, the extensive management review and certification process itself, in its primary purpose of providing visibility of program status to management, did not identify these faults.

Further insight into this treatment of the meteoroid shield as one of several structural subsystems is obtained by a comparison of a listing of the design reviews conducted on both the meteoroid shield and the solar array system. At MDAC-W, the solar array system was considered a major subsystem and was placed under the direction of a full-time project engineer.

The Board is impressed with the thoroughness, rigor and formalism of the management review system developed by Apollo and used by Skylab. Great discipline is imposed upon everyone by this system and it has served very well. In a large program as geographically dispersed and intrinsically complex as Skylab, such visibility of program status and problems is a management necessity. We therefore have no wish to alter this management system in any basic manner. But all systems created by humans have their potential flaws and inherent hazards. Such inherent flaws and weaknesses must be understood by those who operate the system if it is not to become their master. We therefore wish to identify some of those potential flaws as they have occurred to us in this investigation, not to find fault or to identify a specific cause of this particular flight failure but to use this experience to further strengthen the management processes of large and complex endeavors.

As previously noted, the management system developed by NASA for manned space flight places large emphasis on rigor, detail and thoroughness. In hand with this emphasis comes formalism, extensive documentation, and visibility in detail to senior management. While nearly perfect, such a system can submerge the concerned individual and depress the role of the intuitive engineer or analyst. It may not allow full play for the intuitive judgment or past experience of the individual. An emphasis on a management system, can, in itself, serve to separate the people engaged in the program from the real world of hardware. To counteract these potential hazards and flaws, we offer the following suggestions.

- Deployable systems or structures that have to move, or that involve other mechanisms, devices, or components in their operation, should not be considered as a piece of structure or be the basic responsibility of a structures organization.
- A complex, multi-disciplinary system such as the meteoroid shield should possibly have a designated project engineer who is responsible for overseeing all aspects of analysis, design, fabrication, test and assembly.
- Management must always strive to counteract the natural tendency of engineers to believe that a drawing is the real world. First-hand experience with how hardware behaves and can fail is of the essence to design engineers. Possibly, some design engineers should be required to spend time in testing, operations, or failure analysis. Such experience may not contribute to cleverness or sophistication of analysis, but something equally valuable—actual experience—may be added to the design group. An unfamiliarity with hardware, first hand, makes it difficult to conceptualize a living, breathing, piece of hardware from an analysis or a drawing.
- The extensive use of the computer for complex analyses can serve to remove the analyst from the real world. One should, therefore, require a simplified or supporting analysis that provides an understandable rationale for the phenomena under consideration before accepting the results of a computer analysis.
- The emphasis on "visibility to management" in the review process should not be extended to the point that one can be led to believe the job is completed, or the design is satisfactory, when such visibility

is provided. A major emphasis on status, on design details, or on documentation can detract from a productive examination of "how does it work" or "what do you think."

- Today's organizations seldom include the old-fashioned chief engineer who, relatively devoid of administrative or managerial duties, brings total experience and spends most of the time in the subtle integration of all elements of the system under purview. Perhaps we should more actively seek and utilize these talented individuals in an engineering organization.

SIGNIFICANT FINDINGS

1) The launch anomaly that occurred at approximately 63 seconds after lift-off was a failure of the meteoroid shield of the orbital workshop.
2) The SAS-2 wing tie downs were broken by the action of the meteoroid shield at 63 seconds. Subsequent loss of the SAS-2 wing was caused by retro-rocket plume impingement on the partially deployed wing at 593 seconds.
3) The failure of the S-II interstage adapter to separate in flight was probably due to damage to the ordnance separation device by falling debris from the meteoroid shield.
4) The most probable cause of the failure of the meteoroid shield was internal pressurization of its auxiliary tunnel. This internal pressurization acted to force the forward end of the tunnel and meteoroid shield away from the orbital workshop and into the supersonic air stream. The resulting forces tore the meteoroid shield from the orbital workshop.
5) The pressurization of the auxiliary tunnel resulted from the admission of high pressure air into the tunnel through several openings in the aft end. These openings were: (1) an imperfect fit of the tunnel with the aft fairing; (2) an open boot seal between the tunnel and tank surface; and (3) open stringers on the aft skirt under the tunnel.
6) The venting analysis for the tunnel was predicated on a completely sealed aft end. The openings in the aft end of the tunnel thus resulted from a failure to communicate this critical design feature among aerodynamics, structural design, and manufacturing personnel.
7) Other marginal aspects of the design of the meteoroid shield which, when taken together, could also result in failure during launch are:
   a) The proximity of the meteoroid shield forward reinforcing angle to the air stream
   b) The existence of gaps between the orbital workshop and the forward ends of the meteoroid shield
   c) The light spring force of the auxiliary tunnel frames
   d) The aerodynamic crushing loads on the auxiliary tunnel frames in flight
   e) The action of the torsion-bar actuated swing links applying an outward radial force to the meteoroid shield
   f) The inherent longitudinal flexibility of the shield assembly
   g) The nonuniform expansion of the orbital workshop tank when pressurized
   h) The inherent difficulty in rigging for flight and associated uncertain tension loads in the shield.
8) The failure to recognize many of these marginal design features through six years of analysis, design and test was due, in part, to a presumption that the meteoroid shield would be "tight to the tank" and "structurally integral with the S-IVB tank" as set forth in the design criteria.
9) Organizationally, the meteoroid shield was treated as a structural subsystem. The absence of a designated project engineer for the shield contributed to the

lack of effective integration of the various structural, aerodynamic, aeroelastic, test fabrication, and assembly aspects of the meteoroid shield system.

10) The overall management system used for Skylab was essentially the same as that developed in the Apollo program. This system was fully operational for Skylab; no conflicts or inconsistencies were found in the records of the management reviews. Nonetheless, the significance of the aerodynamic loads on the meteoroid shield during launch was not revealed by the extensive review process.
11) No evidence was found to indicate that the design, development and testing of the meteoroid shield were compromised by limitations of funds or time. The quality of workmanship applied to the meteoroid shield was adequate for its intended purpose.
12) Given the basic view that the meteoroid shield was to be completely in contact with and perform as structurally integral with the S-IVB tank, the testing emphasis on ordnance performance and shield deployment was appropriate.
13) Engineering and management personnel on Skylab, on the part of both contractor and government, were available from the prior Saturn development and were highly experienced and adequate in number.
14) The failure to recognize these design deficiencies of the meteoroid shield, as well as to communicate within the project the critical nature of its proper venting, must therefore be attributed to an absence of sound engineering judgment and alert engineering leadership concerning this particular system over a considerable period of time.

CORRECTIVE ACTIONS

1) If the backup orbital workshop or a similar spacecraft is to be flown in the future, a possible course of action is to omit the meteoroid shield, suitably coat the orbital workshop for thermal control, and accept the meteoroid protection afforded by the orbital workshop tank walls. If, on the other hand, additional protection should be necessary, the Board is attracted to the concept of a fixed, nondeployable shield.
2) To reduce the probability of separation failures such as occurred at the S-II interstage Second Separation Plane, both linear shaped charges should be detonated simultaneously from both ends. In addition, all other similar ordnance applications should be reviewed for a similar failure mode.
3) "Structural" systems that have to move or deploy, or that involve other mechanisms, equipment or components for their operation, should not be the exclusive responsibility of a structures organization.
4) Complex, multi-disciplinary systems such as the meteoroid shield should have a designated project engineer who is responsible for all aspects of analysis, design, fabrication, test and assembly.

OBSERVATIONS ON THE MANAGEMENT SYSTEM

The Board found no evidence that the design deficiencies of the meteoroid shield were the result of, or were masked by, the content and processes of the management system that were used for Skylab. On the contrary, the rigor, detail, and thoroughness of the system are doubtless necessary for a program of this magnitude. At the same time, as a cautionary note for the future, it is emphasized that management must always be alert to the potential hazards of its systems and take care that an attention to rigor, detail and thoroughness does not inject an undue emphasis on formalism, documentation, and visibility in detail. Such an emphasis can submerge the concerned individual and depress the role of the intuitive engineer or analyst. It will always be of importance to achieve a cross-fertilization and broadened experience of engineers in analysis, design, test or operations. 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 this learning process. The experienced chief engineer, whose time can be spent in the subtle integration of all elements of the system under review, free of administrative and managerial duties, can also be a major asset to an engineering organization.