ESD-TR-85-324

Technical Report
742

The Solar Shield: A Thermally Insulating, Broad-Band, Electromagnetic Window for Satellites

M.S. Powell
D.M. Nathanson
E.B. Murphy

2 June 1986

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

Prepared for the Department of the Air Force
under Electronic Systems Division Contract F19628-85-C-0002.

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the Department of the Air Force under Contract F19628-85-C-0002.

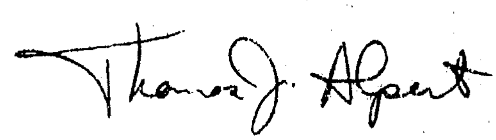
This report may be reproduced to satisfy needs of U.S. Government agencies.

The views and conclusions contained in this document are those of the contractor and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the United States Government.

The ESD Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



Thomas J. Alpert, Major, USAF
Chief, ESD Lincoln Laboratory Project Office

Non-Lincoln Recipients

PLEASE DO NOT RETURN

Permission is given to destroy this document when it is no longer needed.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

THE SOLAR SHIELD: A THERMALLY INSULATING, BROAD-BAND, ELECTROMAGNETIC WINDOW FOR SATELLITES

M.S. POWELL
Group 61

D.M. NATHANSON
Group 73

E.B. MURPHY
Consultant

TECHNICAL REPORT 742

2 JUNE 1986

LEXINGTON MASSACHUSETTS

ABSTRACT

A space-qualified, thermally insulating, broadband, electromagnetic window for satellite applications is described. A multiple-layer construction is used, with each layer consisting of quartz fiber paper sandwiched between two sheets of Kapton. The measured insertion loss is less than 0.25 dB at frequencies up to 50 GHz. When exposed to full solar radiation (127 W/ft^2), about 5 W/ft^2 are transferred through the thickness of the window into a 20°C background in the interior of the satellite. Under eclipse conditions, about 3 W/ft^2 are radiated from the satellite into the cold space background compared with nearly 40 W/ft^2 without the window. The reasons for this performance are explained, and detailed descriptions of the experimental evaluations are given. A brief summary of the space-qualification testing is also included.

A-1

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

THE SOLAR SHIELD: A THERMALLY INSULATING, BROADBAND, ELECTROMAGNETIC WINDOW FOR SATELLITES

I. INTRODUCTION

A satellite scheduled for launch in the near future includes an add-on, extremely-high-frequency (EHF) communications system. In order to accomodate this new system, holes had to be cut in the existing ultra-high-frequency (UHF) downlink reflector, through which the EHF antennas will transmit and receive. These holes, if left uncovered, would permit unacceptably large temperature fluctuations inside the satellite. Thus there was a need to develop a "solar shield" that is thermally insulating and relatively opaque to the solar spectrum but virtually transparent at both the uplink and downlink frequencies (44 and 20 GHz). In addition to having these performance characteristics, the shield also had to be fabricated of materials suitable for a space environment and sturdy enough to survive the rigors of a rocket launch.

This report describes the design and performance of such a solar shield. Under orbital conditions, energy transfer at wavelengths ranging from the infrared to the ultraviolet will be restricted to only a few watts per square foot, whereas at EHF wavelengths, most of the energy will be transmitted (over 94 percent, corresponding to an insertion loss of 0.25 dB). The efficiency of the solar shield is not a result of maintaining tight tolerances; fabrication requires only a normal amount of care.

Section II describes the design of the solar shield. The basic design concepts are outlined, the particular choices of materials are explained, the additions to the basic design required for space qualification are listed, and the fabrication procedure is reviewed. Section III describes the shield's evaluation and performance at wavelengths ranging from the infrared to the ultraviolet. In Section IV, the various techniques, both theoretical and experimental, used to evaluate the shield's performance at EHF wavelengths are described, and the results are presented. Brief descriptions of all the tests used to assure that the shield is space-qualified, along with the results of the tests, are given in Section V. As with most development projects, the solar shield was fabricated in a limited period of time; therefore, Section VI addresses existing problems, especially quality control, and includes recommendations for improvement. This is followed by a summary. Finally, details of the fabrication procedure are given in the Appendix.

II. DESIGN

A. CONCEPTS

The inner face of the solar shield will be exposed to a relatively benign environment inside the satellite; the outer face will be exposed alternately to a very hot heat source and a very cold heat sink as the satellite moves from full sun into eclipse. Thus, in general, there will be a large temperature difference between the two faces and a corresponding tendency for energy to be transferred from the hotter to the colder.

Multiple layers of thermal shielding were used to inhibit heat transfer between these two faces. Conduction was virtually eliminated by using polyester netting (mesh) to keep the layers separated. The heat transferred through the shield by the processes of absorption, transmission, and re-radiation is roughly proportional to the inverse of the number of layers. A thermal analysis indicated that only five layers of a reasonably opaque material would be sufficient to reduce the energy flow to an acceptable upper limit for this application.

Because of the multiplicity of layers, the finished assembly turned out to be electrically thick — the netting alone contributed about 80 mils, or three-tenths of a wavelength at the uplink frequency. Furthermore, most of the materials under consideration were flexible. The netting placed between these flexible layers served only to guarantee a minimum separation; no attempt was made to restrict the maximum other than by gently pulling the entire assembly taut. This made it impossible to hold any sort of tolerances in layer spacing and, therefore, impossible to use RF matching techniques such as using a half-wavelength thickness. Instead losses were minimized by using only low-loss materials. These materials were either thin or had a low dielectric constant or both.

B. MATERIAL CHOICES

Quartz was selected as the primary material because of its superior radiation stability and attractive dielectric properties. Quartz in fabric form had first been proposed by Eagles[1] for thermal control surfaces on satellites.

In previous applications, the filament size of the quartz fiber was 8 to 10 μm. This large diameter was warranted so that the fiber would be strong enough to be woven. Fortuitously, quartz paper* with filaments only one to two microns in diameter became available. Table 1 illustrates the advantage that the paper enjoys over the quartz cloth: the quartz paper is only one third as massive and yet transmits a third less solar radiation than the quartz cloth. Light is trapped and reflected numerous times by the multitude of filaments in the paper. To some extent, the holes in the weave of the fabric contribute to its greater transmission. For thermal control the obvious choice was the quartz paper.

---

* Mead Corp. quartz paper grade 153A.

TABLE 1

Quartz Fiber Properties

Material	Percent Transmission Visible Range	Mass (MG/cm^2)	Fiber Diameter (Microns)	Number of Fibers Per cm^2
Stevens #581 Fabric (10 mils)	30	28	8-10	25,000
Mead Quartz Paper #153-A-7050 (20 mils)	20	9	1-2	130,000

Quartz paper also provides a very good compromise between low dielectric constant and thinness: it has a dielectric constant of about 1.27 and is only about 0.02 in. thick. This compares favorably with woven quartz cloth, which although slightly thinner is much denser and therefore has a significantly larger dielectric constant. It also compares favorably with shuttle tile material, which is also made of quartz fibers, and which can be obtained with a dielectric constant as small as 1.2 but is difficult to machine to thicknesses less than about 1/4 in. without breakage.

The one disadvantage of the quartz paper is that it is somewhat flimsy. Additional structural support was provided by fusing one side of the paper to FEP teflon-coated Kapton* in a laminating press. Kapton was chosen for this purpose because of its proven stability as a thermal blanket material and its resistance to solar irradiation. However, its dielectric constant is fairly large ($\epsilon_R = 3.25$), as is its loss tangent ($\tan\delta \simeq .01$), so a layer as thin as possible was desirable. A one-mil thick film was chosen as an acceptable compromise between thinness and strength.

The FEP Teflon ($\epsilon_R = 2.01$, $\tan\delta = .0008$) was also one mil thick. It was used as "glue" to bond the quartz paper to the Kapton. It melts slightly during the fusing process and flows into the quartz paper. Although Teflon tends to become brittle in a space environment, in this instance it needs to survive only for the duration of the launch. Once the satellite is in orbit, any forces exerted on the shield will be minimal, and the Teflon becomes superfluous.

The unbonded side of the quartz paper was covered with a one-mil sheet of plain Kapton†. The entire assembly, Figure 1(a), was bonded around the perimeter, covering the quartz paper for cleanliness while preventing only loose quartz fibers from escaping.

A non-outgassing, polyester netting‡ was chosen to separate the composite layers from each other.

* DuPont Corp. Kapton film type 200F011.
† DuPont Corp. Kapton film type 100H.
‡ Apex Mills style B-29, 190 mesh/in^2.

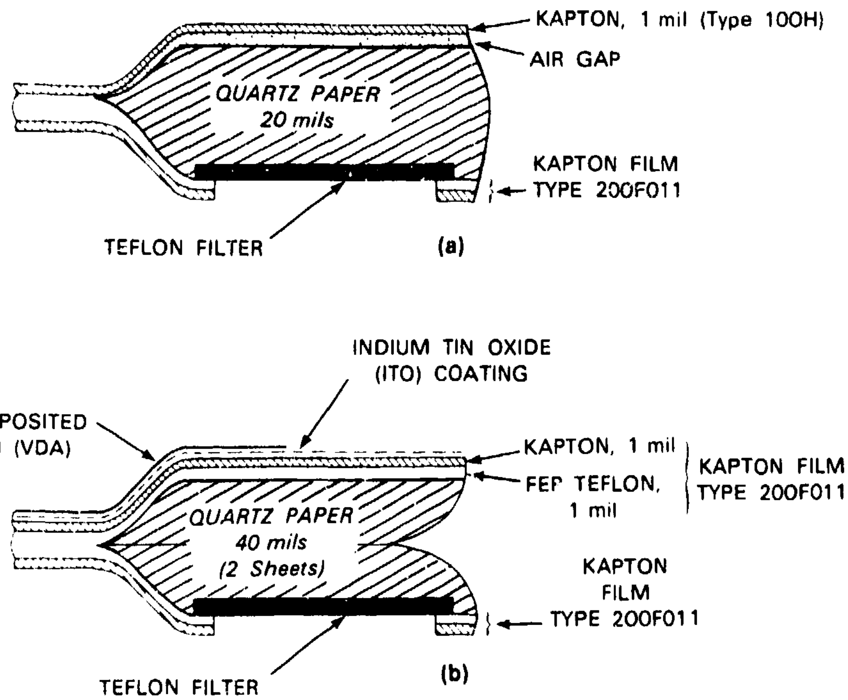


Figure 1. Construction of solar-shield typical inner layer (a) and outermost layer (b).

C. SPACE QUALIFICATION

The preceding section describes the basic configuration of the solar shield. There are five sandwich layers, each separated from the next with sheets of polyester netting. Each layer is composed of quartz paper sandwiched between two sheets of Kapton and held in place with a Teflon "glue". There are, however, some modifications to this basic design that were added to assure that the shield would survive both the launch and orbital environments. For instance, only one side of the quartz paper is bonded, rather than both, to prevent the paper from being pulled apart when the package expands during launch.

To allow air trapped in the package to escape, holes are cut through the Teflon-coated Kapton and covered with PTFE Teflon filters* which bond to the FEP Teflon coating during the laminating process. Because this venting alone is not nearly sufficient, the package is also stitched together with polyester thread. The thread prevents excessive ballooning during launch; the pinholes in the Kapton produced by the sewing needle provide additional escape routes for the trapped air.

The outermost layer, Figure 1(b), is slightly different from the others; it has a double thickness of quartz paper to minimize solar transmission to the inner layers. This reduces internal temperature gradients and guarantees negligible heating effects. It is quilted with fiberglass thread, which has better ultraviolet (UV) and temperature resistant properties than polyester. To

* Millipore Corp. type LS filters.

prevent the accumulation of free electrons on the solar shield, the outward-facing sheet of Kapton is coated prior to lamination with a semiconducting layer of indium-tin oxide (ITO) a few hundred Angstroms thick. This provides a high-resistance path to an aluminum layer that is subsequently vacuum-deposited around the perimeter, on top of the ITO. The aluminum is connected to the satellite with grounding straps made from aluminum tape with conductive adhesive.

The innermost, or back, package has vacuum-deposited aluminum applied on the visible face in the same pattern as the outermost package. The sole purpose of this aluminum is to define by its absence the regions through which the EHF signals will pass so that no one will inadvertently put metallized tape. which would degrade the signal, in these regions when the solar shield is installed on the spacecraft.

D. FABRICATION OVERVIEW

In this section, the fabrication procedure is outlined. Details such as temperatures can be found in the Appendix.

The individual sandwiches are, in general, formed by placing a sheet of quartz paper on top of a sheet of Teflon-coated Kapton, covering the paper with a sheet Kapton, and bonding the entire assembly in a laminating press to form a sealed package. When it is received from the Mead Corporation, the quartz paper contains a neoprene binder which is lossy at EHF frequencies and would impair the RF performance. This binder is removed prior to the bonding process by baking the quartz paper at high temperature. The paper is not cut to shape until just prior to assembly in order to minimize fraying at the edges that could be caused by excess handling. The Teflon-coated Kapton is prepared only by punching the vent holes, for which the location is not especially critical, and covering these holes with PTFE Teflon filters. After the bonding process, the fused Kapton films are trimmed, and then the edges are reinforced by taping them with Kapton tape. The entire package is then quilted in parallel rows roughly two inches apart. Finally, a template is used for locating and punching mounting holes.

Since the outermost, or front, layer which faces the earth contains two sheets of quartz paper rather than just one, Teflon-coated Kapton is used for both sides of the package, rather than just the back. Here the front sheet of Kapton is covered with the antistatic coating prior to the laminating process.

Three layers of polyester netting are attached to the remaining four sandwiches on the outward-facing side for thermal control. This is done simply by sewing the netting to the sandwiches all along the fused Kapton perimeter. It prevents the adjacent sandwiches from coming into contact with each other. Because these sandwiches are sheltered from the direct rays of the sun, UV resistance and temperature are not of concern, and polyester thread is used.

Aluminum is vacuum-deposited around the perimeters of both the front (outermost) and back (innermost) sandwiches after bonding.

Finally, Kapton tape tabs are attached around the perimeter of each sandwich in a staggered fashion so that the tabs on one sandwich will not be aligned with the tabs on either of the adjacent sandwiches. Starting with the back layer, the layers are stacked up one at a time, and the tabs from the lower layer are folded over the layer on top, thus fastening the two layers together while leaving open regions to permit venting. The tabs on the very front layer are not folded over; rather they are reserved for attaching the solar shield to the satellite and are covered with Teflon film to protect the adhesive prior to installation.

III. THERMAL AND SOLAR PERFORMANCE

A. EXPERIMENTAL EVALUATION

During the development phase, the solar transmission of a single sandwich was measured by placing a small sample in a Beckman spectrophotometer and measuring the relative transmission as a function of wavelength from 0.35 to 2.5 μm, which covers about 90 percent of the solar spectrum. The resulting curves were then digitized, weighted according to the amount of solar energy available at each wavelength, then integrated numerically to find the overall fraction of solar energy that would be transmitted through the shield.

The same technique was used to determine the characteristic long wavelength transmission property. Data were obtained and integrated between 2.5 and 50 μm, and weighting was relative to blackbody radiation at 300K.

The results were used to refine the thermal analysis and confirm our choice of a five-layer design. They were also the reason for introducing a second sheet of quartz paper into the outermost sandwich.

A nearly final version of the solar shield was subjected to tests in which conditions corresponding both to eclipse and exposure to full sun were simulated. This version did not have any ITO on the outermost surface but was otherwise substantially the same as the flight version. The presence or absence of the ITO is not expected to affect thermal performance.

Heat loss through the solar shield was determined by placing the shield in a vacuum chamber with a liquid nitrogen cold wall and measuring the power required to maintain the inner, insulated face of the shield at an equilibrium temperature of 20°C (Figure 2). Because at equilibrium the input power must be equal to the power radiated from the outer face of the shield, measurement of the temperature of the outer face could be used to find the effective sink temperature. This sink temperature was then used to correct the measured heat transfer in order to predict the actual heat loss during eclipse.

A similar experiment (Figure 3) was performed to find the energy transmitted through the shield and into the satellite when it is exposed to full sun. The insulating blanket was removed from the back face of the shield, and the power required to maintain this face at 20°C was measured. This power input was maintained while a solar simulator was used to irradiate the front face of the solar shield with a spectral energy density approximating that from the sun at earth orbit. The system was allowed to come to equilibrium, and the new temperature at the back face of the shield was recorded. Then, with the simulator turned off, the power required to maintain this new, hotter equilibrium temperature was determined. The difference between the two power levels, after correcting for the effects of the nonzero sink temperature, is an upper limit on the rate at which energy will be transferred through the shield when it is exposed to full sun.

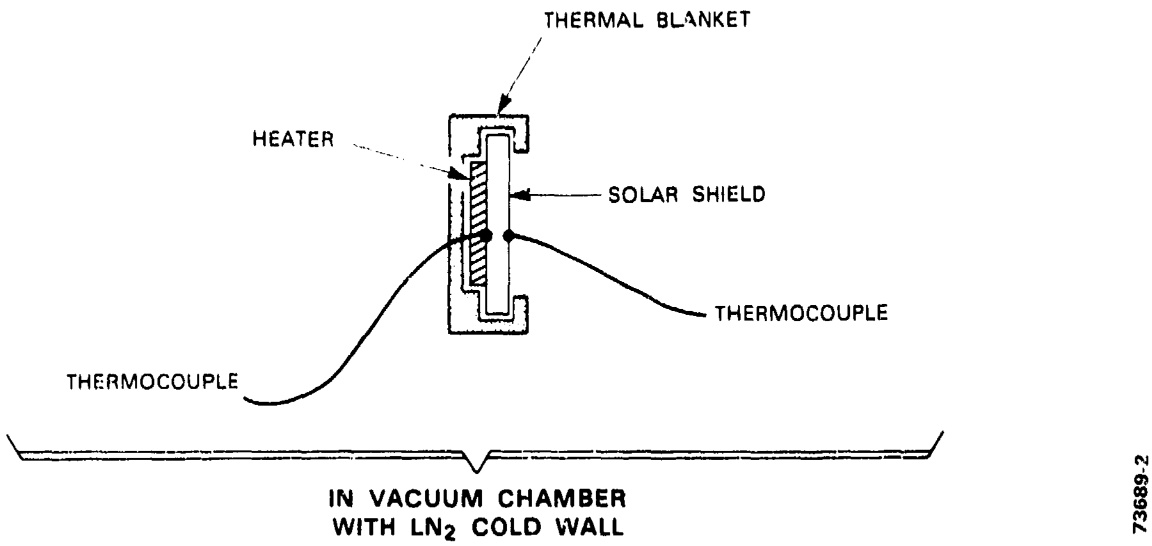


Figure 2. Thermal-transmission test setup.

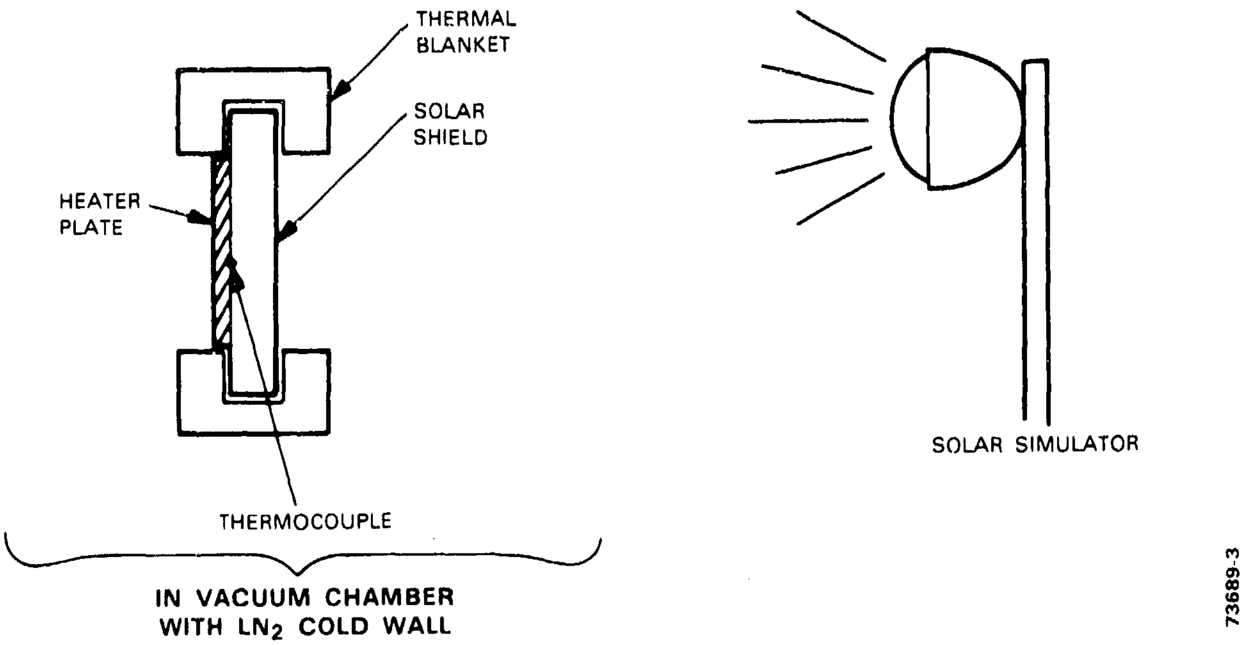


Figure 3. Solar transmission.

To simulate end-of-life conditions, at which time the surface of the shield may have darkened somewhat, a thin, black plate was placed over the outer face of the shield, and the experiment was repeated.

B. RESULTS

The transmission of a single Kapton/quartz paper/Kapton sandwich, as measured with the Beckman spectrophotometer, was 8 percent at solar wavelengths and 3.3 percent at infrared wavelengths. Short wavelength measurements on a five-layer assembly indicated only that the transmission was less than the 1 percent precision of the spectrophotometer.

The simulation of orbital conditions took into account the effects caused by temperature gradients for both long and short wavelengths. Under eclipse conditions, for which long wavelength radiation is the dominant characteristic, the corrected heat loss was 3.2 W/ft^2. An exposed black surface at 20°C would otherwise radiate 38.9 W/ft^2. During exposure to full sun, the resulting heat input was 4.8 W/ft^2 at the beginning of life and 5.2 W/ft^2 at the end of life. This compares with an incident flux of about 127 W/ft^2 that would be observed at an unprotected black surface. After the test, it was noticed that the test arrangement had been assembled with the double quartz layer last rather than first. Results for the solar-heating case were therefore somewhat conservative.

IV. EHF PERFORMANCE

A. THEORETICAL ANALYSES

The insertion loss was predicted for each design under consideration. This was done using a computer program in which the ABCD matrices were calculated for a plane wave incident on each layer and then cascaded to find the resulting system matrix. The transmission-line characteristics of the shield were then found from the system matrix.

The validity of the predictions based on this analysis depends on the accuracy of the dielectric parameters used to describe the component materials in the solar shield. Unfortunately, these parameters are not well documented for very many materials at millimeter wavelengths. Several approaches were used to overcome this problem.

Where the dielectric parameters had been measured at several lower frequencies, we extrapolated up to 44 GHz. These included the Kapton and the Teflon, both of which had been measured at frequencies up to 24 GHz. This is a reasonably safe technique for estimating the dielectric constants, which tend to vary only slowly with frequency, but is not especially reliable for loss tangents, which may exhibit resonances at some frequencies.

The quartz products were more or less amorphous composites. In these cases, the dielectric constant was assumed to be given by

$$k = \sum_{i=1}^{2} K_i f_i \quad ,$$

where K_i is the dielectric constant of the i^{th} component and f_i its fractional volume. (The two components were quartz and air.) This is a valid approximation when, as in this case, one substance predominates significantly, but it results in a larger value for the dielectric constant than is actually the case when the two components are present in roughly equal quantities. This method cannot be used to estimate the loss tangent, so we simply used the published value[2] for powdered quartz.

The polyester netting, which is mostly holes, was assumed to be the same as vacuum.

Whenever the accuracy of a particular parameter was in question — usually a loss tangent — its value was varied in the computer program to determine how this would affect the predicted insertion loss of the completed solar shield assembly. This enabled us to establish an upper limit for the anticipated loss.

We had already anticipated that because the layers were not tied together they would separate somewhat; in orbit the actual spacing between the layers of the solar shield would not necessarily correspond very closely to the originally designed spacing. We can also expect changes brought about by expansion and contraction as the shield is alternately exposed to sunlight and shadow. Therefore, the insertion loss was computed not only as a function of frequency, angle of incidence and polarization, but also as a function of the distance between layers. This was to ascertain whether or not the loss would remain small under a wide variety of conditions.

B. EXPERIMENTAL PROCEDURE

The insertion loss of many materials and combinations of materials was measured. During the development stage, these were all 12-in. square samples. To obtain the various combinations, the materials were stacked up in the desired sequence and clamped at the edges in a wooden frame built for this purpose. None of the layers were bonded or sewn together, as was done later for the flight version, and in only a few instances was any Teflon included in these prototype solar shields.

Of particular interest are the three configurations most closely resembling the final version of the solar shield. All were composed of five sandwich layers. In all three cases, there were fewer sheets of netting between the composite layers, but this netting was slightly thicker (8.5 mils). None of these contained any Teflon, nor did they include the antistatic (ITO) coating. One of the three was otherwise identical to the flight version; the second contained a third sheet of quartz paper in the outermost sandwich; the third contained two more sandwiches, adjacent to the outermost, with double thicknesses of quartz paper.

The loss was measured by placing the sample in its test frame between a transmitter and a receiver and then comparing the received signal to that received after the sample was removed. Measurements were taken using swept-frequency techniques in 3- to 4-GHz bands between 18 and 50 GHz, with the emphasis on the higher frequencies. (In particular, no data were obtained between 22 and 29 GHz.) Most measurements were at normal incidence, but some data were taken at 20° incidence. The collimating lenses in the test setup (shown schematically in Figure 4) were used to produce a narrow beam with a fairly uniform phase front, approximating the plane-wave incidence assumed for the theoretical calculations.

Multipath reflections, which would lead to spurious results, were reduced in two ways. Because it produced a narrow beam, the collimating lens eliminated reflections off the table top and the test frame. The slanted dielectric panels acted as free-space attenuators and reduced the magnitude of round-trip reflections relative to the direct-path signal.

To establish whether or not we had succeeded in eliminating the multipath reflections, we varied the distance between the sample and the transmitter, thereby changing the relative phase of any multipath signal. This in turn produced a change in the total received power, with the magnitude of the change depending on the amplitude of the multipath signal.

Once the final design had been established, data were taken only at the uplink and downlink frequencies, at angles of incidence ranging from 0° (normal incidence) to about 20°. For most measurements, the actual flight configuration was simulated more closely than had been the case during the development phase. In particular, the shield was placed in close proximity to the receiving antenna, and the free-space attenuator between the two was eliminated. In some, but not all, instances we used prototypes of the flight antennas and positioned the shield in the same relative orientation as it will be on the satellite.

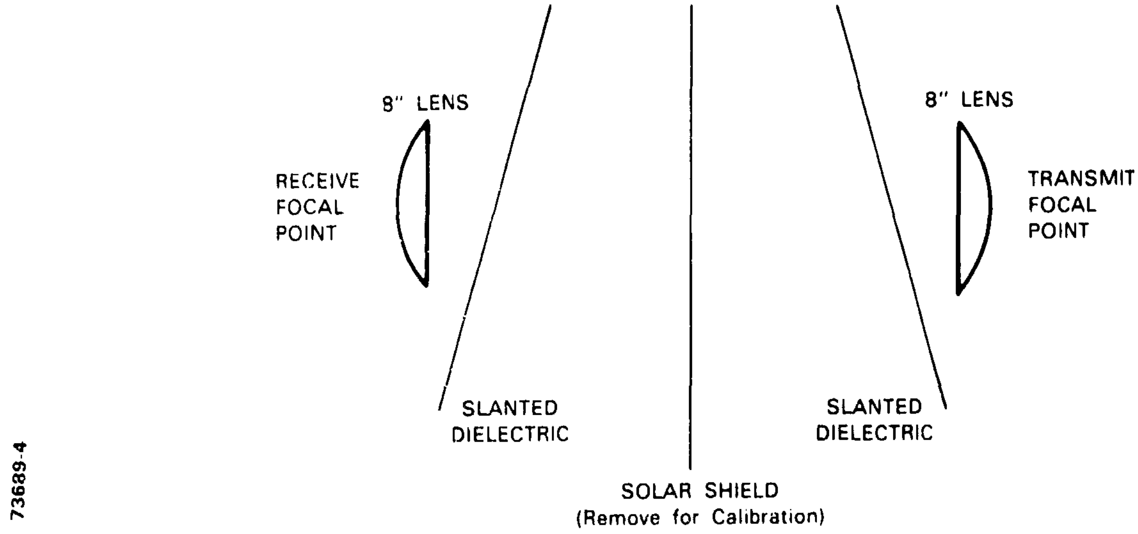


Figure 4. Insertion loss test setup.

C. PREDICTED RESULTS

The parameters used to define the solar shield's constituent materials are shown in Table 2. As can be seen be examining the values for the dielectric constants and for the thicknesses, the design for the individual layers is very similar to the classic "A" sandwich[3] construction, in which a thicker layer of material having a low dielectric constant is sandwiched between thin sheets of material having a larger dielectric constant. This is well known to be a low-loss design. Calculations of the insertion loss (Figure 5) of each of the individual sandwiches confirmed the low-loss nature of this design over a broad frequency band. These losses are predominantly reflective, therefore the reflections from the five layers tend to cancel each other except for those configurations in which the layers are all roughly 180° apart or a multiple thereof. Because of this characteristic, there is a wide range of interlayer spacings for which the loss will remain low. The lower the frequency, the wider this range will be. As indicated in Figure 6, the solar shield has a maximum permissible spacing of about 80 mils, beyond which the loss becomes large in the uplink band as half-wavelength separation between layers is approached.

In the flight design, three layers of netting, a total of 21 mils thick, were used to separate the sandwich layers. Although this spacing corresponds to a minimum loss in both the uplink and downlink frequency bands, the losses should also be acceptable over a wide range of frequencies and angles of incidence (Figure 7).

In the preceding calculations, we have assumed that the spacings between the layers are precisely defined and that all the spacings are identical. Neither of these assumptions is likely to be true simply because the individual layers were not fastened together. For small variations from

TABLE 2 Solar Shield Materials			
Material	**Dielectric Constant**	**Loss Tangent**	**Thickness (.001")**
Quartz Paper	1.27	.002	20
Kapton	3.25	.0098	1
Teflon	2.01	.0008	1
Polyester Netting	1.0	0	Variable

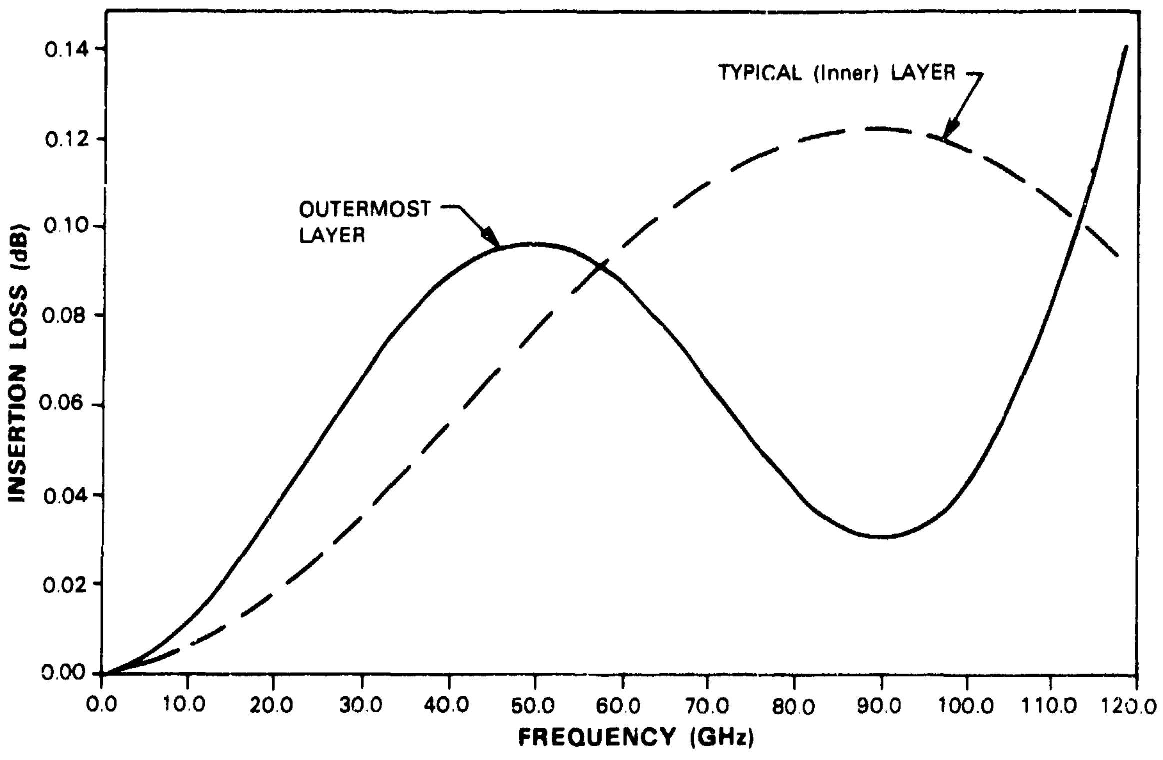


Figure 5. Insertion loss of the solar shield's constituent layers (calculated).

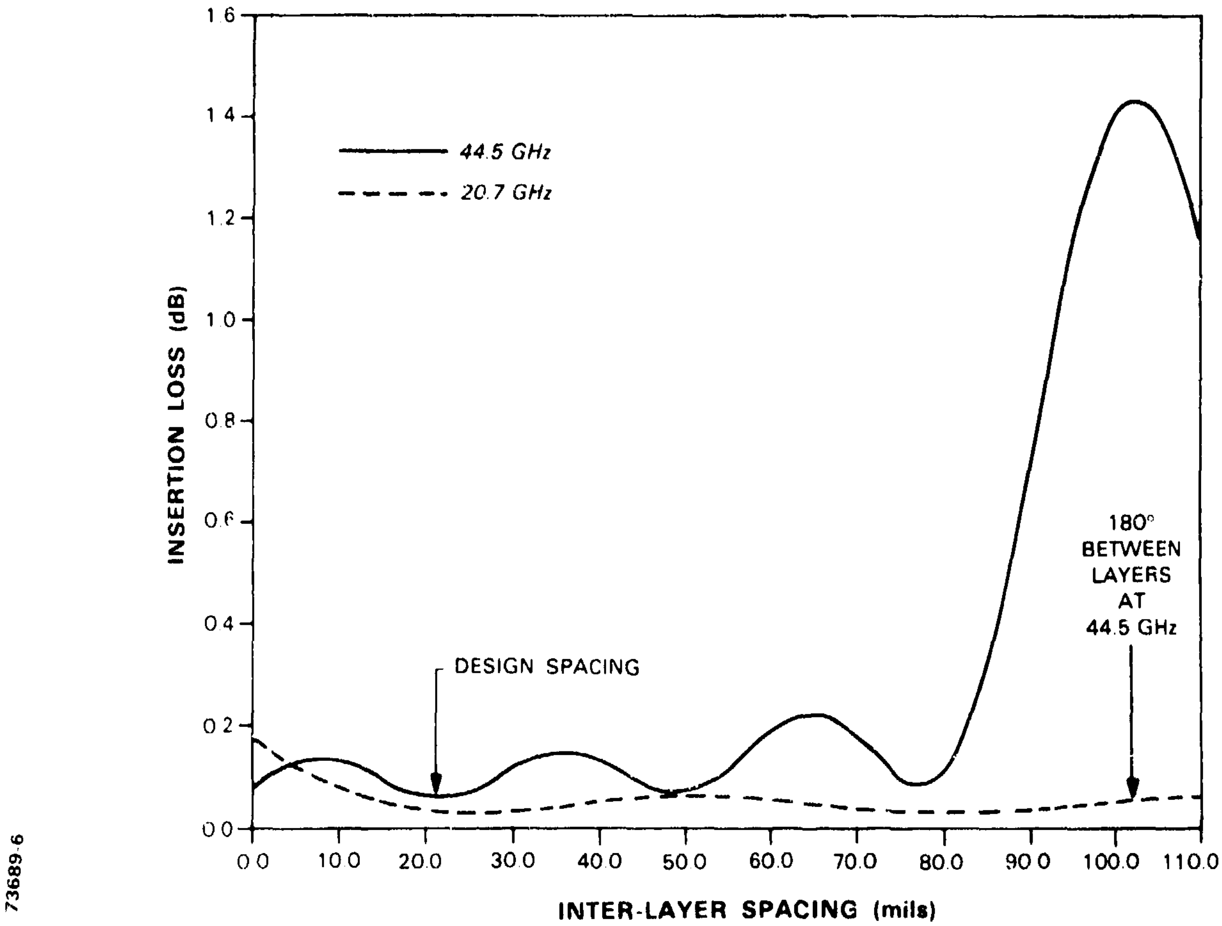


Figure 6. Insertion loss of the solar shield at normal incidence (calculated).

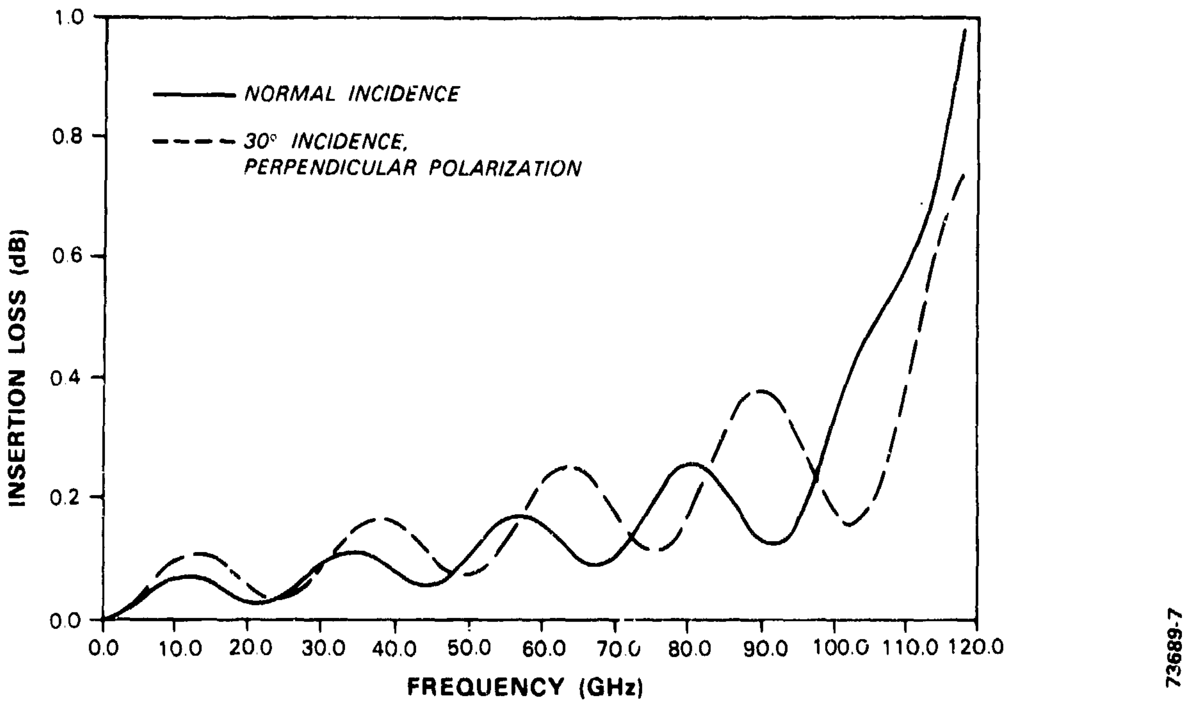


Figure 7. Predicted insertion loss of the solar shield at two angles of incidence.

uniform spacing ($< \lambda/8$), the major effect is to increase very slightly the peak insertion loss in the low-loss region (Figure 8). Because the layers will probably be separated by a somewhat greater distance than the thickness of the intervening netting, the maximum usable frequency should be somewhat less than calculated.

Errors in the estimated values of the various loss tangents would also affect the calculated insertion loss. However, this effect is small; at 44.5 GHz, the effect of doubling the loss tangent of each of the constituent materials is to add only about 0.06 dB to the calculated loss. This result is fairly independent of angle of incidence and distance between layers.

Finally, all the calculated results are for the flight version of the solar shield and include the effect on the one-mil Teflon bonding layers. These layers were not included in the prototype shields used to obtain most of the measured data. However, the predicted difference between the two designs does not exceed 0.05 dB under any of the conditions tested and is usually considerably less.

Despite all these uncertainties, it seemed reasonably safe to anticipate that in the 18- to 50-GHz band the measured loss of both the prototype and the flight versions of the shield should not exceed 1/4 dB.

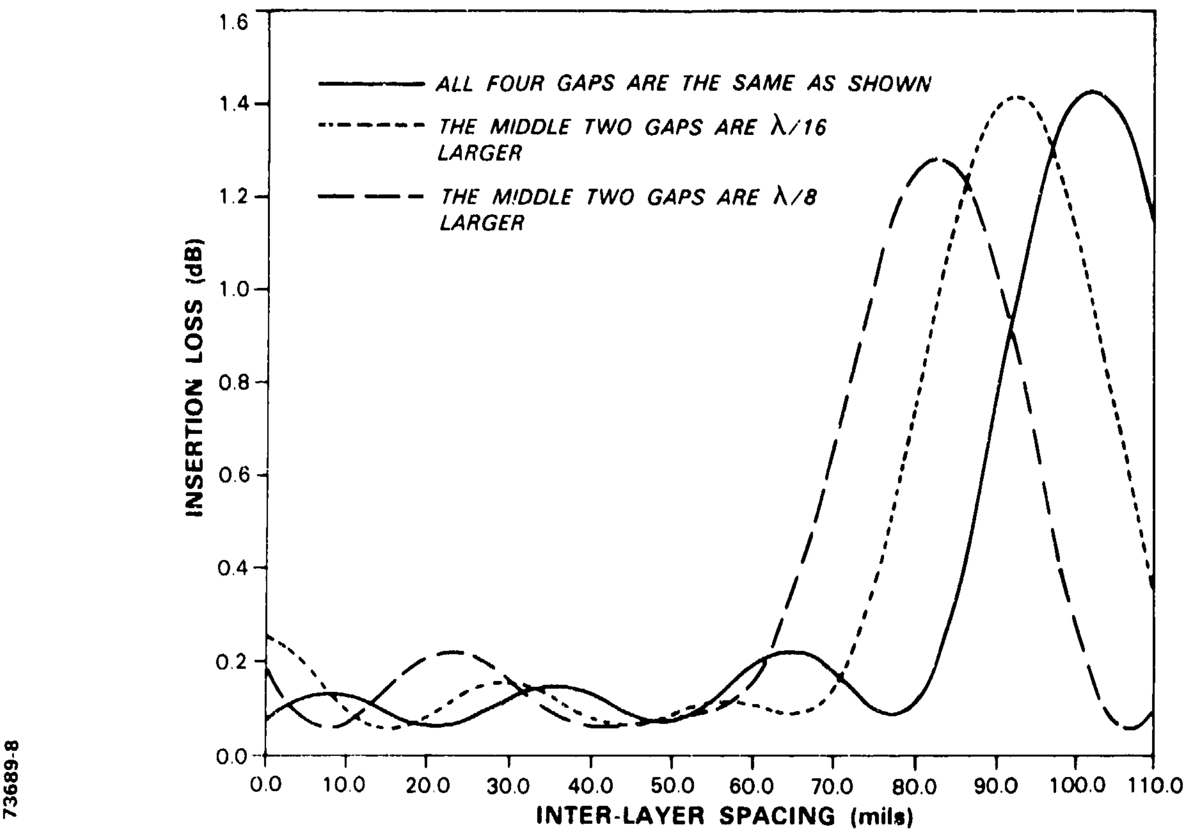


Figure 8. Insertion loss of the solar shield at normal incidence 44.5 GHz.

D. EXPERIMENTAL RESULTS

In the case of the prototype shields, the measured loss varied smoothly and only slightly as a function of frequency. This is evidence that we were successful in eliminating the multipath signal that would otherwise have produced an amplitude variation in the received signal as the phase relative to the direct signal changed with frequency. This was confirmed in those instances for which the sample was moved along the axis between the transmitter and the receiver in a deliberate attempt to vary the relative phase of any multipath signal. The variation in the received signal was almost immeasurable, certainly less than 0.05 dB.

The assumption that the dielectric parameters of the netting were the same as for free space was verified experimentally: we could not distinguish between the insertion loss of the empty frame (the reference) and that of the frame with 20 layers (0.17 in.) of netting.

Because the layers were unconstrained, we did not expect any close correlation between the predicted and measured values of the insertion loss. We did expect, however, that the loss should be small. This was indeed the case: The maximum measured loss of all three prototype assemblies was only 0.2 dB.

These results were confirmed for quasi-flight versions of the solar shield, versions that did not include the ITO coating, so that the only difference between these and the prototype shields was the existence of the bonding Teflon layers. As predicted, the effect of these bonding layers could not be measured.

Later measurements taken on the flight solar shields which did include the ITO coating suggest that the effect of the ITO is to add roughly 0.05 to 0.1 dB to the total loss at both 20 and 44 GHz. Because the effects of varying the spacing between layers are of the same magnitude, these results are not conclusive; rather they are based on average values of the measured loss.

When the solar shield was tested in a mock-up of the satellite, results generally agreed with the previously obtained data. One exception occurred when a steerable, pencil-beam antenna was used as the receiving antenna. When the antenna pointing corresponded to near-normal incidence, reflections off the antenna (which was only a few inches from the shield) were re-reflected off the solar shield and directed back to the antenna. This produced a received signal that varied between about 0.1 dB gain and 0.5 dB loss as the signal was swept across the frequency band. Moving the antenna's pointing away from normal incidence corrected this problem; for example, by the time the angle of incidence was increased to 12°, the magnitude of the reflection had decreased so much that no ripple was evident and the measured loss remained below 1/4 dB.

V. SPACE QUALIFICATION

In order to determine whether or not the solar shield could survive the rigors of launch and a number of years in orbit, several shields were subjected to a battery of tests. These tests are described below.

In preparation for the qualification tests, photographs were taken of each of the composite layers on a light table just prior to assembly of the five-layer shield. The purpose of these photographs was to show any existing pinholes or cracks in the quartz paper. Each shield was attached to a frame for the duration of the qualification tests. This frame simulated that portion of the satellite to which the shield would actually be attached during flight. After testing was completed, the qualification shields were removed from their frames, taken apart, and the individual layers were re-photographed on a light table.

We found in general that the weakest component in the solar shields was the quartz paper but that the visual inspection portion of the fabrication procedure was sufficient to weed out those layers that might not pass the testing.

A. STRUCTURAL INTEGRITY: SHOCK, VIBRATION, AND ACOUSTIC TESTS

For vibration testing, each solar shield (on its test frame) was mounted on an Avco fixture and vibrated at an rms level of 20.7 g's for three minutes along each of three orthogonal axes (Figure 9). Shock testing was done on the same fixture and consisted of three pulses with a peak

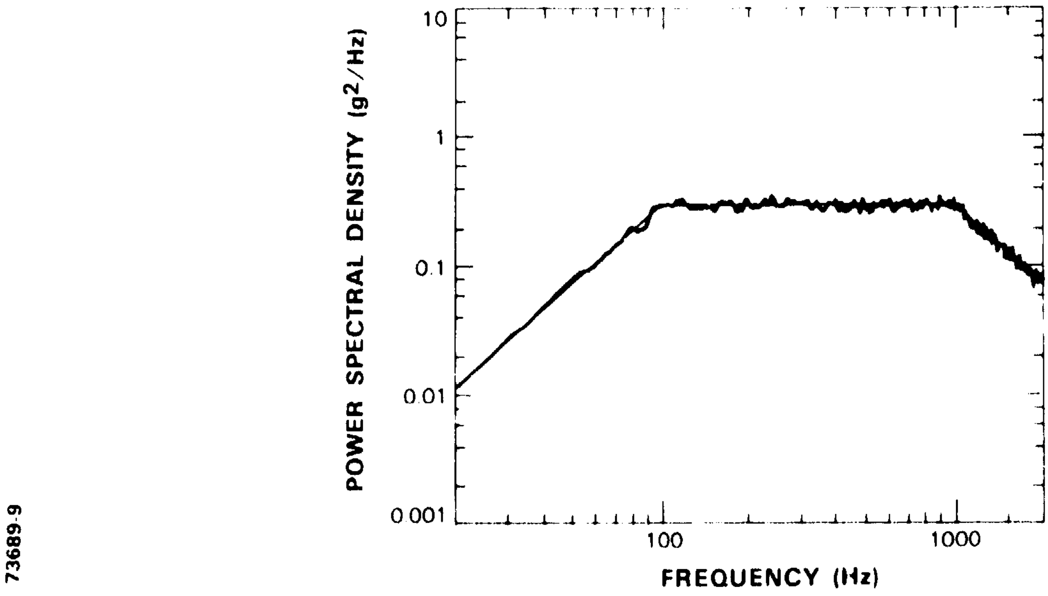
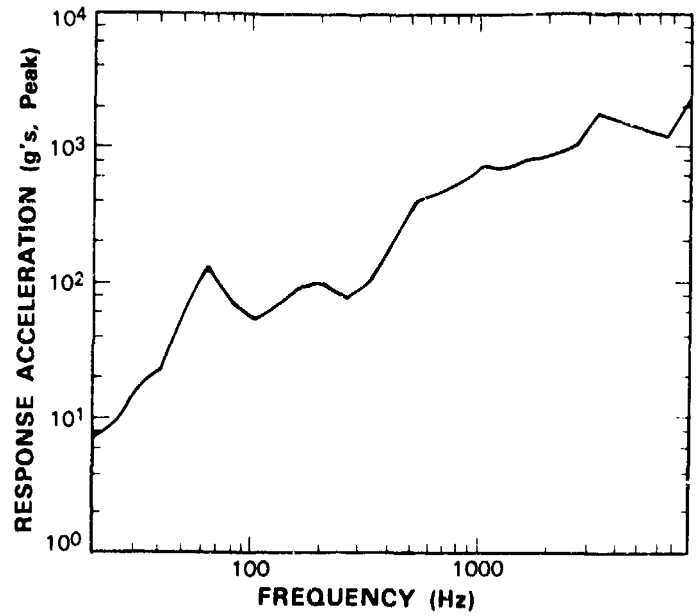
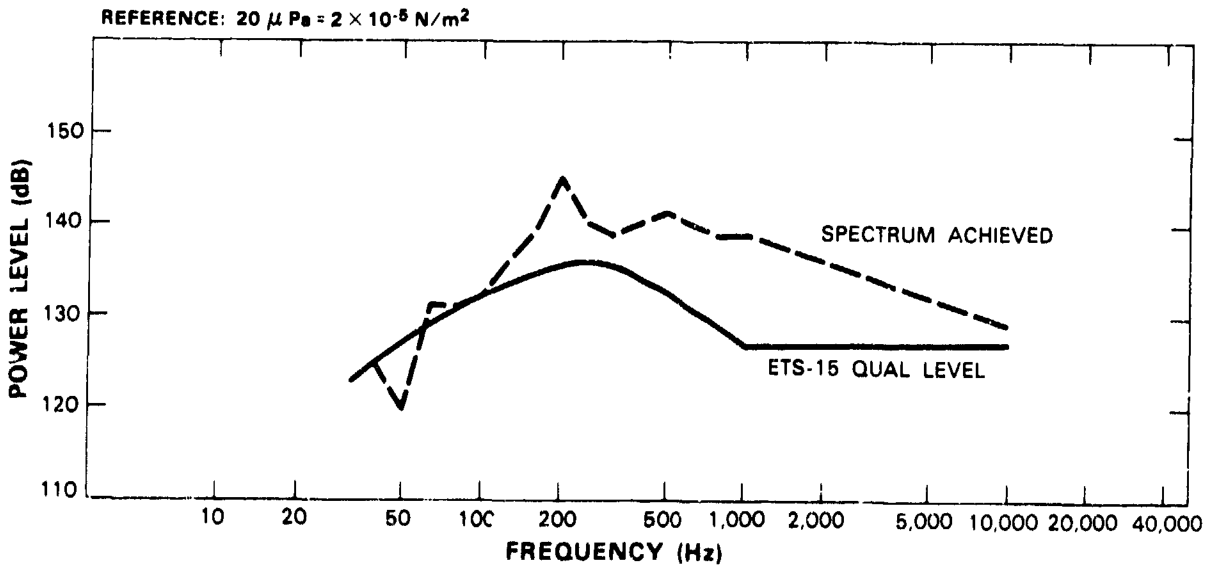


Figure 9. Vibration test spectrum.



73689-10

Figure 10. Shock test spectrum.



73689-11

Figure 11. Acoustic test noise spectrum.

acceleration of 2000 g's along each axis (Figure 10). Acoustic testing was performed by Noise Unlimited, Inc. (Somerville, NJ) and consisted of exposing the shield for three minutes to the noise spectrum shown in Figure 11. The visual inspections performed at the time of these tests and the more detailed examination of the individual layers after all testing was completed indicated that the solar shield will survive the launch. There were only a few small new cracks or voids in the quartz paper (Figure 12), none of which would impair the shield's performance. The envelope shown in Figure 12 would never have been selected for flight because of the original damage near the bolt hole on the right-hand side. It was included in the qualification tests so that we could determine if there was any room for errors during the visual inspections. The "after" photograph clearly demonstrates that even obviously flawed envelopes should be able to survive launch without excessive deterioration.

B. THERMAL TESTS

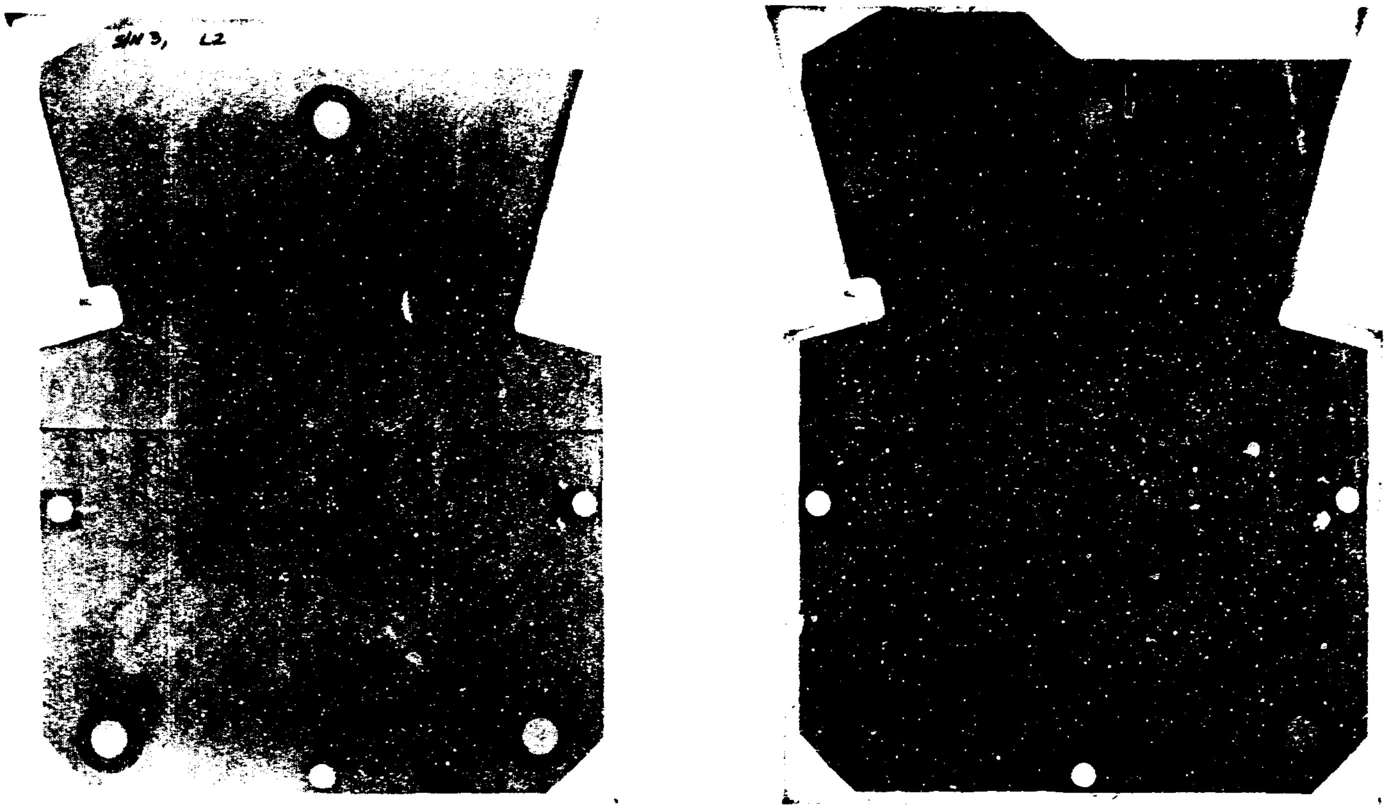
In addition to the rather severe temperature extremes and gradients to which the shield was exposed during the tests to determine heat transfer through the shield under orbital conditions, it was also subjected to about 90 hours, 24 cycles, of thermal cycling. The front surface, which would face outside of the satellite, was cycled between -130°C and +145°C; the back surface, facing the interior of the satellite, was simultaneously cycled between -40°C and +75°C. (All temperatures are ±5°C.) These temperatures were considerably more extreme than would be encountered in orbit. Nevertheless, there was no evidence of any damage occurring because of this test.

C. VENTING AND PARTICLE CONTAMINATION

The individual layers of the solar shields had been quilted to prevent excessive ballooning when the external pressure dropped during launch. The quilting solved this problem but introduced the possibility that loose quartz fibers would escape through the needle holes and contaminate the satellite. A few escaped fibers would be acceptable; a blanket of quartz dust would not be. Therefore, only a qualitative test was performed.

To simulate the effects of launch, the solar shield was first subjected to qualification-level shock and vibration testing, then placed in a Mt. Vernon vacuum chamber where the external pressure was reduced at a rate comparable with that which will occur during launch (Figure 13). The first part of the test was to free any loosely woven fibers; the second was to determine how many of these fibers will be pushed through the perforations by the out-rushing air. To collect these fibers, we suspended the solar shield horizontally in the vacuum chamber, directly above a matrix of glass slides. The configuration assured that even if there was some sideways drift caused by the exiting air, the particles would still land on some of the slides with the same density as if there were no lateral drift. An air baffle in front of the exhaust served to minimize turbulence in the region of the solar shield and the glass slides.

The experiment was terminated when the pressure dropped below about 100 Torr, at which time the rate of pressure change with respect to time became so small that no more fibers were



(a) BEFORE

(b) AFTER

Figure 12. "Before" and "after" photographs of a single layer subjected to qualification tests.

73689-12

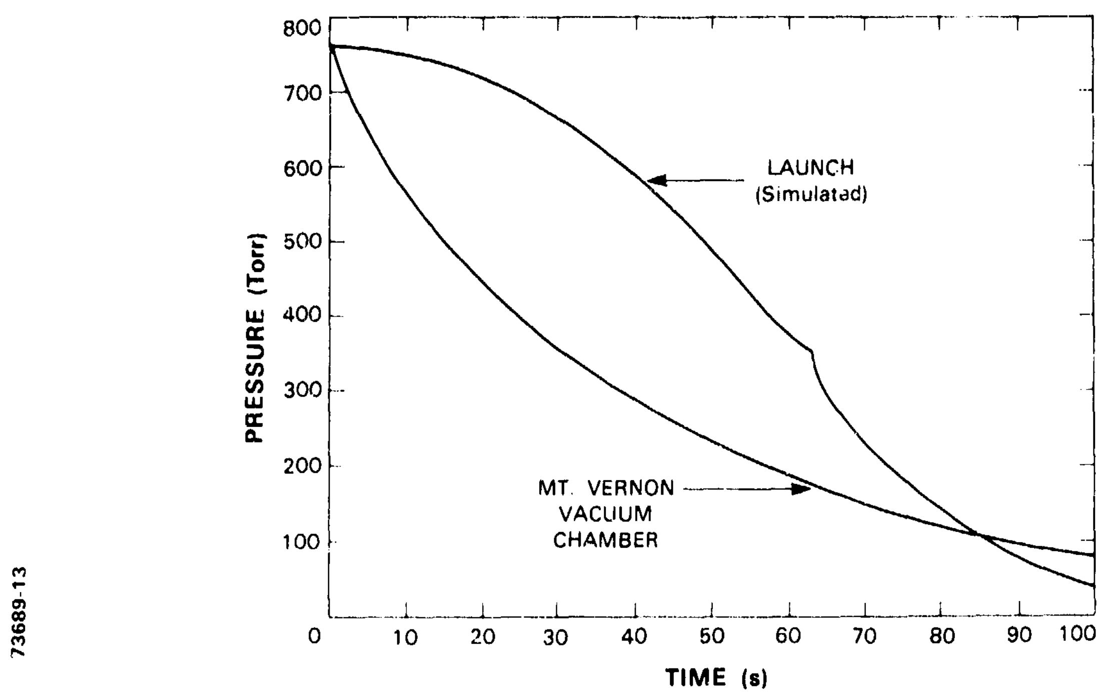


Figure 13. Solar shield venting test.

likely to escape from the solar shield. To prevent in-rushing air from blowing any quartz fibers off the glass slides during the backfilling operation, the inlet to the vacuum chamber was constricted so that it took approximately ten minutes for the pressure to return to ambient. Covers were placed over each slide and the entire matrix transported to the photography lab where the slides were photographed. To determine the background level of particle contamination, the vacuum portion of the experiment was repeated with new, clean slides without placing a solar shield over the slides.

Oblique lighting was used to make any particles stand out and photographs were taken of the glass slides. These showed that the dirtiest test slides were only slightly dustier than the control slides. All of the slides appeared clean to the naked eye. Thus it appears that the solar shield will not contaminate the satellite.

D. ANTISTATIC TEST

A test was performed to determine whether or not the antistatic coating (the ITO) on the outermost layer of the shield would be sufficient to drain off the impinging solar electrons. A small solar shield was fabricated especially for this test. It was made smaller than usual so that the entire surface could be bombarded with electrons in the Lincoln Laboratory linear accelerator. Conductive aluminum tape was used to ground the shield to its aluminum frame which was connected, in turn, to the accelerator's walls. The assembly was suspended inside the accelerator, and a mirror was placed so that the shield could be viewed from the side (Figure 14). A Faraday cup placed behind the shield was used to determine the flux density.

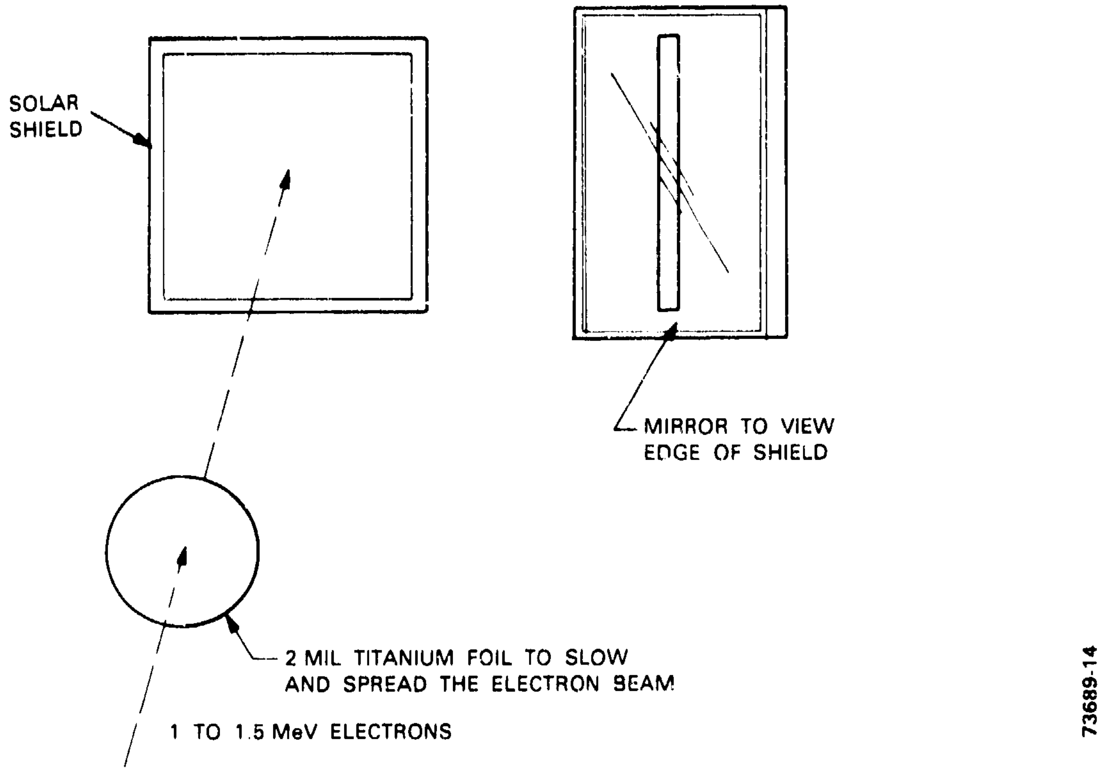


Figure 14. Antistatic test.

With an impinging flux of about 1 nA/cm^2, which is roughly ten times the normal solar flux, there was no evidence of any arcing, nor did the shield expand as would have occurred if there had been any significant charge accumulation. Thus it would appear that the ITO coating will provide adequate charge drainage.

VI. PROBLEMS AND RECOMMENDATION

As with all components being developed for space flight, there is a certain amount of inertia in the design process: once a certain design, or even a particular portion of a design, has been space-qualified, one becomes exceedingly reluctant to make any changes. This is especially true when there are no plans for large-scale production of the component; the savings derived from decreased production costs or from increased yields are completely cancelled by the costs, both in time and money, or requalifying the design. Therefore, the purpose of this section is to address those aspects of the design that could, but probably will not, be improved.

A. QUARTZ PAPER FRAGILITY

After the neoprene binder is fired off, the quartz paper, which is roughly 93 percent voids and only 7 percent quartz fibers, becomes quite frail. Although bonding the paper to the Teflon-coated Kapton in general provides the necessary mechanical support, it is quite easy to damage the paper during cutting and other handling prior to the bonding. It is also fairly probable that the paper will be somewhat damaged in the vicinity of the Teflon venting filters during the bond process; the additional thickness of the filters causes the quartz paper underneath the filters to be compressed considerably more than the adjacent paper during the laminating process, which tends to break the quartz fibers in that area. Finally, excess pressure from the sewing machine foot during the quilting process can damage the paper quite severely. The flaws introduced in any of these procedures may cause the solar shield to fail environmental testing, especially vibration tests.

It was found empirically that careful inspection of the quartz paper at each stage of the fabrication, along with a visual inspection of the finished sandwich layer on a light table prior to the final assembly, was sufficient to weed out those layers not likely to pass testing. In particular, we found that although pinholes in the quartz paper were acceptable, true voids, typically holes 1/8 in. in diameter or larger, would often grow even larger during vibration; similarly, incipient cracks were permissible, but any crack through which the light from the light table was clearly visible was likely to propagate. Thus the problem is not whether or not we can build a shield that will survive the launch, but rather to minimize the time and materials that would be wasted by low yields at any step of the fabrication process.

Damage caused by handling prior to bonding is not terribly wasteful simply because very little time is invested at this stage of the process. This damage can be reduced by very careful handling: the quartz paper should never be folded, or even bent very much, and a template should be used for all cutting to avoid fraying the edges

There is often a tendency to try to salvage quartz paper that appears only slightly flawed. This is a false economy: any sandwich made from paper that is damaged this early in the fabrication process will almost surely fail sooner or later and all too often not until the last possible moment. Therefore. any damaged quartz paper should be discarded without hesitation.

The flaws in the vicinity of the filters could be completely eliminated by eliminating the filters. These filters are an excellent example of the previously mentioned design inertia; they are completely superfluous because almost all of the venting is through the needle holes poked in the Kapton during the quilting process and not through the filters. Because this particular problem reduces the yield from the bonding process from close to 100 percent to somewhat less than 50 percent, it would be foolish to retain this aspect of the design in any future solar shields.

Damage caused by excessive pressure of the sewing machine foot is a serious one, primarily because it occurs near the end of the fabrication procedure. The problem is exacerbated by the fact that although too much pressure will cause the quartz to crack, too little pressure will cause the thread to snarl. This pressure must be adjusted empirically. The best advice we can give here is to say that, "Practice makes perfect." (As this advice also applies to recognizing flaws in the quartz paper, there will probably be plenty of rejected sandwiches available for practicing during the start-up phase of any production run.) However, it does not take very long for someone familiar with a sewing machine to learn to produce neat, untangled quilting without damaging the quartz paper.

B. ITO: OBTAINING AN ACCEPTABLE SURFACE RESISTIVITY

While evaluating the solar shield design, we noticed that the indium-tin oxide (ITO) coating exhibited the perverse tendency to change the value of its surface resistivity as a function of time, even when it was merely sitting on a shelf. This tendency is a problem because the purpose of this coating is to prevent the build-up of static charge from the impinging solar electrons without attenuating the EHF signals. If the surface resistivity is too large, charge may accumulate; too small and the EHF signal will be attenuated.

The main cause of this behavior is that ITO is highly reactive.[4] Merely exposing the coating to the atmosphere at room temperature is sufficient to cause the coating to oxidize further. Placing the coating in a vacuum is sufficient to somewhat reverse this process as the oxygen is outgassed.

There are also other minor effects that are more permanent. Long-term exposure to moisture, for example, can permanently increase the surface resistivity. Heating the ITO will tend to realign the crystal domains in addition to driving off some of the oxygen; this tends to permanently reduce the resistivity.

Once the satellite is in orbit, there will be no more oxygen available to combine with the indium-tin alloy. In fact the combination of the vacuum and the solar heating will tend to drive the resistivity to a minimum. Hence our problem is not so much to prevent the ITO from oxidizing as it is to determine whether or not the surface resistivity that will finally be obtained in orbit is acceptable. It has been established[5] that once an ITO coating has been vacuum-annealed at one temperature, subsequent heat treatments at the same or lower temperatures will not further reduce the resistivity. Hence the procedure for determining the in-orbit surface resistivity is to vacuum-bake the coating for a minimum of four hours at a temperature slightly greater than the anticipated in-orbit maximum. Because the surface resistivity is also somewhat temperature-dependent, it is necessary to allow the coating to cool to room temperature while still in a vacuum, prior to measuring the resistivity, if reproducible results are to be obtained.

Of course, the coating will reoxidize during subsequent testing and storage, but this additional oxidation will be reversed once the coating is in orbit.

C. VDA ADHESION

It is always necessary to verify that the vacuum-deposited aluminum (VDA) has adhered fully to its substrate, otherwise the possibility exists that small flakes of aluminum might peel off and eventually end up shorting an electrical connection. We have found that although VDA adheres quite well to an ITO substrate, it does not always adhere well to plain Kapton. Therefore, although the VDA used to ground the solar shield adheres well to its substrate (the ITO), the VDA applied to the back surface of the shield (plain Kapton) is potentially the source of many problems.

The adhesion can almost always be improved by keeping the substrate clean. In particular, oil and grease on the substrate will cause the adhesion to be poor. The yield can be improved by wearing gloves during fabrication to prevent fingerprints from contaminating the surface. Cleaning the substrate with isopropyl alcohol or Freon-TF* will also significantly improve the adhesion. (Never use ethanol; it dissolves ITO.)

Because the present installation procedure allows the use of metallized tape to attach the solar shield to the spacecraft, it is necessary to define the regions through which the EHF signal will be transmitted; any metallization in these regions would tend to alter both the pointing and the strength of the signal. The function of the VDA on the back surface of the solar shield is to define the "keep out" region. However, it is not really necessary to use metallized tape; plain (i.e., unmetallized) Kapton tape would be equally effective for holding the shield in place. If plain Kapton tape were used, then applying VDA to the back surface of the solar shield would not only be superfluous, but also actually counterproductive; an otherwise acceptable sandwich may have to be discarded if the VDA adhesion is not adequate. Therefore, we recommend that in the future the VDA be eliminated from this sandwich and that only Kapton tape be used to attach the shield to the spacecraft.

D. TOLERANCES

In passing through the solar shield, the EHF signal is attenuated slightly. This attenuation occurs primarily because of reflections from each sandwich. In general, these reflections are not in phase with each other and the magnitude of the loss remains small. However, in those instances for which the layers are a half-wavelength apart or a multiple thereof, the reflections from each layer will be in phase and the overall loss becomes quite large.

---

* DuPont Corporation.

For this particular application, the spacing between the layers is less than a half-wavelength, so there is not a problem; the actual spacing between the sandwiches serves only to limit the maximum frequency for which the shield can be used. However, it is conceivable that one might want to extend the usable frequency range at some time in the future.

In that case a problem arises from the fact that the current configuration makes it difficult to determine an upper limit for the frequency; the layers are flexible and the netting between them guarantees only a minimum spacing, but not a maximum. Furthermore, the layers tend to separate from each other. In addition to the separation caused by the fact that the sandwiches are usually somewhat puckered, instead of lying flat, and in addition to the fact that the netting between sandwiches is often somewhat wrinkled, there is also the ballooning that will occur during launch because of the reduction of the external pressure.

All of these effects serve to increase the spacing between layers and therefore reduce the maximum usable frequency. This problem is readily solved simply by sewing all five sandwiches together rather than quilting them individually. There will still be some tendency for the shield to be thicker between the rows of stitching than it is at the rows, but the difference in thickness will be relatively small. This minor modification should make it possible to extend the maximum usable frequency from about 50 GHz to somewhere in the vicinity of 100 GHz.

There would be some slight degradation in the thermal performance because the layers would be closer together and because of the additional conduction path provided by the thread. Both of these effects, however, should be so small that the net effect is still negligible.

VII. SUMMARY

A thermally insulating, broadband, electromagnetic window, or "solar shield," has been described. This shield comprises five composite layers with each layer consisting of quartz paper sandwiched between two sheets of Kapton.

Spectral transmission measurements and analysis indicated that the multiplicity of layers selected could minimize energy transmission at wavelengths ranging from the infrared to the ultraviolet. Tests were conducted to confirm that the arrangement met thermal requirements. Realistic simulation of orbital conditions led to the conclusion that no more than 5.2 W/ft^2 will be transferred through the shield under normal conditions.

The insertion loss at EHF frequencies was minimized by using only low-loss materials. Theoretical calculations of the insertion loss for a variety of shield configurations indicated that the losses should remain low, less than 0.5 dB, for frequencies up to 100 GHz and less than 0.25 dB for frequencies below 50 GHz. These predictions were confirmed experimentally between 18 and 50 GHz.

The tests used to assure space qualification and the results of these tests were described. The solar shield was shown to be fully qualified for space applications.

Finally, potential problems were identified and suggestions for solving these problems were offered.

ACKNOWLEDGMENTS

Of the many people who helped with this project, there are two who deserve special thanks for their continuing commitment to this project and for their moral support: Walter Robar who was responsible for most stages of the fabrication procedure and whose careful handling of the materials was essential for its successful completion, and Josephine Cataldo who developed to a fine art the techniques for quilting the individual packages and attaching the netting.

REFERENCES

1. A.E. Eagles, S.J. Babjak, and J.H. Weaver, "Fabric Coatings: A New Technique for Spacecraft Passive Temperature Control," Prog. Astronaut. Aeronaut. **49**, 113 (1979).

2. W.B. Westphal and A. Sils, "Dielectric Constant and Loss Data," Technical Report AFML-TR-72-39, Air Force Materials, Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, OH (April 1972).

3. R.C. Johnson and H. Jasik, Eds., Chapter 44 in *Antenna Engineering Handbook*, Second Edition (McGraw-Hill, New York, 1984).

4. J.L. Vossen, "Transparent Conducting Films," in *Physics of Thin Films*, Volume 9 (Academic Press, New York, 1976).

5. J.A. Thornton and V.L. Hedgecoth, "Transparent Conductive S_n-doped Indium Oxide Coatings Deposited by Reactive Sputtering with a Post Cathode," J. Vac. Sci. Technol. **13**, 117 (1976).

APPENDIX

(This appendix is reproduced from Lincoln Laboratory Manual 68)

1.0 SCOPE

Material requirements and fabrication procedure for a microwave transparent solar heat shield for satellite window.

1.1 Theory - Quartz is normally transparent to visible light. Quartz paper traps light through multiple reflections within the 1 to 2-μm-diameter fibers. Woven-quartz products previously used for passive thermal control have 8 to 10-μm-diam filaments. For the same weight, there are sixteen times more fibers in the quartz paper than in the quartz fabric.

Quartz paper is quite fragile after the neoprene binder is fired off. It becomes more durable when bonded in a Kapton/FEP envelope, but must be handled carefully to avoid tearing.

1.2 Performance of Kapton/quartz paper envelopes is as follows:

a. RF insertion loss is less than 1/4 dB at B band (approximately 44 Ghz).

b. For an interior background temperature of 20°C, heat input through the solar shield is less than 14 W/ft^2 under full solar exposure; in shadow the heat loss out the window is less than 8 W/ft^2.

c. Solar transmission through the shield is less than 1%.

2.0 APPLICABLE DOCUMENTS

TRW Drawing:

#C-324169	Interface Control Drawing FEPAC

MIT Lincoln Laboratory Drawings:

S-207315	Solar Shield Assembly
S-112495	Solar Shield VDA Mask Assembly
B-112428	Hole Punch
S-213021	Primary (Front) Envelope Assembly
S-213022-G1	Secondary (Middle) Envelope Assembly
S-213022-G2	Secondary (Back) Envelope Assembly
S-112504	Shipping & Storage Containers
S-213021-3	Kapton Template

MIT Lincoln Laboratory Specifications:

PRS-193	VDA Coating over ITO/Kapton
SSTPL-322	Solar Shield Qualification Test Plan
SSTPL-323	Solar Shield Acceptance Test Plan
PRS-198	Transparent Conducting Coating (ITO) on Kapton
MS-8-12	Adhesion Tape Test on Thin Films

3.0 MATERIAL REQUIREMENTS

Material requirements for the solar shield are listed in Table I.

TABLE I
MATERIALS FOR A MICROWAVE TRANSPARENT SOLAR HEAT SHIELD

Item	Code #	Thickness	Source
Kapton/FEP (Teflon)	200F011	2 mils	(Dupont) Brownell Co. Woburn, MA
Kapton/FEP with Indium Tin Oxide (ITO)/Vacuum Deposited Aluminum (VDA)	200F011	2 mils <2 ohms/sq.	Scheldahl Materials Div. Northfield, MN Microcoatings Westford, MA
Kapton	Type H	1 mil	(Dupont) Brownell Co. Woburn, MA
Quartz Paper	TS153A	20 mils maximum roll width 12.5 in. length 250 ft.	Meade Corp. Research Laboratory Chillicothe, OH
Teflon (TFE) Filter	Type LC PW04700	47 mm 10-μm vent	Millipore Corp. Bedford, MA
Polyester Mesh	B2A	190 mesh 7 mils	Apex Mills Lynbrook, NY
Kapton Tape	CHR #K250	1 mil 1 & 2 in. wide	Shelley Co. Wellesley, MA
Aluminum Electrical Grounding Tape	3M#1170		(3M) Brownell Co. Woburn, MA
Polyester Sewing Thread	100% spun	Size 50 (5 mil)	Woolco Stores
Fiberglass Sewing Thread	B-4	0.014 in.	Owens Corning Fiberglass Braintree, MA

4.0 FABRICATION PROCEDURE

4.1 Special Equipment

a. High-temperature (600°C) oven to handle required quartz paper size.

b. Vented area.

c. Quartz-paper-size hot press (315°C).

d. Ultraviolet reflection spectrophotometer.

e. Vacuum bake chamber.

4.2 Cleaning Quartz Paper

a. Cut quartz paper sheets using a lightweight template and a blunt-nosed shoe knife. Typical size is 11.5 in. x 17 in., or as required.

b. Weigh one out of lot to nearest gram, and record (lot is typically up to 24 sheets). Use a carrying tray to facilitate weighing and prevent damage to the fragile quartz paper after binder removal.

4.3 High-Temperature Oven in Vent Hood

a. Fire off neoprene binder in high-temperature oven. Voluminous fumes occur.

b. Place up to 24 sheets (lot) in oven, and raise temperature to prefire (150°C) for 2 hours.

c. Raise temperature to 550°C and hold for 2 hours.

d. Cool to approximately 50°C and remove quartz paper to clean, low-temperature oven. Store at 50°C.

e. Weigh to nearest gram. Typical weight loss 15%. Verify with coupon (see section 4.4).

4.4 Quality Verification

a. Verify cleanliness on two 1-1/2-in.-diam. test coupons punched from one sheet by measuring ultraviolet reflection spectroscopically. Reflection values should be within 5% of curve shown in Fig. 1. Save coupon discs, note weight, and record run.

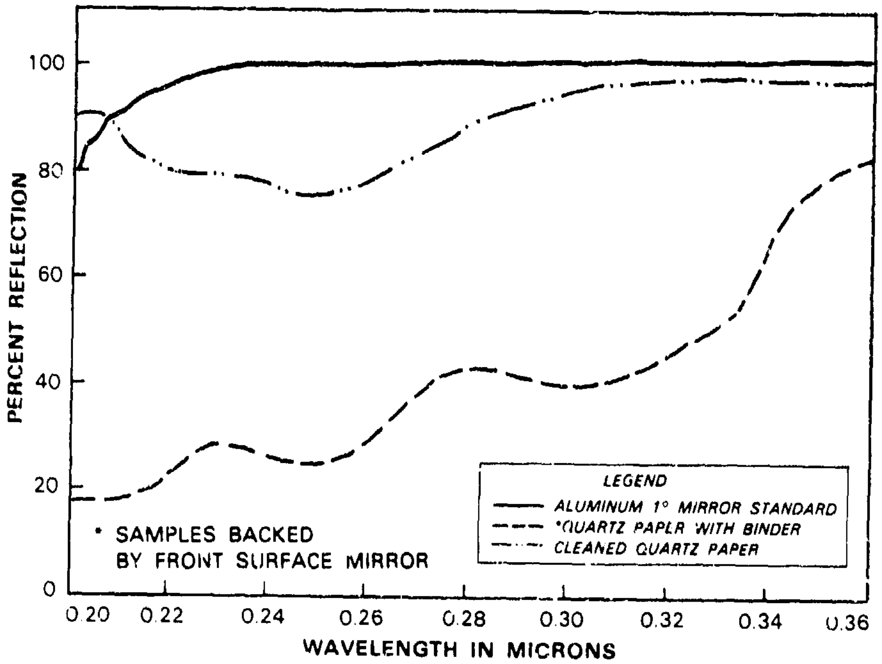


Fig. 1. Cleanliness by ultraviolet reflection.

4.5 Storage

a. Keep quartz paper covered and protected in a plastic box sealed with tape. Any airborne contaminant will tend to condense on the micron-size fibers if left exposed to air.

4.6 Forming Individual Envelopes

See Fig. 2 for front-envelope sketch.

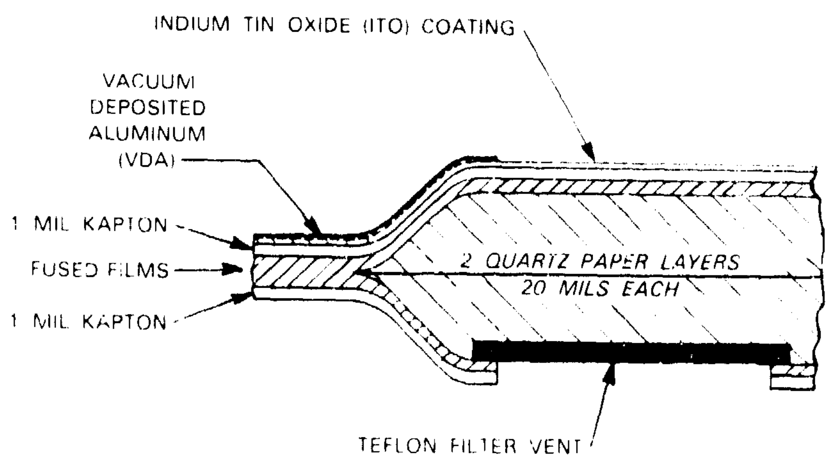


Fig. 2. RF solar shield front envelope.

4.6 Forming Individual Envelopes (Continued)

The rationale for bonding only one side of the secondary envelopes with Kapton FEP is to avoid splitting the quartz paper apart during venting. The front envelope will split between quartz paper layers.

a. Front (primary) envelope shall consist of the following per Lincoln Laboratory engineering drawing S-213021.

Front Film-	Kapton/FEP/ITO/VDA
Quartz Paper-	2 layers
Back Film-	Kapton/FEP

The ITO-coated Kapton shall have been tested and approved under PRS-198. The surface resistivity shall be between 50K and 1 megohm per square (5×10^4 to 10^6 ohms/square).

b. Middle (secondary) envelopes shall consist of one bonded side per Lincoln Laboratory engineering drawing S-213022-G1.

Front Film-	Plain 1-mil Kapton
Quartz Paper-	One Layer
Back Film-	Kapton/FEP (2-mil)

c. Back (secondary) evelope shall consist of the following per Lincoln Laboratory drawing S-213022-G2.

Front Film-	Plain 1-mil Kapton
Quartz Paper-	One Layer
Back Film-	Kapton/FEP/VDA

d. Punch out 1-in.-diam holes in Kapton/FEP film for 47-mm-diam Teflon filters, as per Lincoln Laboratory engineering drawing S-213021-3. All filters on the envelopes shall face into the satellite.

The overall size of the Kapton envelopes is 20 13/16 in. x 15 3/4 in. The quartz paper is 19 13/16 in. x 14 3/4 in. This requires two sheets.

e. Hydraulic press FEP fusion bonding: cure package as follows and per Fig. 3.

Pressure-	3 psi
Temperature-	290°C (554°F)
Time-	10 min.

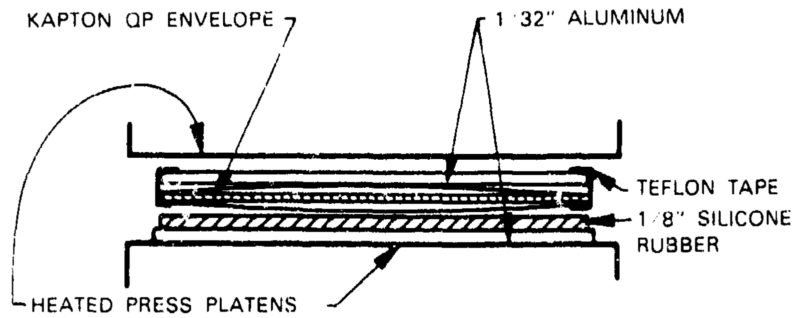


Fig. 3. Press envelope assembly.

4.6 Forming Individual Envelopes (Continued)

f. Press package assembly shall consist of:

2 aluminum plates - 21 in. x 15 in. x 1/32 in.
1 sheet silicone rubber sponge - 21 in. x 15 in. x 1/8 in.
1 Kapton/FEP with filters
1 quartz paper (except front envelope)
1 Kapton plain (except front envelope)

g. While hot, remove from press between aluminum plates (which will act as permanent tray holders).

h. Reinforce hole and edge locations with Kapton tape per Lincoln Laboratory Engineering drawings S-213021 and S-213022.

4.7 Vacuum-Deposited Aluminum

Vacuum-deposited aluminum (VDA) shall be applied selectively to the front and back envelopes, respectively, per Lincoln Laboratory drawings S-213021 and S-213022-G2. The surface resistivity shall be less than two ohms per square per PRS-193.

4.8 Quilt Stitching

Any ballooning of envelopes on launch is to be avoided to prevent distortion of adjacent items. The following quilting, as shown in Fig. 4, is performed:

a. Stitching shall be six stitches per inch. The front envelope uses fiberglass thread with Singer Q needle (0.036 in. diam). The secondary envelopes use Sears Kenmore #9 needle (0.027 in. diam) with polyester thread. See Section 3.0 for specific thread identification.

b. Stitch rows shall be approximately 1.5 in. ± 0.5 in. apart.

4.8 Quilt Stitching (Continued)

c. Random orientation is necessary. Rows shall take any direction (i.e. horizontal, vertical, or diagonal). No contiguous envelope shall have an identical row pattern.

d. Rows shall start and end 0.5 in. in from any edge.

e. **CAUTION** - Regardless of stitch-row location or direction, **NEVER** stitch through a filter.

f. Minor repairs, except in the active region of the ITO-coated surface, are acceptable. Use Kapton tape to patch any small tears and to secure unraveling thread. If there are so many flaws that they cannot be repaired with three inches of half-inch-wide tape, the envelope is unacceptable and should be rejected.

4.9 ITO Vacuum Bake

Exposure to sunlight in orbit will cause the surface resistivity of the ITO to change unless this coating is annealed first, as described below.

a. Thermocouples shall be attached only to the back (uncoated) side of the primary envelope with Kapton tape.

b. The primary envelope shall be baked at a temperature between 130°C and 140°C for a minimum of four hours after the pressure has dropped below 10^{-4} torr. (Heating may begin before the required pressure is reached.)

c. After the heat is turned off, the envelope shall remain in vacuum for at least another 96 hours (four days).

d. Air shall not be reintroduced into the chamber until <u>immediately</u> before the surface resistivity is to be measured. The surface resistivity shall fall between 5×10^4 and 1×10^6 ohms per square.

e. If the surface resistivity is greater than 1×10^6 ohms/square, the entire procedure may be repeated at a temperature of not greater than 260°C.

f. Reject the envelope if the final resistivity does not fall between 5×10^4 and 1×10^6 ohms/square.

4.10 Netting

a. On the front of each of the secondary envelopes three separating layers of polyester mesh (See Table I) shall be installed. Sew a polyester seam on the three layers of polyester netting wrapped around the perimeter of each envelope.

b. Reinforce envelope edges with Kapton tape over the wrap-around polyester mesh.

c. Resew over the tape.

4.11 Final Assembly

a. The five envelopes shall be fastened together and mounting tapes provided using Kapton tape per Fig. 4.

b. Venting between envelopes shall be per Lincoln Laboratory Engineering drawing S-207315.

c. Use solar shield metal template to punch TRW mounting holes through netting and five envelopes.

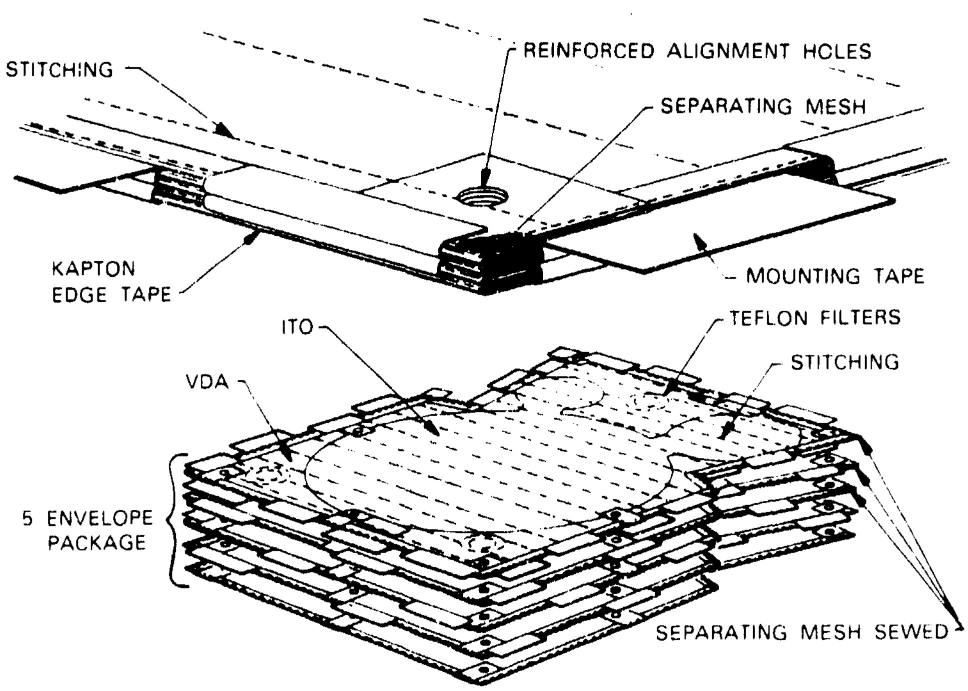


Fig. 4. Five-envelope package.

5.0 QUALITY ASSURANCE

5.1 Performance Requirements

The solar shield must pass the performance requirements of SSTPL-322 and SSTPL-323.

a. Keep a quality assurance number record of each envelope, date and run (e.g., 5-20-84-4, made 20 May 1984, 4th envelope) per Appendix I.

b. Keep weight record of quartz paper/Kapton envelopes; note whether primary or secondary envelopes. Any large deviation from the standard shall be rejected.

c. Any significant stiffness in envelope indicates too much quartz paper impregnation into the FEP and is to be rejected.

d. Be sure ITO/aluminum side of primary envelope is tape-tested per MS-8-12 to verify VDA adhesion per PRS-193.

e. Protect all envelopes in a shipping case (S-112504) to prevent any mishandling.

5.2 Flaw Criteria for Envelope Acceptance/Rejection

Record the quality of each envelope by photographing over a light table.

Criteria for rejection in the active area (the active area is defined by the VDA mask, S-112495):

a. Reject envelope if there are any holes of larger than 1/8 in. diam in active area.

b. Reject if more than five holes of 1/64 in. to 1/8 in. diam occur in the active zone.

c. Reject if cracks are greater than five mils wide and longer than 1/2 in. in the active area.

d. Reject if there are five cracks of any size in active zone.

e. Active area requires 100% bonding between quartz paper and FEP; in passive area 50% bonding is required.

f. Flaws in the passive area are tolerable if they do not jeopardize the physical integrity of the envelope.

Appendix I

QUALITY ASSURANCE RECORD FOR INDIVIDUAL SOLAR SHIELD ENVELOPES

This record will be filled out and kept with the individual envelope that it describes.

Check appropriate Lincoln Laboratory drawing number

S-213021 (front envelope) ________

S-213022-G1 (middle envelope) ________

S-231022-G2 (back envelope) ________

Envelope number (per PS-1-17, section 5.1a) ______________________

Quartz paper quality check:

Date ______________, Notebook & page nos. __________________

VDA tape test (per PRS-193, section 3.2), front and back only:

Date ______________, by _________________

Vacuum bake (per PS-1-17, section 4.9) front envelope only:

Date ______________, resulting surface resistivity ________________,

Notebook & page no. ____________________, by ____________________

Quilting (per PS-1-17, section 4.8)

Number of repairable flaws __________________

Repaired on ____________________, by ________________

Final Inspection (per PS-1-17, section 5.2)

Photo lab. no. ______________________

Check one: pass _____ fail _____

Date ______________, by ____________________

Additional comments:

Accepted by _______________________, date ________________

unit engineer

Integrated into A315, SN __________________,

Layer no. (1 = front, 5 = back) ______________,

By ____________________, Date _______________

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER ESD-TR-85-324	2. GOVT ACCESSION NO. AD-A170 334	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Solar Shield: A Thermally Insulating, Broad-Band, Electromagnetic Window for Satellites		5. TYPE OF REPORT & PERIOD COVERED Technical Report 6. PERFORMING ORG. REPORT NUMBER Technical Report 742
7. AUTHOR(s) Marcia S. Powell, David M. Nathanson, and Edward B. Murphy		8. CONTRACT OR GRANT NUMBER(s) F19628-85-C-0002
9. PERFORMING ORGANIZATION NAME AND ADDRESS Lincoln Laboratory, MIT P.O. Box 73 Lexington, MA 02173-0073		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element No. 33109N
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Systems Command, USAF Andrews AFB Washington, DC 20334		12. REPORT DATE 2 June 1986 13. NUMBER OF PAGES 56
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Electronic Systems Division Hanscom AFB, MA 01731		15. SECURITY CLASS. (of this Report) Unclassified 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

None

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

spacecraft EHF window
spacecraft thermal protection
low-loss EHF window
broad-band EHF window

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A space-qualified, thermally insulating, broad-band, electromagnetic window for satellite applications is described. A multiple-layer construction is used, with each layer consisting of quartz fiber paper sandwiched between two sheets of Kapton. The measured insertion loss is less than 0.25 dB at frequencies up to 50 GHz. When exposed to full solar radiation (127 W/ft^2), about 5 W/ft^2 are transferred through the thickness of the window into a 20°C background in the interior of the satellite. Under eclipse conditions, about 3 W/ft^2 are radiated from the satellite into the cold space background compared with nearly 40 W/ft^2 without the window. The reasons for this performance are explained, and detailed descriptions of the experimental evaluations are given. A brief summary of the space-qualification testing is also included.