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MEMORANDUM

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PERFORMANCE OF SOLAR SHIELDS

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Marshall Space Flight Center, Alabama

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16. ABSTRACT

The loss of the micrometeoroid shield from the Orbital Workshop section of Skylab I, about 63 seconds after lift-off, proved to be the harbinger of a prodigious effort to quickly develop a workable substitute for the carefully tailored passive portion of the thermal control system.

This paper describes the intensive ten-day around-the-clock effort in which numerous potential thermal shield materials were assessed, and during which period ten specific shield designs were developed and carried through various stages of development and test.

Thermal shield materials data are discussed, including optical, strength, fatigue, out-gassing, tackiness, ultraviolet radiation, and material "memory" properties.

Specifically addressed are thermal shield materials selection criteria and the design, development, and test requirements associated with the successful deployment of Skylab thermal shields, and specifically the two thermal shields subsequently deployed over the exposed gold foil skin of the Orbital Workshop.

Also considered are the general performance and thermal improvements provided by both the "parasol" design deployed by the Skylab I crew, and the "sail" design deployed by the Skylab II crew.

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SUMMARY

The urgency of the crippled Skylab precipitated a massive all out effort by NASA and many contractors to save the country's first space station. In ten short days, hundreds of designs and materials were considered and tested. Within about three days, the long list of possibilities began to narrow down to about ten prime candidates, four of which were finally flown. The JSC parasol, the MSFC SAIL II and the JSC SEVA SAIL were launched with the Skylab I crew. The Skylab II crew carried a backup JSC Parasol to Skylab later, as additional insurance.

The deployment of the compact, no EVA, JSC parasol dropped temperatures inside the OWS by $16.7°C$ ($30°F$) in two days, but the shield deployed only 75 percent and this, coupled with changing, α/ϵ, caused a gradual increase in temperature again. Ground testing also showed a decrease in breaking strength and elongation as a result of UV/vacuum degradation which caused some concern about the parasol strength and ability to remain intact.

The MSFC SAIL II was deployed over the parasol during EVA by the Skylab II crew. The OWS external temperature dropped $55.6°C$ ($100°F$) within the first few hours, and the mean internal temperature dropped by $3.9°C$ ($7°F$). Deployment of this shield was less than anticipated too, being about 89 percent deployed.

The "composite" thermal shield consisting of parasol and sail served to shield the Skylab quite successfully, and the mission planned for Skylab was successfully accomplished. In fact, several additional unplanned activities were completed. The saga of the saving of Skylab will doubtless stand as an outstanding engineering testimonial to the many dedicated engineers and scientists from the numerous involved aerospace contractors and the National Aeronautics and Space Administration.

THE SKYLAB PROBLEM

The spectacular launch of the unmanned Skylab on Monday, May 14, 1973, proceeded without a hitch. Nearby, on Pad B, a CSM (Command and Service Module) sat perched atop a Saturn IB rocket which was to carry the three members of Skylab's first crew from Pad B to rendezvous and dock with Skylab, whereupon the crew would enter the space station and activate it. Skylab would be home to them for 28 days.

After Skylab went into almost exactly the predicted orbit, certain time line events began to occur like clockwork. The radiator cover jettisoned, the refrigerator system came on, the payload shroud was jettisoned, and the ATM (Apollo Telescope Mount) deployed as planned. Just as Skylab was leaving ground contact, there was an indication of an anomaly in the deployment of the micrometeoroid shield. This deployable hinged shield consisted of 2014 — T6 aluminum panels, 0.635 mm (0.025-in.) thick, and provided a thermal control function as well as providing micrometeoroid protection. During the ascent it was strapped tightly against the OWS (Orbital Workshop) wall, but when deployed it was to stand out 12.7 cm (5 in.) from Skylab's skin. Word came that there was an indication of partial and premature deployment of the shield, and that there was also an indication of a problem with the two Workshop solar arrays. The Canarvon and Honeysuckle (Australia) tracking stations reported that there was an indication that the solar arrays had begun to deploy, but there was no indication that deployment was complete. An hour and 38 minutes after launch, the Flight Director of Goldstone (Calif.) sent up backup signals to activate the secondary system for deploying the OWS solar arrays, but the desired response did not materialize. By now, serious difficulty was apparent.

With only the electrical power available from the ATM solar arrays, the Skylab was reduced to about half the total power. As temperature data soon confirmed, the loss of the micrometeoroid shield during ascent posed an even more immediate and serious problem. Workshop temperatures were going out of control.

Skylab had been designed and built with a predominantly passive thermal control system, which did not require the "barbecue" (slow turning) method of temperature control used on many previous spacecraft. Instead, black and white thermal control paints were used on the exterior to balance out the incident solar radiation and earth's infrared and reflected solar radiation or albedo. Additionally, the outside of the OWS was covered with a goldized kapton tape which was supposed to "see" the underside of the micrometeoroid shield (teflon

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coated aluminum). This combination gave Skylab an integrated temperature condition which was biased slightly cool for internal habitability. Providing a small amount of additional heat was deemed a more attractive solution to the designers than providing refrigeration if the Skylab had been biased warm.

It became apparent that the vehicle attitude would have to be changed to provide shade for the OWS, at least partially. Therefore, the memorable vehicle attitude jockeying contests began. Habitability experts wanted attitudes to keep the interior of the OWS cool to prevent toxic outgassing of the polyurethane foam insulation used in the OWS walls and to prevent food spoilage, while the power management personnel wanted the ATM solar array pointed at the sun, to get more power and keep the batteries charged. The resultant vehicle attitude changes almost resembled a "hunting" servo system for several days until, by trial and error, the optimum attitudes were finally established for best compromise conditions.

During these gyrations the CMG's (control moment gyros) occasionally "saturated" in which case they could no longer perform their precessional vehicle positioning task. The TACS (thruster attitude control system) would then have to be invoked to "unsaturate" the CMG's. Fortunately, due to temperature conditions on the day of launch, Skylab lifted off with 355,858 N/sec (80,000 lb-sec) of total impulse rather than the red line value of 266,893 N/sec (60,000 lb-sec), and this proved most fortuitous in the long run. So, the untimely departure of the micrometeoroid shield had indeed upset many of the carefully laid plans including the systems operations and the general time line of events and, for a while, real time changes were the rule rather than the exception.

During those first trying days, the OWS external temperatures rose 111°C (200°F) above the expected normal, and inside temperatures were finally stabilized at approximately 52°C (125°F). These temperatures were high enough to make habitability extremely uncomfortable, if not to completely preclude long term habitability. The immediate problem became one of providing some means of reducing and maintaining control of the OWS temperature.

SOLAR SHIELD DESIGN RATIONALE

The loss of the micrometeroid shield had upset the basic thermal conditioning of the OWS. A number of possible solutions were quickly conceived and considered in some detail. One immediate idea at Marshall Space Flight Center (MSFC) was to cover the exposed goldized kapton with a more suitable thermal

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control material such as S-13G[1]. The painting scheme required the CSM to approach close enough to the OWS to spray on a coat of the S-13G material. Immediate questions arose about the feasibility of spraying in hard vacuum, so a test was conducted in which S-13G was sprayed at 0.0013 N/cm^2 (10^{-5} torr) in a vacuum chamber. This idea, however, never gained wide support because of the complexity of the apparatus required to do the job and the probability of Skylab external contamination, although it was proved theoretically possible.

In a fever pitch, ideas involving some form of thermal shield began to predominate around-the-clock design sessions going on simultaneously at many contractor facilities, at Johnson Space Center (JSC) and at MSFC. The thermal shield designs evolved into three basic categories:

1. Shields requiring the use of the CSM in deployment.

2. Shields requiring extra vehicular activity (EVA) in deployment.

3. Shields utilizing the existing scientific airlock located in the wall of the OWS, in deployment.

Because the first two categories required EVA around the Skylab "cluster" and because the total feasibility of Skylab EVA was, at that juncture, still relatively unknown, the ideas using the scientific airlock appeared to be intuitively more attractive. However, regardless of deployment method, there were certain basic materials selection criteria which had to be met. These were as follows:

1. Light weight

2. Compact

3. Deployable

4. Good strength

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1. S-13G composition is as follows: ZnO-67 percent (by weight), RTV-602-32 percent (by weight), and tetramethylguanidine and mixed amines being the remainder. This material had been jointly developed by the Illinois Institute of Technology Research Institute and the Marshall Space Flight Center and was used extensively over the exterior of Skylab as a thermal control paint.

5. Good α/ϵ [2] (preferably 0.2 to 0.3)

6. Good elongation.

7. Ultraviolet (UV) degradation resistance

8. Thermal cycling stability

9. Nonparticle generating

10. Nonoutgassing in space vacuum

11. Nonflammable (stowed), nontoxic, nonodorous

12. Nontacky

13. Acceptable "memory" characteristics

Several of these material requirements deserve a brief word of explanation. Items 1 and 2 are relatively self-explanatory, and were inherent constraints imposed by the necessity of the packaged shield to fit in the very limited stowage area of the CM for flight to rendezvous. Item 3, deployability, was also a basic requirement, since the exposed OWS skin to be covered actually was a projected rectangular area roughly 6 by 7.3 m (20 by 24 ft), and transport of fixed or rigid systems of those dimensions was out of the question. The requirement for strength is self evident, bearing in mind nevertheless that typically small, compact, and light weight systems deployable to relatively large dimensions must sacrifice something in terms of strength. Strength considerations became of crucial concern later when it became apparent that the Thruster Attitude Control System (TACS) on the OWS was violently flapping the initially deployed thermal shield, but more about that later.

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2. Ratio of solar absorptance (α) to infrared emittance (ϵ) — a measure of the thermal performance of a material in space. The temperature of a body in space varies as the fourth root of the ratio α/ϵ of the surface exposed. For example, polished aluminum foil has an α/ϵ of about 5, and develops a space equilibrium temperature of about 150° C (302° F). A painted black body has an α/ϵ of about 1, and would stabilize at about 25° C (77° F). A painted white body has an α/ϵ of about 0.2, and would maintain a space temperature of about -50° C (-58° F). White paints typically provide the best possible heat protection mechanism in space.

Good α/ϵ ratio was a key factor also, and one which was the precursor to all others in the initial selection criteria. If the thermal shield wouldn't lower the temperature, it wasn't acceptable. In fact, the changing α/ϵ of the initially deployed parasol, coupled with incomplete deployment coverage, finally required deployment of a second thermal shield over the first. The prime intent in the initial selection of materials with suitable α/ϵ was to regain the normal OWS cool bias thermal condition.

Good elongation was an important factor too, because in the UV uninhibited environment of Skylab orbit, the damage to many of the materials otherwise attractive for shield design, can be considerable. UV radiation produces photochemical reactions in polymers (especially polyamides, i.e., nylon), sometimes involving cross-linking, but mostly involving polymer chain scission which is quickly manifested by a reduction in elongation and reduced strength. As we shall see later, appreciable effort went into UV/vacuum testing to determine degradation rates of strength and elongation, and tests concerned with criterion number 7, UV degradation, constituted the bulk of the massive test program carried out during the thermal shield development period.

Criterion number 8, thermal cycling stability was important because a temperature excursion of about -40° C to 93° C (-40° F to +200° F) was expected, depending on the Skylab attitude, Earth orbital position and the material being used. Thermal cycling stability was especially important to shield designs employing coating materials such as S-13G.

The requirement that the thermal shield be nonparticle generating and nonoutgassing (criteria 9 and 10) came about naturally because of the sensitive optics of the ATM system and other experiments, and was important in order to avoid contamination of thermal control surface. Every material selected for use on the outside of the Skylab had to meet MSFC-SPEC-50M02442, a specification which controlled the amount of outgassing permissible from materials to be used in the design. The thermal shield could not be allowed to copiously outgas. Particulate contaminants were strictly forbidden, since in zero-g, particulates frequently prove to be electrostatically attracted to adjacent surfaces, and in the case of many of the sophisticated optical systems used, this would seriously compromise or prevent data taking. Also, particulate contaminants are known to provide attractive, but false targets for star tracking instruments to lock onto.

The CM environmental control system imposes constraints on the flammability and toxicity criteria applied because the CM environmental control system uses relatively high partial pressure of oxygen, which enhances

flammability. Since the system is closed, toxicity of the breathing air cannot be tolerated. The aspect of odor was also considered, although it is highly probable that even genus mephitis would have been carried in the CM if that would have guaranteed a successful thermal shield!

Criterion 12, nontackiness, was important to shield designs employing any kind of coatings. This fact could affect deployment; it could cause distortions of the deployed shield, or it might possibly cause coatings or thermal control materials to stick and peel off, where coatings were used in the design.

The final requirement, the "memory" characteristic of the material also proved to be important in some of the thermal shield designs because of the material "memory" or tendency to return, to some degree, to the stowed configuration or shape. Therefore, what appeared to be a relatively straightforward design problem to some of the enthusiastic shield designers, turned out to be a nightmare of complexity when all the Skylab-peculiar design criteria were finally addressed.

Nevertheless, the prodigious effort of NASA and several contractors in the brief 10-day period between the Skylab launch and the launch of the first Skylab crew on May 25, resulted in ten specific designs being evolved, many to very advanced stages of development and even involving terrestrial deployment.

We will now examine the specific designs in that intensive effort to provide a suitable thermal shield.

SOLAR SHIELD MATERIALS AND DESIGNS CONSIDERED

Uppermost in all thermal shield designer's minds was the realization that the shield would have to survive several months in hard vacuum, with direct impingement of ultraviolet (UV) radiation from the sun. The degradation of material such as nylon, due to radiation in space, is limited almost entirely to the UV position of the solar spectrum at 290 to 400 millimicrons UV. The visible portion of the spectrum radiation does not typically possess enough energy, per quantum, to break chemical bonds in ordinary reactions. Infrared and visible radiation does increase the temperature, however, and this has the effect of increasing the reactions (degradation) initiated by the higher

energy UV photons.[3] The materials (mostly non-metallics to meet weight and deployment criteria) which could be considered in shield design are many, but a qualitative comparison of the UV/vacuum stability properties shows clearly the advantage of certain of the materials over others. Table 1 shows this comparison for a number of potential candidates.

TABLE 1. UV/VACUUM STABILITY OF POTENTIAL
THERMAL SHIELD MATERIALS

Material	UV/Vacuum Stability Rating
Beta Glass Fabric	Good
PBI (polybenzimidazole)	Good
H-Film — Kapton (polyimide)	Good
Tedlar (polyvinylfluoride)	Good
Kel-F (polychlorotrifluoroethylene)	Good
Teflon TFE (polytetrafluoroethylene)	Good
Teflon FEP (fluorinated ethylene propylene)	Good
S-13G (ZnO pigment, RTV-602 vehicle)	Good
Dacron (polyester fiber)	Fair
Aluminum Coatings[4]	Fair
Polypropylene	Fair
Nylon (polyamide)[5]	Fair
Mylar (polyester film)	Fair to Poor
Polyethylene	Poor
Polyvinyl chloride	Poor

3. "Space Environmental Effects on Materials: A State of the Art Survey" by Pinson, Schmidheiser and Zumwalt, AEDC-TR-66-12, April 1966.

4. See "Effects of Vacuum — Ultraviolet Environment on Optical Properties of Bright Anodized Aluminum Temperature Control Coatings," James H. Weaver, Technical Report AFML-TR-67-421, May 1968. Report concludes "The combined UV/vacuum radiation was detrimental to the solar absorptance of all bright anodized aluminum coatings."

5. There are actually seven types of nylon:
   1. Nylon 4   from butyrolactam (2-pyrolidone)
   2. Nylon 6   from polycaprolactam
   3. Nylon 6-6 from hexamethylenediamine and adipic acid
   4. Nylon 6-10 from hexamethylenediamine and sobacic acid
   5. Nylon 9   from 9 — amino — nonanoic acid
   6. Nylon 11 from 11 — amino — undecanoic acid
   7. Nylon 12 from 12 — amino — undecanoic acid

Nylon 6 and Nylon 6-6 (numbers refer to carbon rings) accounted for about 25 percent and 75 percent, respectively, of all nylon in the U.S. last year, and candidates were typically one or the other. Because of the double carbon ring, Nylon 6-6 has somewhat better UV degradation resistance than Nylon 6. All four of the thermal shields finally selected for transport to the crippled Skylab used Nylon 6-6 as one of the layers in the material composite making up each of the thermal shields; but, as we shall see later, the engineering trade-off was made differently in the case of one of the thermal shields, when compared to the other three with regard to UV degradation.

A total of 10 thermal shield materials and/or designs were investigated on a crash program basis, during those hectic "10 days in May." The specific materials, their composite construction, and their performance characteristics can be seen in Table 2. Other materials besides those listed in Table 2 were considered, but obvious deficiencies such as gross overweight, inflexibility, high probability of extreme UV degradation and ot' er factors in the screening process narrowed the list to the above. It should be noted that the α and ϵ values cited are initial properties and not the expected properties after UV/vacuum exposure. For instance, the α/ϵ ratio of the sunside for the GT-76 material of the parasol changed from 0.47 initial to 0.57 in 300 equivalent sun hours of ground UV/vacuum exposure. This was due largely to an increase in absorptance, which continued to change with exposure. The resulting temperature rise, coupled with incomplete coverage of the OWS, finally required the deployment of the MSFC SAIL II over the JSC parasol. Even the S-13G material, which had shown only 8 percent degradation in solar absorptance in 1000 hours of ground based UV/vacuum testing, showed more rapid though still acceptable degradation when in the actual deployed position on Skylab. Subsequent investigation on returned samples has shown extraneous contamination to be a factor in the somewhat degraded solar absorptivity performance.

Of the designs listed in Table 2, the JSC parasol, the LRC inflatable and the MDAC/MMC inflatable were intended to be deployed through the OWS scientific airlock, hence did not require any EVA. This was a distinct advantage in the beginning, because EVA around the OWS had not yet been accomplished (except simulated in the Neutral Buoyancy Simulator at MSFC) and there was an element of the unknown involved. In addition, the JSC parasol, designed to be deployed just like a parasol, did not require pressurization, and was relatively simpler than the other two inflatables, although it is probable that the LRC inflatable could have been used. From A UV/vacuum degradation point of view, however, it was believed that the parasol nylon, and certainly the LRC Kapton would fare better over the long term than would the MDAC/MMC Mylar. USAF data[6] showed α degradation of mylar from 0.16 to 0.40 in only 1000 ESH (evuivalent sun hours).

6. Personal communication, Warren Johnson WPAFB, May 1973, USAF Data.

TABLE 2. COMPOSITION, WEIGHT, AND THERMAL CONTROL PROPERTIES OF CANDIDATE MATERIALS FOR SKYLAB THERMAL SHIELD

Design	Sun Side	Intermediate Layer(s)	GWS Side	Materials Weight kg/10 m²	lbs/100 ft²	Initial Sun Side Solar Absorptance α	Initial Sun Side IR Emittance ε	α/ε Ratio	Approx. Equilibrium Temperature (Shield Material Only)
TBC	Kapton	1. Aluminized Side 2. Dacron Net 3. Al-Mylar Scrim-Al 4. Dacron Net 5. Tedlar 6. Tedlar 7. Dacron Net 8. Al-Mylar Scrim-Al 9. Dacron Net 10. Kapton	Aluminized Side	2.4	4.9	0.28	0.67	0.42	44°C (111°F)
JSC Parasol (Schjeldahl GT-76)	2.5 mil International Orange Ripstop Nylon 6-6 1.1 oz/yd²	0.5 mil Mylar	Aluminized Side 3000 Å	0.5	1.1	0.39	0.84	0.47	53°C (128°F)
JSC SEVA (Stand Up EVA) SAIL	Kapton	1. Aluminized Side 2. Nylon 3. Mylar	Aluminized Side			0.31	0.81	0.38	37°C (99°F)
JSC Backup Parasol (Schjeldahl GT-132900)	0.5 mil Kapton	0.45 oz/yd² Nylon Scrim	Aluminized			0.36	0.53	0.68	98°C (208°F)
LRC Inflatable (Schjeldahl Satellite Type Material)	0.5 mil Anodized AL 1235-0	0.5 mil Mylar	0.5 mil AL 1235-0	1.0	2.1	0.19	0.73	0.26	9°C (48°F)
MDAC SAIL (Armalon)	Teflon Cloth		Beta Cloth (X389-7)	2.4	4.9	0.29	0.90	0.32	22°C (72°F)
MDAC/MMC Inflatable a. Major Exposed Area	5 mil Mylar S								
b. Support Tubes GT 300 Tape	5 mil Mylar S	1. Aluminized Side 2. Dacron Net 3. 5 mil Mylar S	Aluminized Side	1.1 / 1.1	Total 2.3 / Total 2.3	0.23 / 0.23	0.65 / 0.65	0.36 / 0.36	31°C (88°F) / 31°C (88°F)
MSFC S-13G Tedlar SAIL I	5 mil S-13G		2 mil Tedlar	6.1	12.4	0.16	0.90	0.18	-17°C (2°F)
MSFC S-13G NMD* SAIL II	5 mil S-13G	1. 2.5 mil International Orange Ripstop Nylon 6-6 1.1 oz/yd² 2. Aluminized Side	0.25 mil Mylar	3.9	7.9	0.24	0.90	0.27	10°C (50°F)
RI Spring Tape Driven Window Shade	Silverized	2 mil Teflon	Inconel	1.0	2.1	0.04	0.66	0.07	-8°C (18°F)

TBC — The Boeing Company
JSC — Johnson Space Center (NASA)
LRC — Langley Research Center (NASA)
MDAC — McDonnell Douglas Astronautics Company
MMC — Martin-Marietta Company
RI — Rockwell International Company
*NMD — National Metallizing Division of Standard Packaging Corporation

In the aggregate, however, the parasol seemed the best of the three SAL deployable schemes. The SEVA SAIL appeared to be a very viable contender too. It met all the requirements, but it did require the use of the CSM as the means of erecting this SAIL. This scheme did provide, however, another means of deploying a thermal shield, and for that reason, was also selected as one of the three thermal shields which finally were stowed in the Skylab I CSM. On a subsequent flight (Skylab crew II), an improved parasol design, using the GT 132900, was flown. This design would have required jettisoning of the existing deployed parasol, which constituted too great a risk in the opinion of most NASA officials.

To continue, the Boeing design came along somewhat later. Deployment and other design details and criteria could not be worked out soon enough to make the May 25th launch.

The RI spring tape driven window shade scheme involved more deployment complexity, and the shield also had an extremely low α/ϵ ratio, which would have biased the OWS very cool, and subsequently have required more electrical power to produce an acceptable habitable environment inside. The MSFC S-13G Tedlar SAIL was in the same category, giving very cool temperatures, and having the additional disadvantage of excessive weight.

The MDAC SAIL used an Armalon-like material which had excellent UV/vacuum degradation characteristics, but it suffered from another deficiency. Test data taken at MSFC in May 1973 on the optical "see through" characteristics of Armalon type material indicated that an integrated value of 20 percent transmission could be expected through the Armalon. This was a definite disadvantage. The MSFC SAIL II, on the other hand, employed a thermal control material about which much was already known since it had been used on many spacecraft, including Skylab. For an EVA deployed system, the MSFC SAIL II had a relatively simple, straightforward deployment system using 2 poles locked at their apex and a radiation resistant PBI (polybenzimidazole) rope system which facilitated deployment of the material much as a SAIL is hoisted — hence the analogy.

After careful and continuous scrutiny of all aspects, NASA management wisely decided to take up to the Skylab the JSC parasol, the MSFC SAIL II and the JSC SEVA SAIL, with deployment in that order. This scheme was jokingly referred to as the "belt, suspenders and rope" approach — if any one failed, there were at least two other options to effect thermal shielding of Skylab. Later the JSC backup parasol was added, providing yet another option, if all else failed.

The following will address in more detail the development of the two systems ultimately employed — the JSC parasol and the MSFC SAIL II.

PARASOL AND SAIL, DESIGN AND DEVELOPMENT

JSC Parasol

The JSC parasol was designed to provide a 6 by 7.3 m (20 by 24 ft.) canopy over the exposed goldized Kapton of the OWS. The parasol could be deployed from the OWS in a "shirt sleeve" environment — EVA wasn't required, and the parasol could be jettisoned in case of difficulty. It fit the existing TO-27 Experiment canister, it weighed about 35.2 kg (77.5 pounds) including the TO-27 hardware, and it finally was deployed through the scientific airlock (SAL) which fortuitously for Skylab, happened to be appropriately located. Elements of the system were the GT-76 canopy, a canopy mast, a mast hub with four sets of deployment springs, four telescoping deployment tubes, seven extension rods, and the TO-27 canister support tripod.

The deployment sequence involved the threading of the mast sections, one at a time, through the SAL, thereby projecting the closed parasol out to a distance of about 9.9 m (16 ft.). The telescoping tube array was then released and the parasol was shoved out to a distance of 7.3 m (24 ft.), at which point the deployment of the parasol began automatically. The deployment was observed through the CSM window. The crew then retracted the parasol to a distance of about 20.3 cm (8 in.) from the nearest point to the goldized Kapton of the OWS.

Because the deployment time line sequence resulted in extension during the darkness period of the orbit, some delay in final physical disposition resulted when Skylab re-entered the sunlight.

The basic mechanical design was ingeniously simple and straight forward, and as noted earlier, did not require EVA. These were cogent and sound reasons for the decision to deploy the JSC parasol first.

The Skylab external configuration (Fig. 1) is shown at the time of ingress by Astronauts Conrad, Kerwin, and Weitz, the Skylab I crew. At this point, the Solar Array System (SAS) beam had not yet been released.

The general packing arrangement can be seen in Figure 2. An existing TO-27 canister was employed.
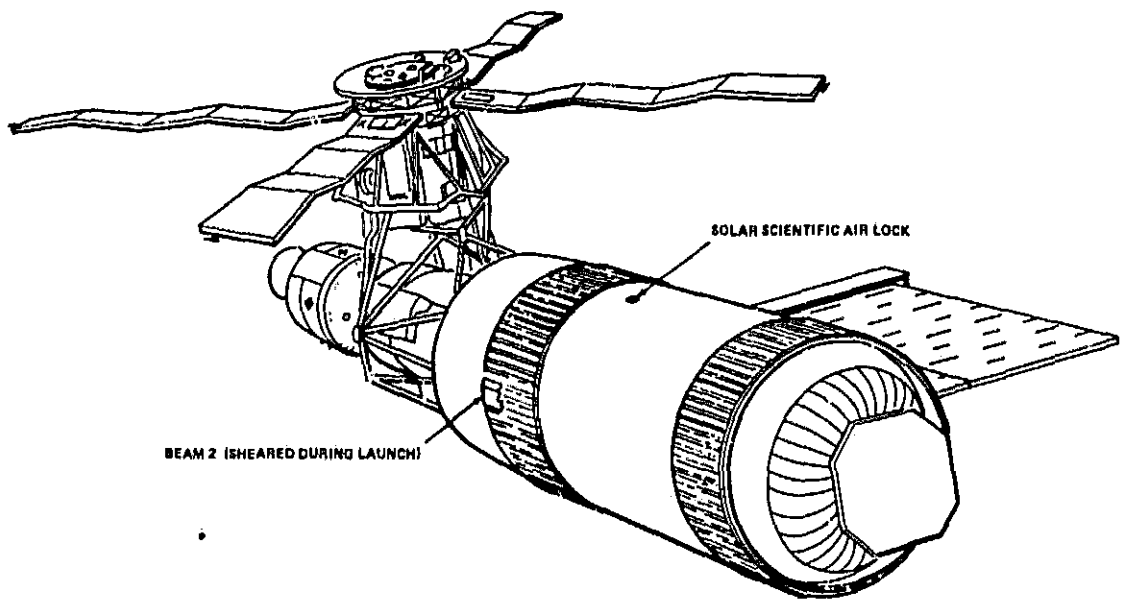
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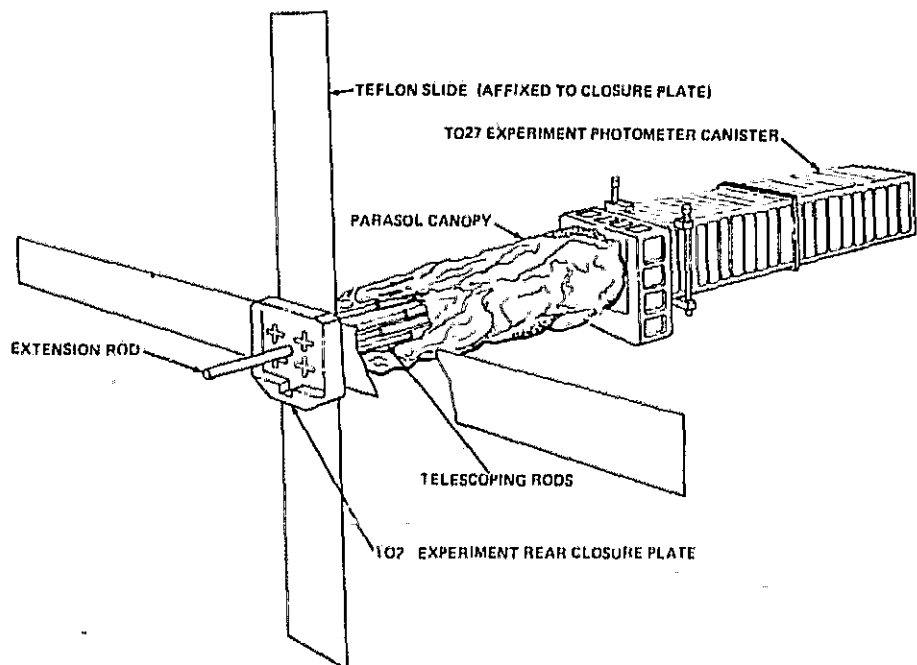Figure 1. JSC parasol external configuration at ingress.

Figure 2. JSC parasol general packing arrangement.

The canopy rods were projected to the maximum height of 7.3 m (24 ft.) above Skylab (Fig. 3). At this point the parasol deployment was completed, and the retraction to the final position near the OWS skin had not yet occurred.
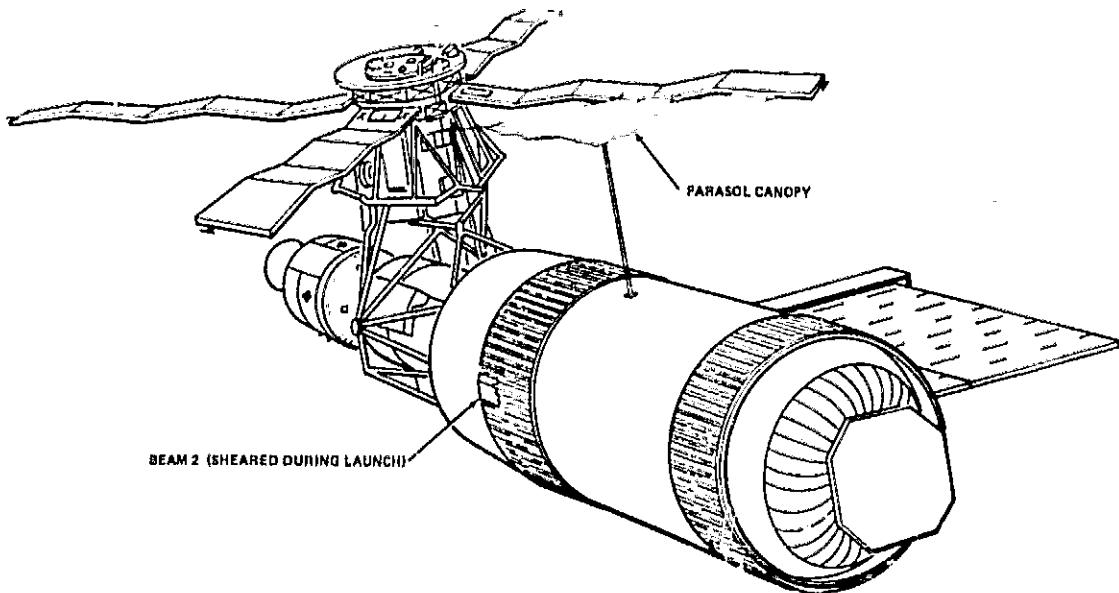

Figure 3. JSC parasol full extension and full deployment.

A sketch (Fig. 4) of the unique telescoping tube locking mechanism which projected the corners of the 6 by 7.3 m (20 by 24 ft.) parasol is shown. The material used was 6061-T6 aluminum.

An actual photo (Fig. 5) was taken as the Skylab I crew left Skylab prior to the visit of the Skylab II crew. This view shows the incomplete coverage which resulted. The implications of this reduced shielding will be treated in more detail later.

One of the anticipated design advantages of the JSC parasol was to have been the ability to rotate the parasol, thereby allowing some measure of shielding thermal control. After the deployment of the parasol on May 27, 1973, crew comments and thermal instrumentation indicated that the parasol did not fully deploy. On June 19, 1973, the crew actually did rotate the parasol in an attempt to acquire additional coverage, but ground telemetry data quickly indicated that the rotation obtained was in excess of the intended amount. The crew also noted increasing OWS wall temperatures. The crew was then asked to return the

LOCK TAB

ROLL BEAD
STOP

ROLL BEAD
(TYPICAL)

END FITTING

2.5 cm DIA.
(1.0 in.)

2.2 cm DIA.
(0.875 in.)

TYPICAL JOINT (6 PLACES)

0.95 cm DIA.
(0.375 in.)

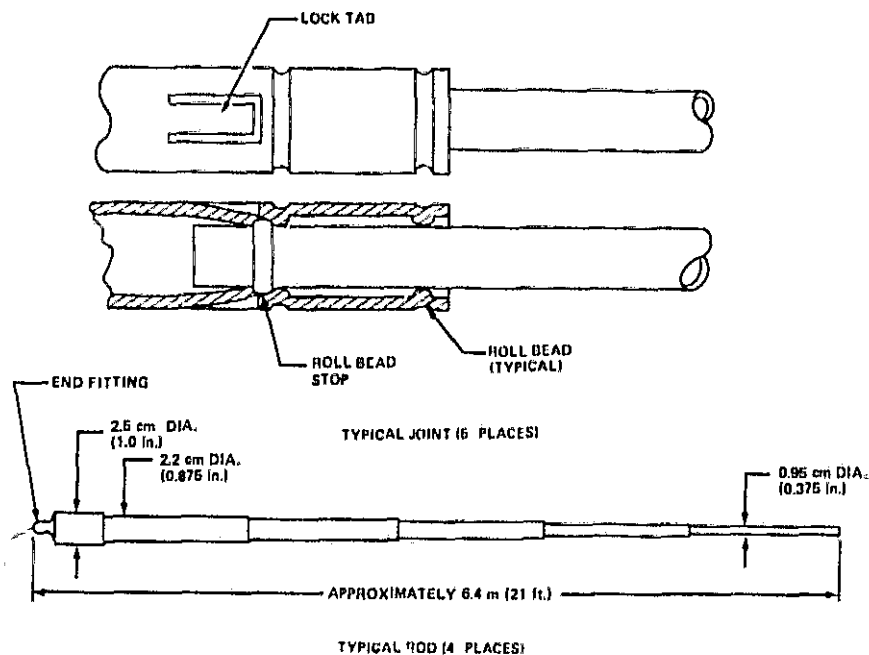APPROXIMATELY 6.4 m (21 ft.)

TYPICAL ROD (4 PLACES)

Figure 4. JSC parasol telescoping tube design.

parasol to the original position, they did so, and no further attempts to use the rotation design feature of the parasol were ever made. The sketch (Fig. 6) shows the planned versus the actual coverage attained by the parasol.

MSFC II

The MSFC SAIL II was designed to provide a 6.8 by 7.4 m (22.25 by 24.42 ft.) thermal shield, or sunshade over the exposed goldized Kapton external skin of the OWS. This thermal shield required EVA, which was performed by the Skylab II crew consisting of astronauts Garriott and Lousma, while Commander Bean directed the operation. The SAIL design permitted either solo deployment, or allowed deployment over the existing JSC parasol, which was the solution finally adopted.

The MSFC SAIL II hardware included twenty-four 6061-T651 aluminum pole sections, each 1.5-m (5-ft.) long, which when coupled, provided two poles 16.8-m (55-ft.) long. Each pole connection had a twist lock arrangement featuring an extremely low temperature silicone "O" ring (SE-5211) which
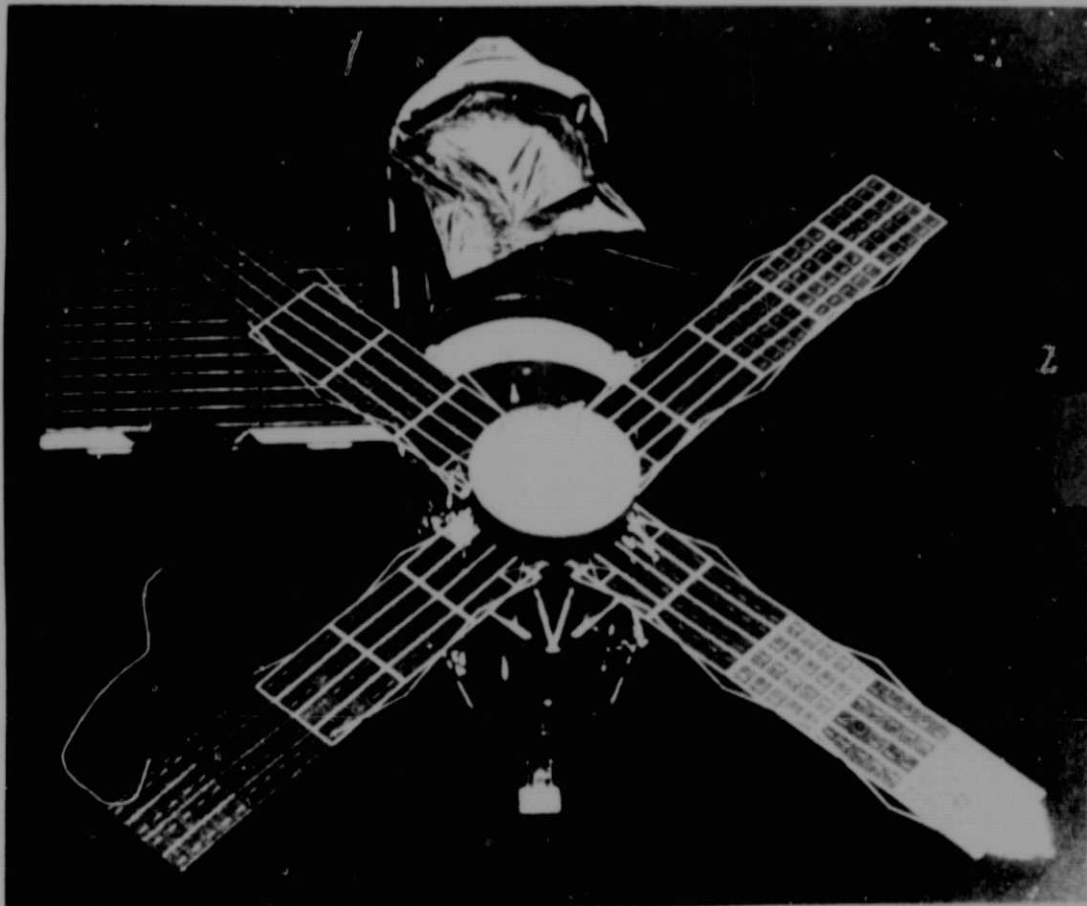
15

Figure 5. Skylab in deployment parasol configuration.

retained its elastomeric properties and maintained the locked position while the Skylab was thermal cycled and maneuvered. Other hardware included two pallets for pole stowage, a pole base plate with a locking feature to provide accurate SAIL positioning, a portable foot restraint adapter which was used with a universal foot restraint from the OWS, and two PBI (polybenzimidazole) solar radiation resistant "clothesline" ropes in non-flammable fiberglass bags, to serve as halyards. Testing of teflon coated fiberglass ropes showed inferior performance with regard to particle generation. The SAIL itself was stowed in a nonflammable fiberglass bag. The finished package weighed 50.8 kg (112 lb), the SAIL accounting for 19.5 kg (43 lb) of the 50.8 kg (112 lb).

The SAIL preparation steps involved sewing 0.9-m (3-ft.) wide NMD material together with special solar radiation resistant PBI thread, using
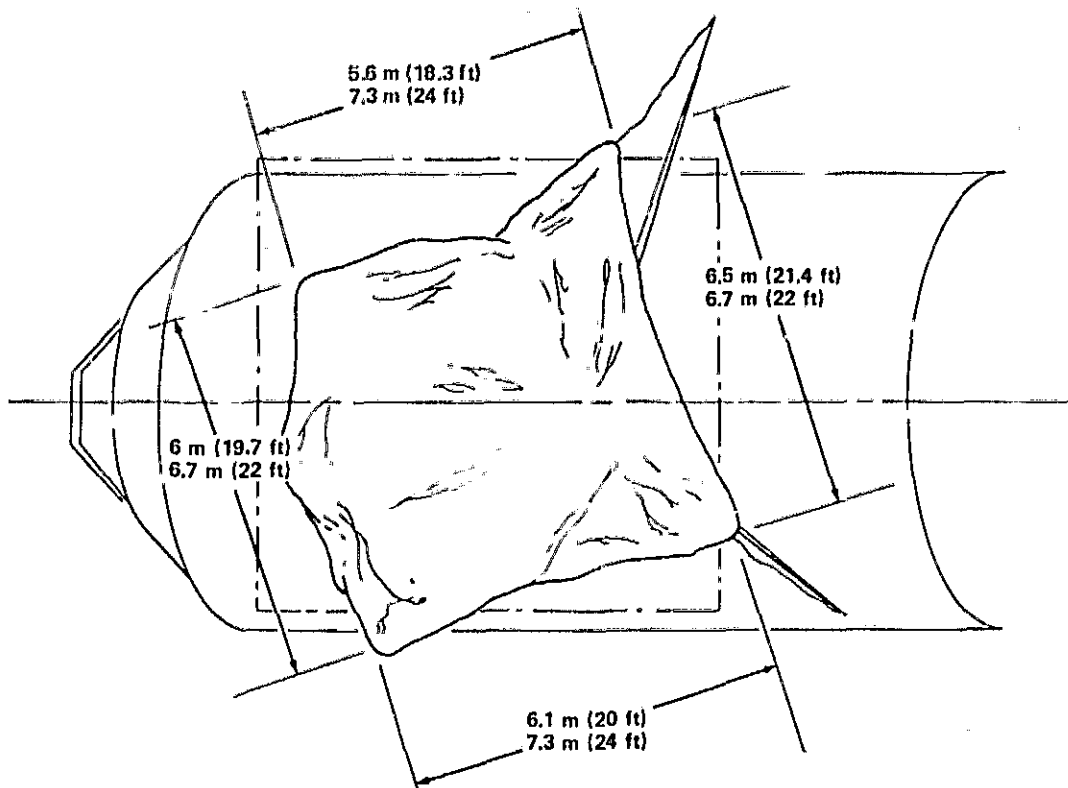
Figure 6. JSC parasol coverage comparison (actual vs. planned).

commercial sewing machines. Skilled seamstresses from International Latex Co., employed by the Johnson Space Center for space suit work, were dispatched by JSC and hurridly flown to the Marshall Space Flight Center, because the critical seamstress skill was the one thing MSFC did not have available. The SAIL edges were folded and sewn to accommodate a PBI rope guide, and grommets were sewn into each reinforced corner to provide means of attaching PBI strappings.

The thermal control material, S-13G, was sprayed onto the flight SAIL in two coats, after a primer coat of GE SS4044 had been applied. After the first SAIL had been hand sprayed in the down position, subsequent SAILS were sprayed with the NMD material in the vertical position to improve the quality. A total of four SAILS were made for potential use.

The press of the impending launch of the Skylab I crew provided constant pressure for speed in the design and development. The flight SAIL had a cure time of 57 hours before folding, and then 76 additional days in the folded condition before use.

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Following room temperature curing, the SAIL was hoisted to the vertical position again where the Mylar side (OWS facing side) was wiped with alcohol dampened cloths. The sunside S-13G material was carefully dry wiped only.

The folding operation was done by a group of U.S. Navy resident underwater simulation training personnel (Seal Team), who were also professional parachute riggers. A unique "accordion" fold was specially developed which precluded air entrapment in the package. The packaged SAIL was then placed in a vacuum chamber which was evacuated to 6.7 N/m^2 (5×10^{-2} torr) in order to extract all air and to collapse the folded material to the ultimate. After removal from the vacuum chamber, the package was a compact 35.6 by 34.3 by 20.3 cm (14 by 13.5 by 8 in.), and the SAIL folds excluded atmospheric pressure sufficiently so that subsequent exposure to the 3.4-N/cm^2 (5-psia) environment of the CM and the OWS did not cause the package to balloon or to burst. This is just another example of one of the many deceptively simple details, not a single one of which could be forgotten or overlooked, if a successful operation was to result.

An unbelievable number and variety of SAIL deployment tests were conducted in those all too brief few days in May of 1973. The design data requirements were drivers for tests which were conducted in that period at MSFC, while similar tests oriented along the JSC parasol lines were being conducted at JSC.

The Appendix constitutes a summary of the MSFC development tests. JSC also conducted development testing, while tests were also being conducted on UV degradation simultaneously at many other installations.[7] JSC and MSFC, in particular, were in continuous contact during the thermal shield development. MSFC benefitted considerably by the variety of special materials and talent provided by the Sister Center, JSC.

The general arrangement and location of the MSFC SAIL II apparatus can be seen in Figure 7.

Design details of the SAIL poles are shown in Figure 8. In testing, it was found that the knurled nuts tended to back off and work loose. Special locking O rings were designed and manufactured to prevent this.

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7. UV degradation testing of GT-76 material was conducted by Thompson Ramo Woolridge, Arnold Engineering Development Center, Goddard Space Flight Center (NASA), Lewis Research Center (NASA), and Johnson Space Center (NASA).

BASE PLATE
ASSEMBLY

REEFING LINES

SAIL POLES
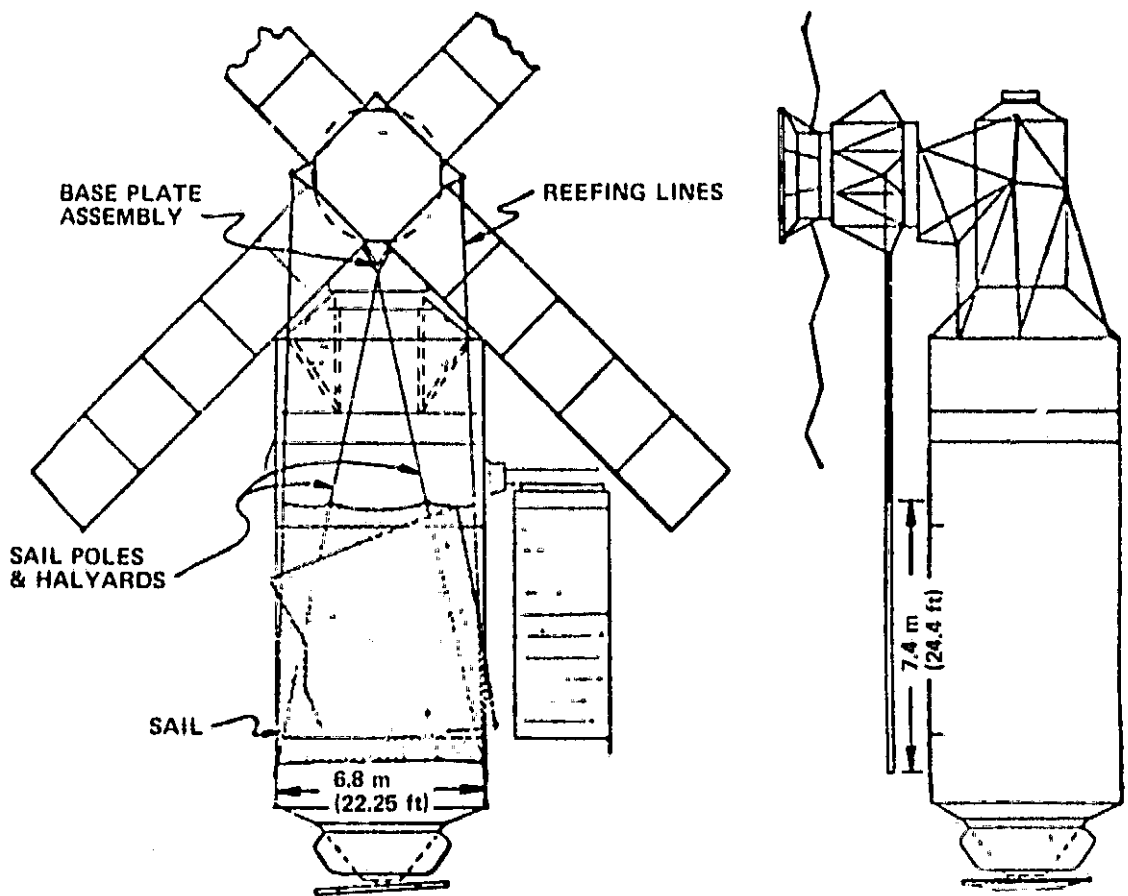& HALYARDS

SAIL

6.8 m
(22.25 ft)

7.4 m
(24.4 ft)

Figure 7.   MSFC SAIL II arrangement.

The pole baseplate (Fig. 9) shows only one of the pole sections inserted. A typical eyed-end fitting and the PBI halyard rope can be seen in the foreground.

The Navy Seal Team parachute riggers (Fig. 10) are at work applying the special accordion fold technique during the SAIL packing.

The MSFC SAIL II in the final packed configuration (Fig. 11) is shown before insertion into the Beta cloth (fiberglass) bag.

A SAIL undergoing a deployment test (Fig. 12) is shown in which the flow of the SAIL material from the bag was being checked. This view is from the OWS side, and the white S-13G material faces the deployment test engineers.
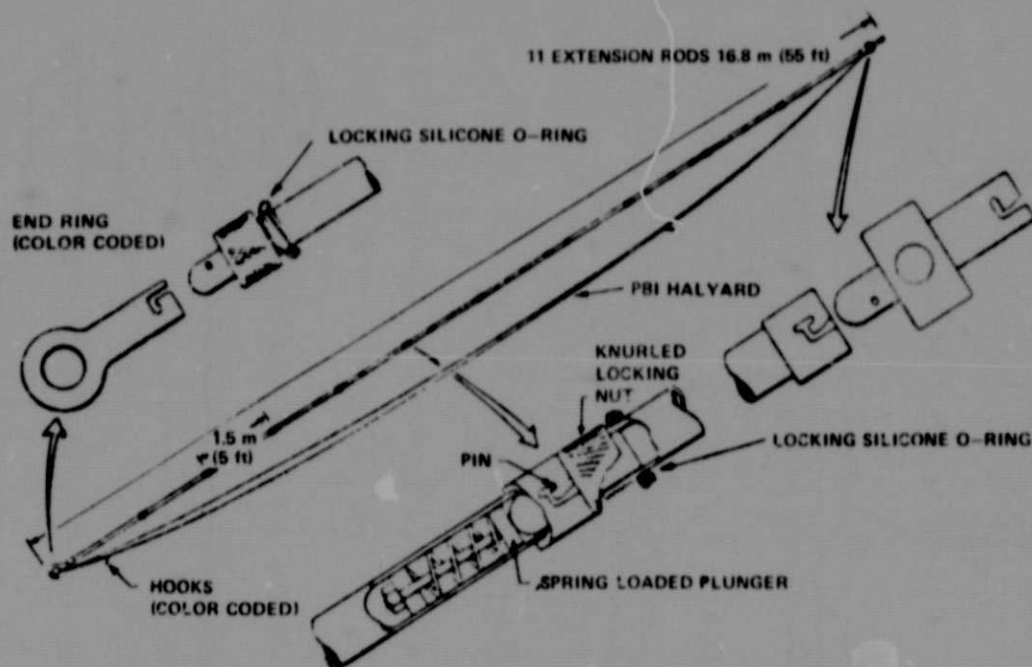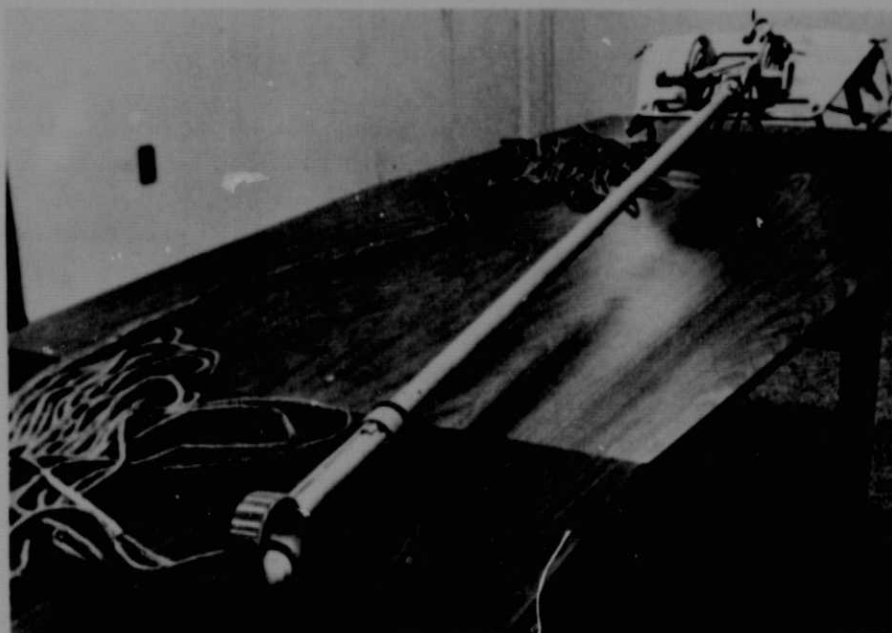
19

Figure 8. SAIL pole design details.

Figure 9. MSFC SAIL II pole baseplate with typical pole section, pole end-eye and PBI halyard rope.
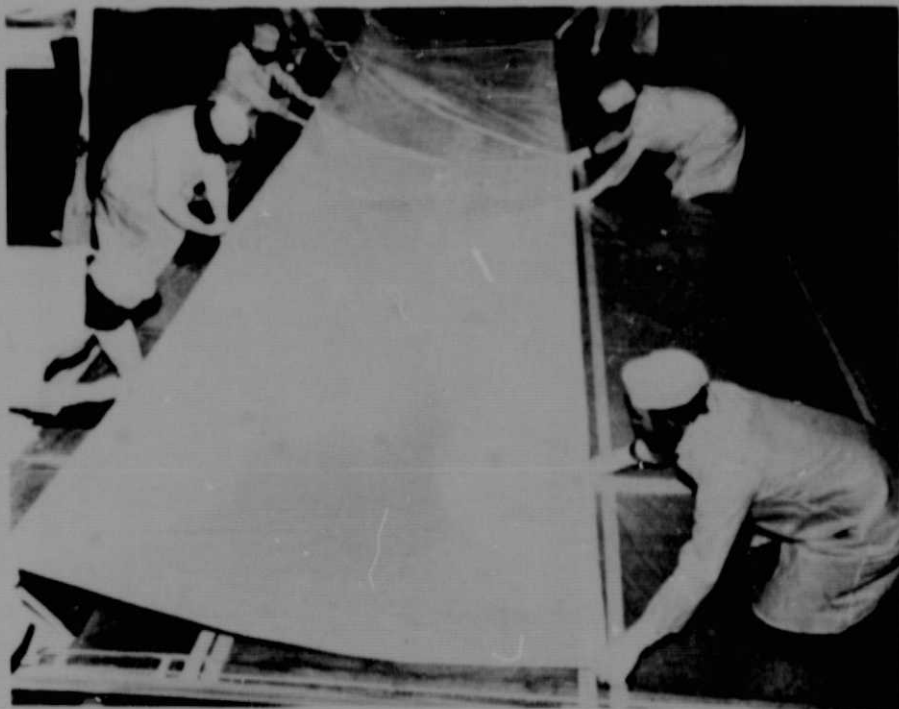
Figure 10. Navy Seal Team packing MSFC SAIL II at MSFC.

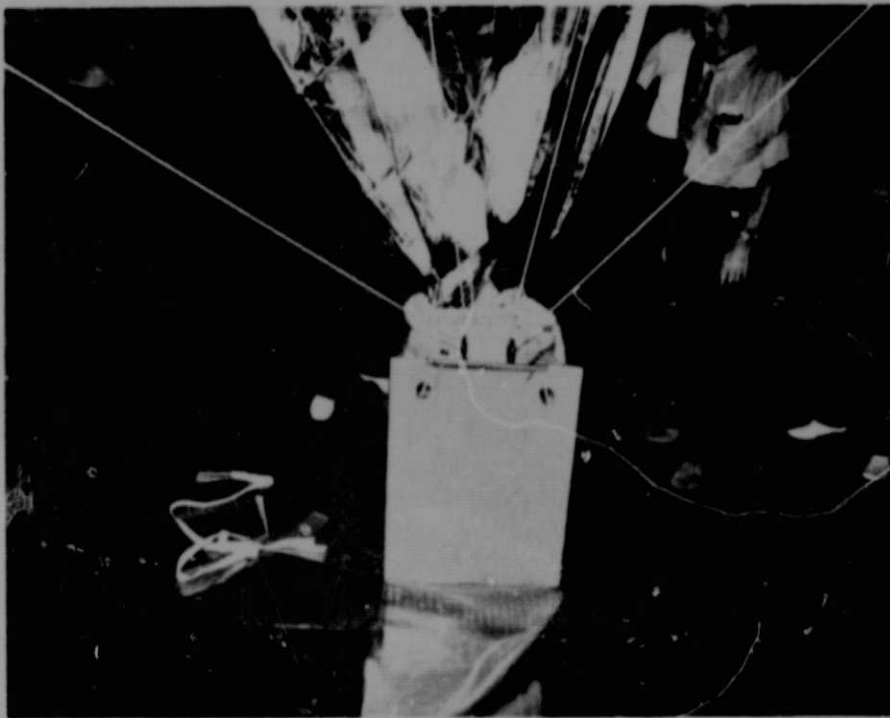Figure 11. MSFC SAIL II in the packed configuration before bagging.

Figure 12. SAIL deployment from beta cloth bag test.

A full scale deployment test (Fig. 13) was conducted at MSFC. This was the final check on a backup SAIL to determine positively that there would be no sticking of the thermal control surfaces during deployment. This was also the final deployment orientation session for the Skylab II crew, who finally deployed the SAIL on Skylab.

The actual deployment proceeded as follows:

Initially, all the required equipment was attached in the Fixed Airlock Shroud (FAS), and a crewman moved to the area where the sunshade EVA workstation was to be mounted on the ATM truss. Then the foot restraints, the sunshade baseplate, and the sunshade bag assembly were transferred to the crewman in the sunshade workstation area by means of the transfer boom. Subsequently, the foot restraint and baseplate were attached to the truss. The crewman in the FAS assembled the poles and transferred them to the other crewman who placed them into the baseplate. Following this, the sunshade was attached to the halyards on the pole assemblies and the sunshade was deployed from the bag, out the length of the poles. Finally, the crewman positioned the forward edge of the sun shade against the OWS aft skirt over the parasol, tied off the reefing lines to the ATM truss and then returned to the airlock.
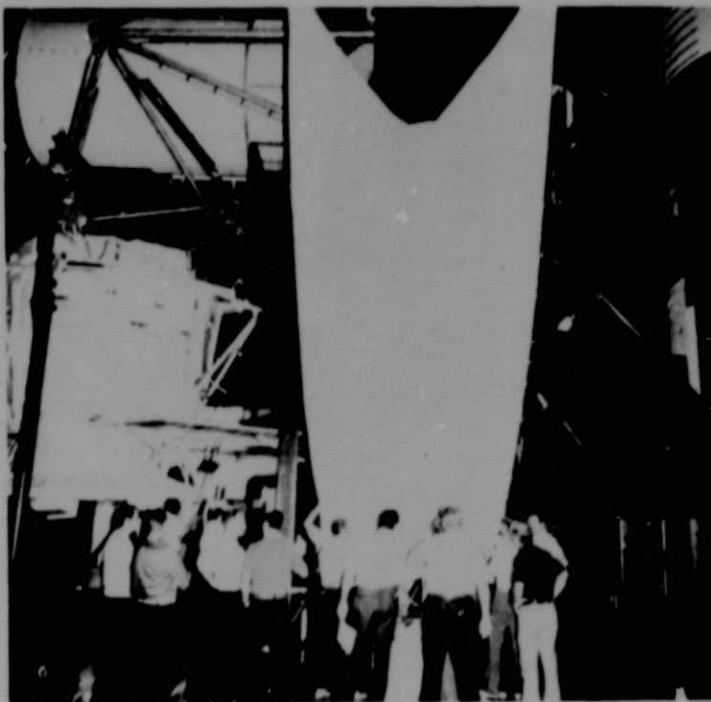
22

Figure 13. Final backup SAIL deployment and Skylab II
crew training exercise.

Figure 14 shows the deployed MSFC SAIL II. The material "memory"
characteristic and evidently a slight excess of material caused some slight
accordioning of the deployed SAIL. Subsequent measurements in the plan view,
of photographs taken during the Skylab III crew fly-around, showed that 89 per-
cent of the expected coverage had been attained. In retrospect, it is highly
probable that the 76 day stowage period in the packed, partially evacuated con-
dition, caused some material set, but in the brief 10 day design, development
and test period available before the launch of the Skylab I crew, no meaningful
"accelerated" aging, or "memory" tests could be devised. Short time memory
and aging tests of witness specimens did not exhibit the accordioning tendency.
The general performance of the thermal shields will be discussed next.

PERFORMANCE OF SKYLAB THERMAL SHIELDS

Temperatures inside the Skylab those first hours rose to unanticipated
peaks, even exceeding the limit of the interior sensors, which was about 48.9°C
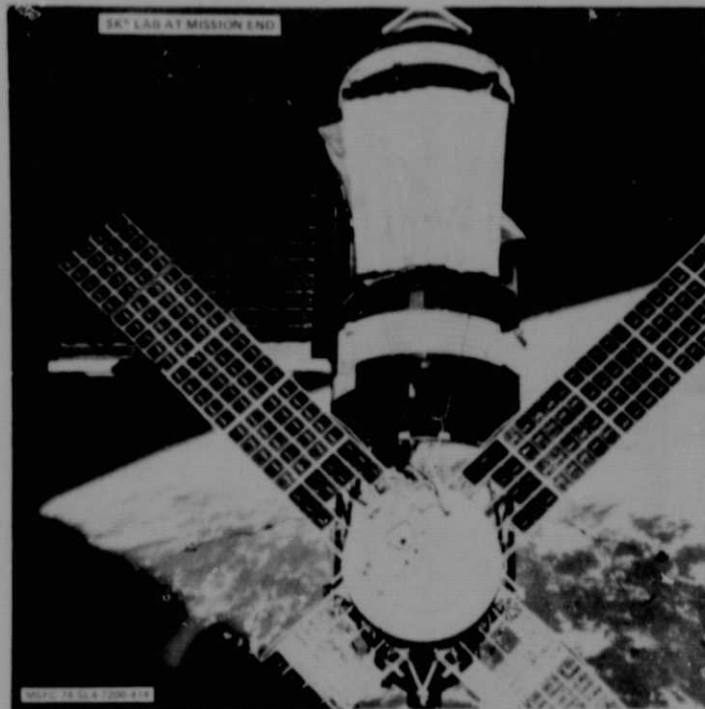(120°F). Fortunately, an elaborate computerized thermal model had been

Figure 14. MSFC SAIL II deployed on Skylab.

developed in advance by thermal engineers at MSFC. By supplying telemetered data to this model, temperatures could be predicted to a certain extent, when other variables such as Skylab attitude, loss of the micrometeoroid shield, and other variables were fed in. The initial studies showed that unless orbital attitude was changed, the mean internal temperature was likely to reach 71.1°C (160°F) during the first 10 days. This gave serious concern about food stored in the food containers and scientific experiment film stored in the film lockers. The food and film containers reached 55.6°C and 50°C (132°F and 122°F) respectively, just before the parasol was deployed. The parasol deployment dropped the food and film containers temperature to approximately 27°C (80°F), except for a few times later when high Beta angles were employed. The Beta angle refers to the acute angle between Earth/Sun line and orbital plane, high Beta angles allowing corresponding increased heating of Skylab.

The early parasol deployment insured negligible damage to food and film. Another serious potential problem resulted from high internal temperatures. Interior OWS wall temperatures of 132°C (270°F) were reached, causing serious concern about the possibility of TDI (toluene diisocyanate) evolving from the aluminum-foil-covered polyurethane foam. Designers also worried about the

complete loss of the Lefkoweld 109 adhesive bond to the OWS interior, and possible displacement of interior insulation. Real time, crash program tests of OWS skin sections, fabricated at the same time as the orbiting OWS, showed that blistering of the foil overcoat would occur, but "the wall should remain integral, and could be expected to meet the normal insulative and structural requirements to be expected in the mission."[8]

The same report concluded that no appreciable TDI from the OWS foam would be emitted below approximately 149°C (300°F), but even if emitted, the TDI would react rapidly with internal OWS moisture to produce far less toxic amines. Specific diagnosis for TDI prior to ingress by the Skylab I crew showed no presence of TDI.

Against that background of extreme urgency, the JSC parasol was easily the most logical means of gaining some immediate relief without the risk of early EVA.

After the JSC parasol was deployed on May 27, 1973, the internal temperatures decreased 16.7°C (30°F) in two days. The crew, however, observed that the shield did not completely open, and a day after the deployment, flight data began to differ from that predicted analytically by the thermal model. During the SL-1/SL-2 storage period the temperature reached 36.7°C (98°F) during a high Beta angle period. During departure of Skylab II crew, fly-around photos confirmed that the actual shade coverage was only 75 percent (Fig. 6).

With the parasol shield, as deployed, solar heating overloaded the Environmental Control System (ECS) and internal temperatures became excessive at high Beta angles.[9] When the MSFC SAIL II was deployed over the parasol on June 19, 1973, the OWS external wall temperature dropped 56°C (100°F) within the first few hours, and the OWS mean internal temperature decreased immediately by about 3.9°C (7°F). Thereafter, the internal temperatures fluctuated in response to Skylab attitide changes, but the combined parasol and sail thermal shield composite maintained the internal temperature within the established habitability "comfort box" most of the time, allowing the operation of heat generating experiments and other equipment through the completion of the Skylab mission.

8. "Skylab Overheating Wall Material Degradation Studies," Materials Division, MSFC, May 15-29, 1973.

9. "MSFC Skylab Thermal and Environmental Control System Mission Evaluation Report," Hopson, Littles and Patterson, NASA Technical Memorandum X-64822.

It turned out that, like the parasol, the sail was also incompletely deployed, and only 89 percent of the OWS sidewall was covered. This was due largely to creases in the sail which refused to flatten out completely after the long storage period experienced before deployment (76 days in the folded condition). Fly-around photos indicated also that more "stretch" could possibly have been employed by slightly different design. While neither of the shields was perfect, the combination of the two did the job nicely.

The decision to deploy the sail over the parasol was a crucial one which took into account several factors of considerably importance, and was intended to provide additional safety margin. Parasol and SAIL materials properties and deployment conditions which were of concern and influenced that final decision, were:

1. GT-76 material UV/vacuum solar degradation affecting:

    a. Breaking strength in the warp (weakest) direction of the material.

    b. Elongation in the warp direction.

    c. Changing α and ϵ with exposure time.

2. Mechanical considerations such as violent flapping of the parasol edge nearest the TAC nozzle, when the TACS fired, and the additional flexing of the GT-76 material due to the flexibility of the extended telescoping support tubes.

3. Possible degradation of the Mylar on the OWS side of the MSFC SAIL II due to earth albedo radiation.

The general trend of degradation of the GT-76 material breaking strength (Fig. 15) is shown in the warp (weakest) direction with continued UV/vacuum exposure as determined in the ground tests. Initially, this was considered quite alarming because the minimum strength required just wasn't known.

Dynamic structural analyses of the flapping of the parasol from the TACS firing finally concluded that 5 pounds-per-inch of width strength would be adequate to prevent tearing, but there was great reluctance, in general, to allow that limit to be approached. The 4000-hour data point shows the result of a measurement taken on a sample of GT-76 parasol material returned from Skylab. This point shows slightly higher strength remaining than the projected curves of the ground based data would imply. Almost all the ground test UV/vacuum test

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INVESTIGATOR	GT 76 TEMP	RAD. SOURCE	CHAMBER CONDITIONS
• AEDC #4	29°C (85°F)	Xe LAMP, 4S	LN$_2$ SHROUD
+ LaRC #1		CARBON ARC W/DEUTERIUM 4S	LN$_2$ SHROUD
O GSFC #2	40°C (104°F)	Xe LAMP, 2S	LN$_2$ SHROUD
⑦ MSFC #7	93°C (200°F)	Xe LAMP, 2S	NO SHROUD
☐ JSC	38°C to 121°C (100°F to 250°F)	CARBON ARC 2.5 s	LN$_2$ SHROUD
△ TRW			
¦ END OF TEST			
● GT-76 (FLIGHT SAMPLE-SKYLAB)		SOLAR	SPACE

BREAKING STRENGTH, PER cm (in.) WIDTH

203.2 (80), 177.8 (70), 152.4 (60), 127.0 (50), 101.6 (40), 76.2 (30), 50.8 (20), 24.4 (10)

RT TEST (BREAKING STRENGTH)

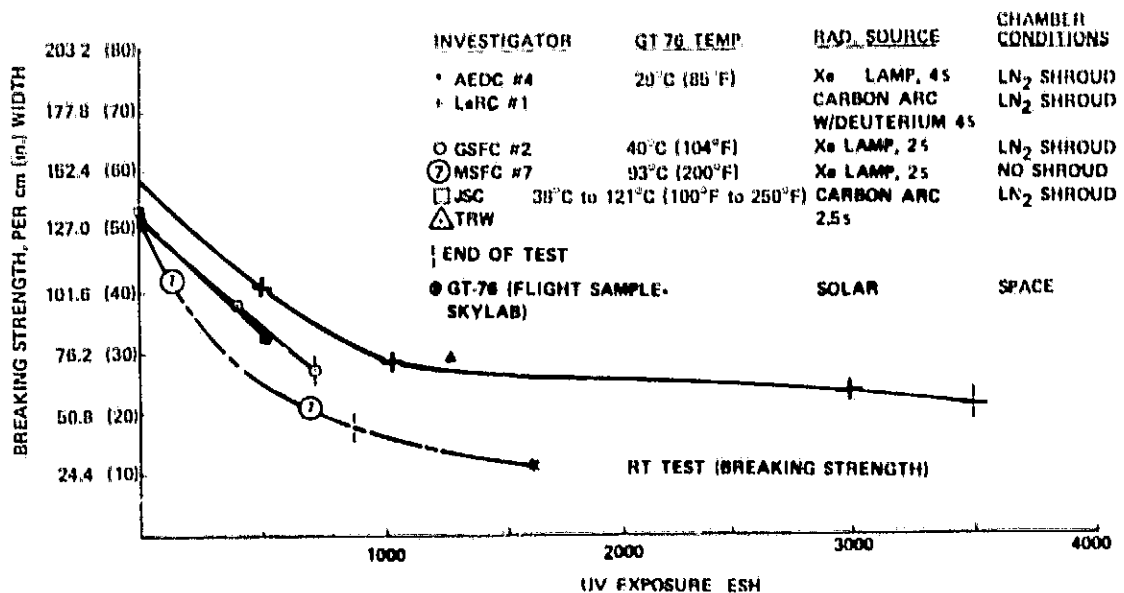UV EXPOSURE ESH — 1000, 2000, 3000, 4000

Figure 15.   GT-76 room temperature breaking strength per centimeter (inch) of width vs. UV/vacuum exposure in equivalent sun hours (nylon to sun, warp direction).

data showed a tendency to be slightly more severe than the actual orbital condition. This could only be concluded in retrospect, however. Since UV source and intensity, substrate temperature, and chamber cold wall arrangement were influential factors in the ground test data; actual test conditions were carefully noted so that flight data comparisons could be made later. Flight samples have given rise to continued tests regarding properties, which are still in progress at the time of this writing.

The effect of UV/vacuum degradation is shown (Fig. 16) on the GT-76 material room temperature elongation. Not unexpectedly, these data also showed an alarming tendency to decrease with increased exposure. This raised concern about the brittleness, primarily of the 2 1/2-mil ripstop Nylon and 1/2-mil Mylar of the GT-76 material being exposed to the sun.

A substrate temperature of about 89.4°C (193°F) for a Beta angle of 73 deg was analytically predicted for the deployed parasol, and we attempted to approach that substrate temperature in most of our testing, although precise control of substrate temperature proved difficult to attain. The MSFC SAIL II deployed-condition temperature was predicted to be about 13.9°C (57°F) for the same 73 deg Beta angle (worst heating case).
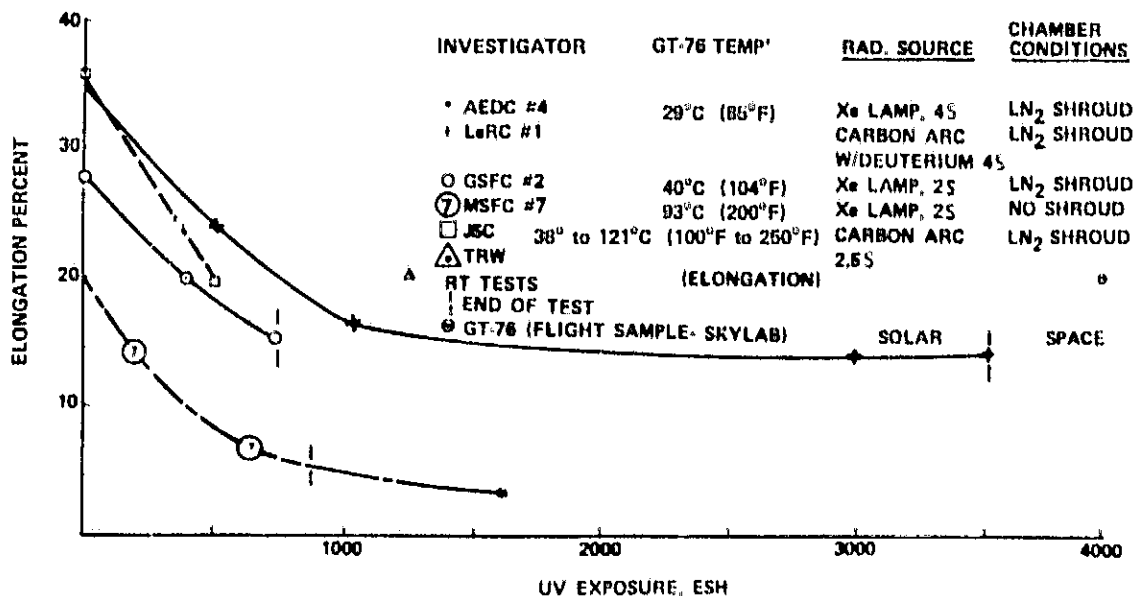
INVESTIGATOR	GT-76 TEMP'	RAD. SOURCE	CHAMBER CONDITIONS
• AEDC #4	29°C (85°F)	Xe LAMP, 4S	LN$_2$ SHROUD
♦ LeRC #1		CARBON ARC W/DEUTERIUM 4S	LN$_2$ SHROUD
O GSFC #2	40°C (104°F)	Xe LAMP, 2S	LN$_2$ SHROUD
⑦ MSFC #7	93°C (200°F)	Xe LAMP, 2S	NO SHROUD
□ JSC	38° to 121°C (100°F to 260°F)	CARBON ARC 2,6S	LN$_2$ SHROUD
△ TRW			
▲ RT TESTS	(ELONGATION)		Θ
┃ END OF TEST			
⊖ GT-76 (FLIGHT SAMPLE- SKYLAB)		SOLAR	SPACE

Figure 16.   GT-76 room temperature elongation in percent versus UV/vacuum
exposure in equivalent sun hours (nylon to sun, warp direction).

The change in the α/ϵ ratio (Fig. 17) is shown for the GT-76 material.
This ratio was obtained from ground based UV/vacuum testing. The isolated
data point at the right is a returned Skylab sample data point.

Early tests of breaking strength and elongation showed little change for
the S-13G covered NMD material of the MSFC SAIL II, as expected, so long
duration tests of these properties were not conducted. Because the 5-mil S-13G
coating provided complete opacity (measured transmittance was 0. 1 percent in
the 2000-4000 Å range) there was no degradation of the Nylon ripstop, and
aluminized mylar substrate.

Figures 18 and 19 show the breaking strength and elongation of the
MSFC SAIL II material tested to 400 ESH, after which the tests were terminated
since no appreciable change was noted.

An early concern was raised about the possibility of degradation of the
backside of the MSFC SAIL II resulting from earth's albedo radiation, since the
sail material "OWS side" layer of the material composite was 1/4-mil Mylar.
Again, UV/vacuum exposure testing was conducted to determine the effect on
breaking strength, elongation and α/ϵ of the exposure of the under side of the
SAIL to the sun.   Timeline estimates indicated an absolute maximum of about
50 hours exposure of the underside of the sail to the sun, to the end of the Skylab
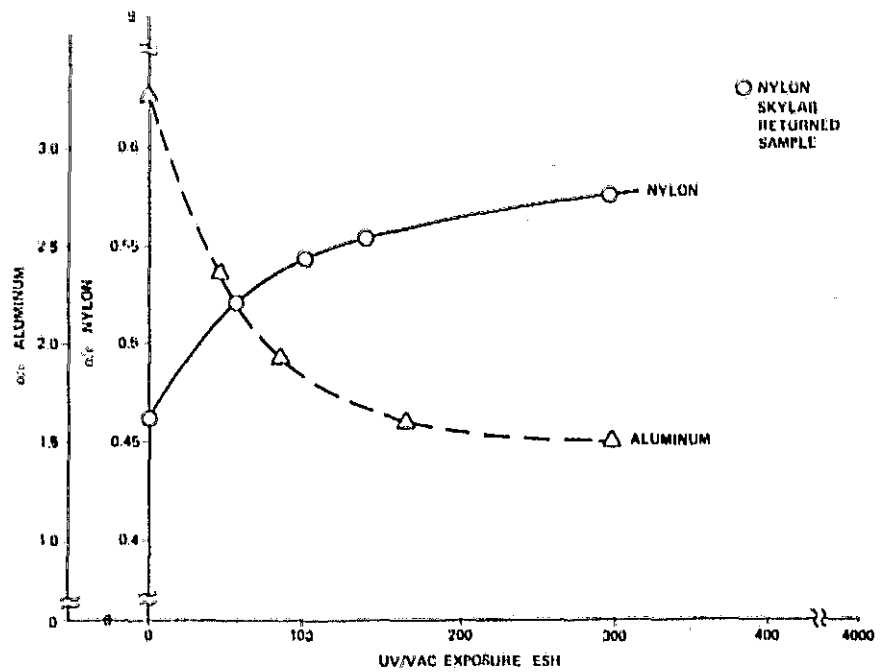mission, so exposure to one hundred ESH was considered quite adequate.

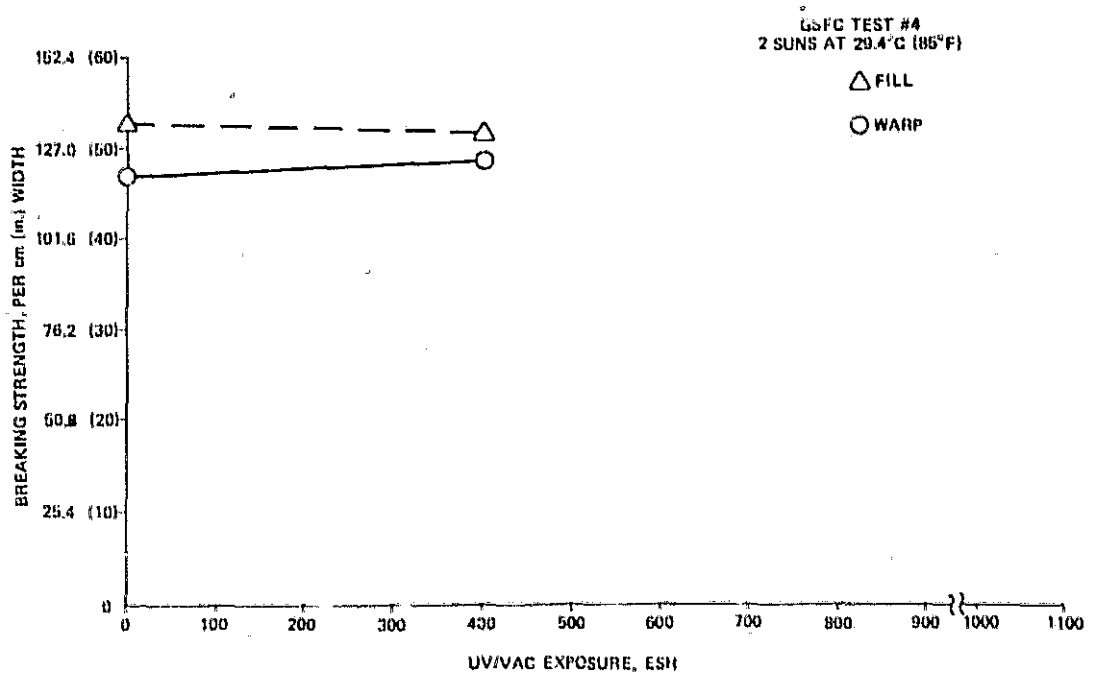Figure 17. GT-76 α/ε versus UV/vacuum exposure (Nylon to sun).

Figure 18. MSFC SAIL II breaking strength versus UV/vacuum
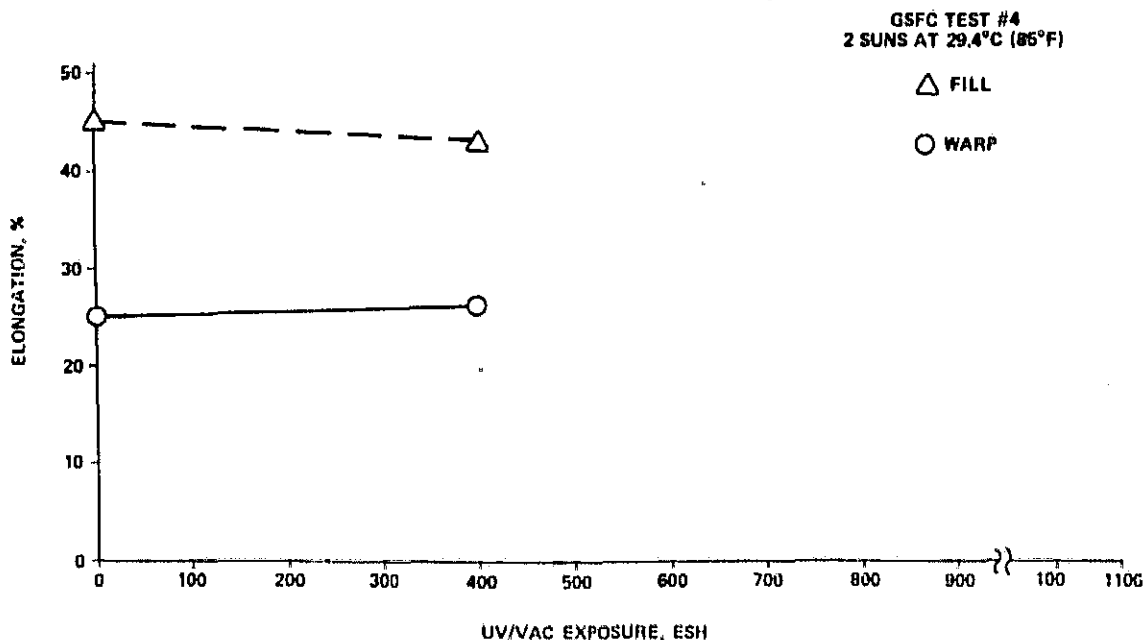exposure (S-13G to sun).

GSFC TEST #4
2 SUNS AT 29.4°C (85°F)

△ FILL

○ WARP

Figure 19. MSFC SAIL II elongation versus UV/vacuum exposure
(S-13G to sun).

Figures 20, 21, and 22 show the breaking strength, elongation, and α/ϵ for the 100-hour UV/vacuum around test exposure. Interestingly, the strength and elongation properties of the S-13G coated MSFC SAIL II actually did not vary much with direction (warp or fill) of the Nylon ripstop weave orientation during the test because the coating tended to distribute the load more evenly. It turned out that breaking strength and elongation did not change appreciably either, for the Mylar backside irradiated SAIL material, but the α/ϵ of the Mylar did change as expected. The absorbtance α changed from 0.18 to 0.27 while the emittance held constant. This shows again the great propensity for change of α/ϵ of Mylar in a UV/vacuum environment. At any rate these tests showed that fears about the damaging effects of earth's albedo on the backside of the MSFC SAIL II were groundless. Furthermore, it turned out that by deploying the sail over the parasol, the backside of the sail was well covered anyway. In addressing the potential UV/vacuum degradation of the MSFC SAIL II, S-13G UV/vacuum degradation data already existed at the time of the thermal shield all-out effort.

Figure 23 shows absorptance (α) data from IITRI (Illinois Institute of Technology Research Institute) for contaminated S-13G at 7.2°C (45°F) substrate temperature and 67.2°C (153°F) substrate temperature, some early ATM flight data, and a data point from a Skylab returned sample of S-13G coated NMD material which
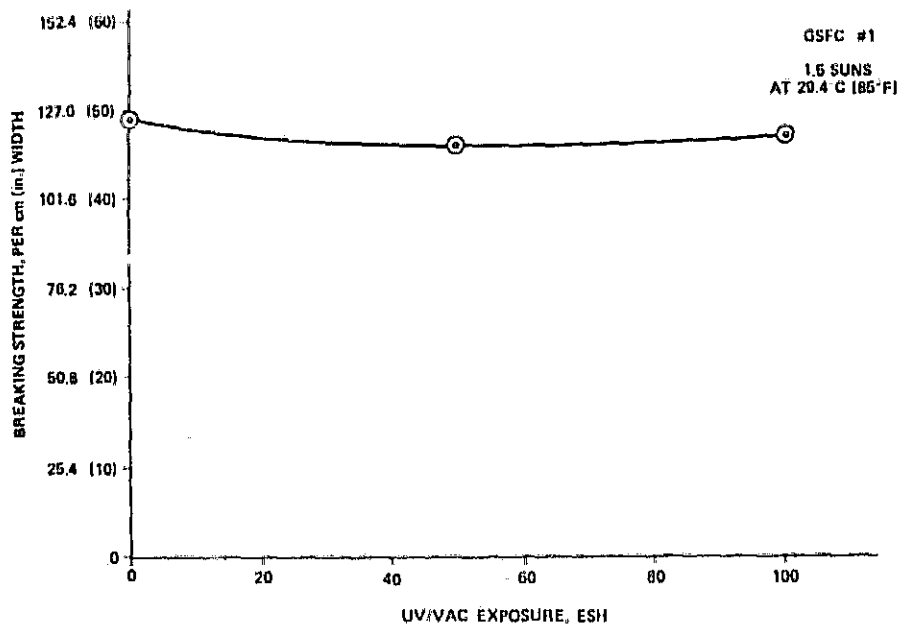
30

Figure 20. MSFC SAIL II breaking strength versus UV/vacuum
exposure (Mylar to Sun).

had "seen" 1176 ESH in orbit. It is interesting to note that the contaminated
S-13G data from the ground testing tracked so well for the S-13G coating on the
ATM, and the recovered flight sample. Earlier laboratory data on absolutely
clean S-13G material showed very little degradation in 4000 ESH, but all
indications are that contamination somewhat influenced the performance of the
S-13G on the MSFC SAIL II, as well as other surfaces on Skylab which were
painted with S-13G. Fortunately, the thermal performance of the S-13G material
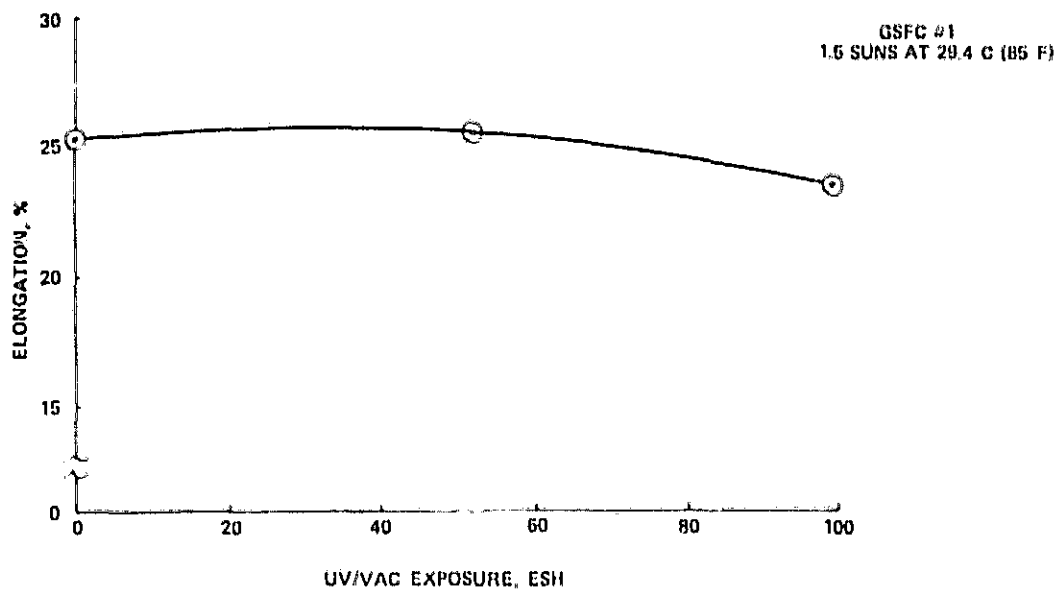was still relatively good in spite of a degree of contamination.

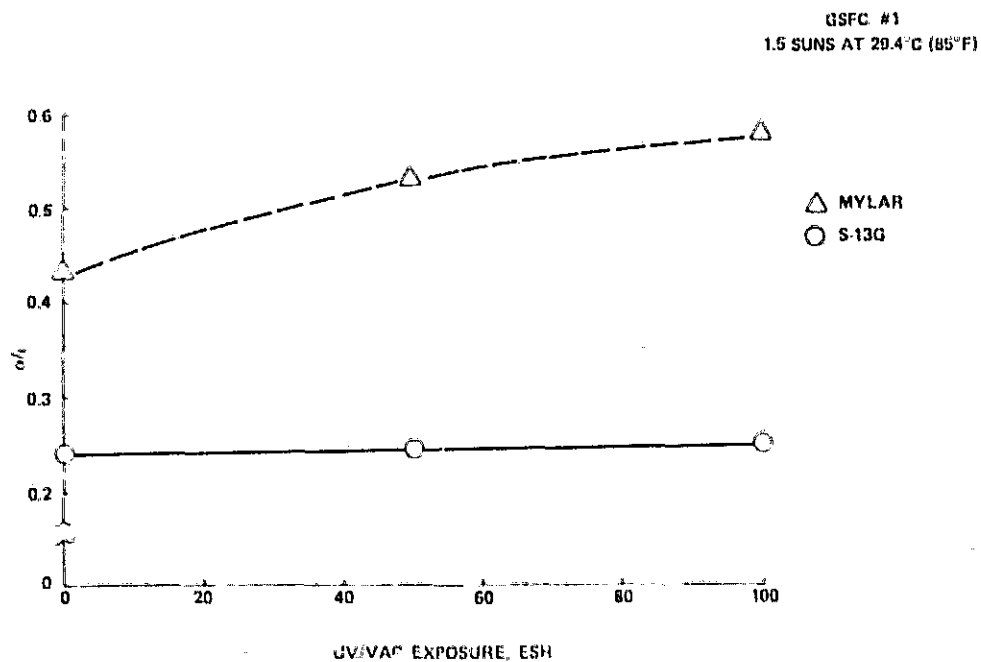Figure 21. MSFC SAIL II elongation versus UV/vacuum exposure (Mylar to sun).

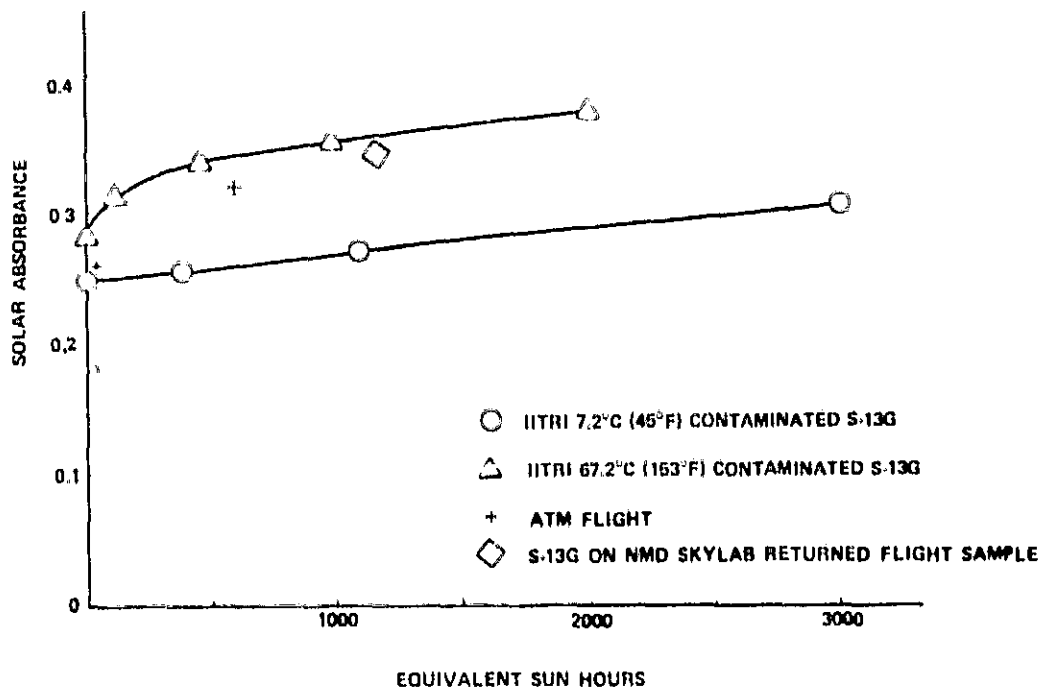Figure 22. MSFC SAIL II α/ε versus UV/vacuum exposure (Mylar to sun).

Figure 23. S-13G thermal control material α vs. ESH (ground and flight data).

APPENDIX — TESTS PERFORMED FOR MSFC SAIL II DEVELOPMENT

1. S-13G coated NMD (MSFC SAIL) butt tensile tests.

2. S-13G coated NMD (MSFC SAIL) 180 deg peel tests.

3. S-13G coated NMD (MSFC SAIL) stickiness (unfolding) tests.

4. GT-76 material breaking strength tests.

5. GT-76 material tear strength tests.

6. GT-76 material elongation tests.

7. 0.635-cm (0.25 in.) diameter PBI rope breaking strength tests.

8. 0.635-cm (0.25 in.) diameter PBI rope modulus tests.

9. 0.635-cm (0.25-in.) diameter PBI rope length change tests under static load with temperature cycling.

10. 0.635-cm (0.25-in.) diameter Teflon coated Beta glass rope modulus under low load conditions.

11. 0.635-cm (0.25-in.) diameter Teflon coated Beta glass rope modulus under high load conditions.

12. 0.3175-cm (0.125-in.) diameter Teflon coated Beta glass cord un-irradiated breaking strength tests.

13. 0.3175-cm (0.125-in.) diameter Teflon coated Beta glass cord un-irradiated elongation tests.

14. 0.3175-cm (0.125-in.) diameter Teflon coated Beta glass cord UV irradiated breaking strength tests.

15. 0.3175-cm (0.125-in.) diameter Teflon coated Beta glass cord UV irradiated elongation tests.

16. On all MSFC SAIL hardware — strength of rope splices and pull-out strength of hardware.

APPENDIX (Continued)

17. Compatibility tests of film and coatings with other coating solvents and cleaning fluids.

18. Continuous precision weight measurements on films, coatings and SAIL hardware.

19. Effect of UV and vacuum on SAIL material breaking strength.

20. Effect of UV and vacuum on SAIL material elongation.

21. Effect of UV and vacuum on SAIL material flexibility.

22. Effect of UV and vacuum on SAIL material α and ϵ.

23. Effect of UV and vacuum on SAIL material solar transmittance.

24. Effect of UV and vacuum on SAIL material weight change.

25. Effect of UV and vacuum on SAIL material particle generation propensity.

26. Microphotographic examination of UV degraded SAIL materials and photos.

27. Thermal cycling tests of MSFC, JSC, Armalon, etc., materials, $-101°C$ ($-150°F$) to Room Temperature (RT) in air.

28. Thermal cycling tests of MSFC, JSC, Armalon, etc., materials, RT to $121°C$ ($+250°F$) in vacuum.

29. Flexibility tests of S-13G coated NMD at LN_2 temperature.

30. RT to LN_2 temperature cyclic tests of GT-76, fluorel GT-76 and S-13G coated NMD.

31. Outgassing (50M02442) testing of MDAC Teflon coated Beta fiberglass, Fluorel coated GT-76, S-13G on Tedlar, S-13G on NMD, GT-76 alone and the red and green paint used for identification on SAILS.

32. S-13G coated NMD "sticking," or tack tests in vacuum under 10.3 N/cm^2 (15-psi) load.

APPENDIX (Concluded)

33. 10 standard spacecraft flammability tests of S-13G coated NMD, GT-76 alone and Teflon coated fibergalss (duct material).

34. 646 measurements of α and ϵ on 31 materials.

35. Evacuation of packed "worst case" Kapton SAIL to determine air retention characteristics.

36. Evacuation of packed S-13G coated NMD SAIL to determine air retention characteristics.
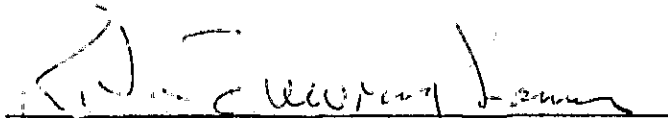
37. Toxicity test of S-13G coated GT-76.

APPROVAL

PERFORMANCE OF SOLAR SHIELDS

By Robert J. Schwinghamer

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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