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STUDY OF ATTACHMENT METHODS FOR ADVANCED SPACECRAFT THERMAL CONTROL MATERIALS

Lockheed

MISSILES & SPACE COMPANY

A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

SUNNYVALE, CALIFORNIA

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STUDY OF ATTACHMENT METHODS FOR ADVANCED SPACECRAFT THERMAL-CONTROL MATERIALS

FINAL REPORT

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Prepared under Contract No. NAS 2-4252
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for

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LOCKHEED MISSILES & SPACE COMPANY

FOREWORD

This report was prepared by Lockheed Missiles & Space Company for the Ames Research Center of the National Aeronautics and Space Administration. The work was performed under Contract NAS 2-4252 and was administered by the Systems Engineering Division of Ames Research Center, with Mr. E. R. Streed as Project Technical Monitor.

The work described in this report was performed from 2 May 1967 to 2 May 1968. This report is the final report for Contract NAS 2-4252.

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The authors also acknowledge the interest and significant contributions of Messrs. O. B. Renalds, W. O. Kassebaum, R. F. Betts, R. P. Warren, and R. S. Nelson, who were members of the Lockheed Missiles & Space Company study team for this contract, and Mrs. H. M. Abbott of the Lockheed Technical Information Center, who conducted the literature survey in support of this study.

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ABSTRACT

An investigation was made to develop attachment methods for a thermal-control composite system comprised of optical solar reflectors (second-surface mirrors) and multilayer insulation. Basic systems design constraints were: (1) Systems must be removable for access to vehicle skin, (2) Nonmagnetic materials must be used in the construction of the composite, (3) attachments should not appreciably degrade thermal conductivity of multilayer, (4) composite system must withstand long-term exposure to high temperature (700°F.) and vacuum environment, (5) structural integrity must be sufficient to withstand loads imposed during an Atlas-Agena launch, and (6) Application techniques must be usable on cylindrical and flat shapes.

Various techniques for attaching the composite system were evaluted. Two composites were fabricated utilizing different attachment methods and were subjected to environmental conditions anticipated for a near-solar spacecraft mission. Both composites employ optical solar reflectors in combination with aluminized polyimide-tissueglass multilayer insulation. However, substrates to which the reflectors are applied differ. In one case, reflectors are bonded integrally to the multilayer, whereas in the other reflectors are bonded to an aluminum expanded-metal substrate which is attached subsequently to posts mounted through the multilayer.

Exposure to flight sinusoidal loads caused the pyrex attachment posts to fracture on one sample. Both systems showed no evidence of structural damage during additional environmental testing.

Section 1
INTRODUCTION

For certain spacecraft designs and missions, it is highly desirable to minimize heating from incident solar energy. This can be achieved by reflecting maximum amount of incident solar radiation with a low solar absorptance (α_s), high emittance ( ) surface, and providing a low thermal conducting path from the low α_s, high surface, to the spacecraft interior. Required combination of properties is achieved by an external, second-surface-mirror, thermal-control surface (low α_s, high ϵ), with multiple-layer insulation (very low thermal conductance) interposed between back side of mirrors and outer skin of spacecraft payload enclosure. The composite system has potential application for thermal protection of solar probes and storage tanks for cryogenic propellants, and for protection of areas on space vehicles adjacent to stabilization or propulsion rockets.

Thermal-control materials comprising the composite system have been employed successfully by LMSC in various spacecraft and study programs (references 1, 2, and 3). However, the materials were utilized separately to perform their intended functions.

The objective of the work described in this report was to review existing methods for attaching the individual thermal-control composites, and to develop attachment methods for a composite system which will withstand vacuum and temperature environments of space, as well as forces resulting from handling and vehicle launch and orbit operations. Since the composite system is designed to act as an insulator, it was of primary importance that mirror and multilayer attachments do not seriously degrade the thermal conductivity properties of the multilayer insulation.

Although numerous data were available on thermal properties of multilayer insulation systems, design of a system utilizing multiple-layer insulation and second-surface mirrors as a unitized form of insulation against high-intensity solar radiation had not been attempted previously.

Various candidate attachment schemes were analyzed during the Phase I portion of the study to select the best engineering approach, and two techniques were selected for development and environmental testing during Phase II.

The objective of the Phase II effort was to apply the thermal-control composite system to cylindrical and flat shapes utilizing the best attachment techniques developed during Phase I. Test specimens were then subjected to environmental tests which were designed to verify acceptable performance during conditions anticipated during launch and orbit operations of a near-solar spacecraft mission.

The study disclosed that each potential application for the composite thermal-control system will dictate the particular attachments required. No single attachment scheme is universally acceptable, as the geometry of the underlying surface, the required thermal conductance, and the allowable weight penalty associated with the composite system dictate which attachments may be utilized. Two separate attachment techniques, with the primary objectives of minimizing heat leak through the insulation system and surviving specific temperature (700^{o}F.) and launch/orbit operations (Atlas-Agena launch and 60 rpm spacecraft spin), were developed and tested. Optimization of each system, in terms of weight trade-off, redundancy, and desired thermal conductance, must still be accomplished by the design engineer responsible for specific intended applications. As an example, if the edges of the multilayer will be directly exposed to solar radiation, and the effective thermal conductivity of the system cannot be reduced by an order of magnitude due to increased parallel conductivity through the multilayer, provisions must be made for allowing an overhang of the mirrors to shield the edges of the blanket from incident solar radiation. Such a requirement would completely rule out one of the attachment methods (mirrors applied directly to the top layer of the multilayer blanket), and require modifications to the alternate technique proposed.

Both Phase I and Phase II technical efforts are discussed in this report which is sectioned by tasks:

- Literature Review
- Summary of Attachment Methods
- Analysis of Various Application Techniques
- Selection of Most Feasible Attachments
- Composite Fabrication
- Environmental Testing.

Section 2
LITERATURE REVIEW

As part of the Phase I effort, a review of published data relating to the use and attachment of each of the components (second-surface mirrors and multiple-layer insulation) that comprise the thermal-control composite system was conducted. Open literature sources, vendor data and trade journals were surveyed. Computer searches were obtained from both the Defense Documentation Center and the NASA Scientific and Technical Information Center.

Reports received from the literature search were reviewed by study-team members, and the information gained served as a basis for selecting candidate attachment schemes. Reports or papers which were deemed applicable to the problem of designing a thermally efficient and practical composite system were abstracted and listed into annotated bibliography which was included as a supplement to the Phase I summary report (references 4 and 5).

Section 3
SUMMARY OF ATTACHMENT METHODS

A matrix which relates candidate attachment schemes for multiple-layer insulation and second surface mirrors to their respective performance limitations is presented in Table 3-1.

Although none of the abstracted reports surveyed during the literature search pertains directly to the particular attachment problem that was investigated during this study, there were some multilayer-insulation attachment methods that have been investigated previously for passive thermal control of cryogenic systems. These attachment schemes were included as possible candidates.

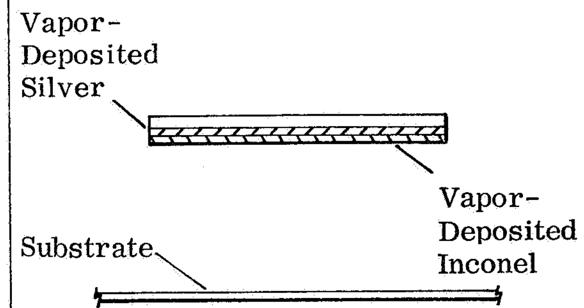
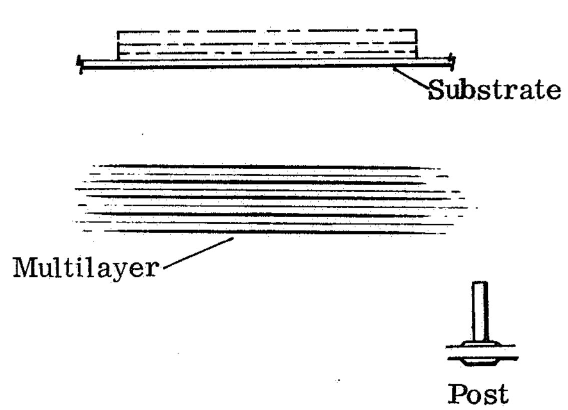
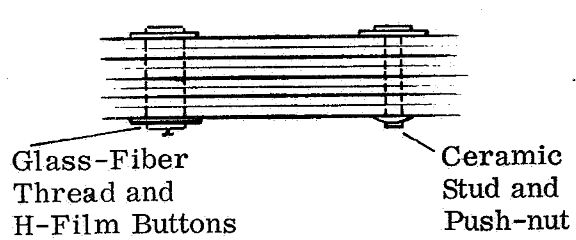
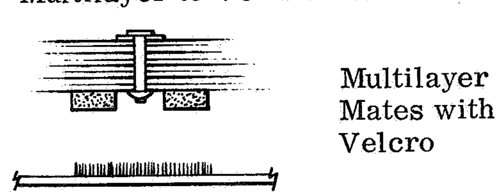
The overall problem of attaching the thermal-control composite was divided into

1. Second-surface mirrors to a substrate;
2. Mirror substrate to multiple-layer insulation or vehicle;
3. Multiple-layer insulation blankets;
4. Multiple-layer insulation to vehicle skin.

Each problem area was investigated separately so that a comprehensive list of possible attachment schemes could be prepared. The most feasible methods of securing the composite system to the vehicle skin were selected by studying each candidate in relation to environmental and handling constraints imposed by intended applications for the system.

Systems selected for environmental testing during the Phase II portion of the study are noted in Table 3-1.

Table 3-1. Matrix of Attachment Techniques

Elements of Composite System	Candidate Attachment Methods	Limitations: Element	Limitations: System
I. Second-Surface Mirrors to a Substrate 	1. Mechanical attachment: metallic track, clips, tabs	1. Loose in holder, subject to thermal warpage	1. Compromises thermal efficiency
	2. Weld to inconel: mirror backing	2. Not sufficient film thickness to weld	2. Not replaceable if mirror is shattered during handling
	a. Ultrasonics		
	b. Brazing		
	3. Adhesive: mirror to substrate	3.	3.
	a. Silicones	a. Temperature limited to 700-800°F.	a. Requires application technique
	b. Double-backed polyimide tape, silicone adhesive	b. Temperature limited to 500-600°F.	b. Requires application technique
	c. Ceramic cements	c. Attack mirror surface	c. Degrades reflective properties
II. Mirror Substrate to Multilayer or to Posts Attached to Vehicle 	1. Tabs welded onto underside of screen or foil. Wire threaded through tabs and twisted onto bonded posts	1. Must have clearance between mirror substrate and multilayer to attach wires	1. Time consuming to assemble; bonded posts tend to shear off during handling and installation procedures
	2. Snapon cap welded to underside of screen or foil fits over post	2. Must apply pressure to mirror and screen; post must be made from ceramic or glass to reduce heat loss	2. Alinement critical for installation; design of receptacle to be made from ceramic/glass difficult
	3. Mirrors attached to top layer of multilayer		
	a. Adhesives or double-backed tape	a. Difficulty in bonding mirrors to assembled multilayer blanket	a. Mirrors no longer removable for possible replacement
	b. Welded to top layer of multilayer	b. Existing welding techniques not applicable to polyimide film and mirrors	b. Weight causes multilayer to sag and tear during loading unless strong thread used
	4. Mirror substrate attached to top layer of multilayer		
	a. Metallic Velcro fasteners	a. Velcro material magnetic	a. Interference with experimentation/communication equipment
	b. Thread onto multilayer buttons	b. Clearance required to tie down to buttons	b. Buttons shear off due to load imposed by mirrors
III. Multilayer Insulation 	1. H-film buttons, glass-fiber thread, silicone-reinforced thread, wire thread	1. Thread chaffing ~~during~~ handling	1. Threading and knotting time; high thermal conductivity for metallic threads
	2. Ceramic studs moored by metallic push-nuts	2. Weight of studs	2. Increased thermal conductivity; tends to tear through multilayer
	3. Teflon buttons and thread	3. Temperature limited to 500°F.	
	4. Sewing blankets together	4. Compresses multilayers together	4. System not readily removable or replaceable
	5. Cylindrical or longitudinal wrap	5. Must be performed at launch site	5. System not readily removable or replaceable
IV. Multilayer to Vehicle Skin 	1. Nylon Velcro fasteners to multilayer and vehicle skin		1. Some alinement of Velcro fasteners necessary for installation
	2. Metallic clips or snaps to multilayer and vehicle skin	2. Clips not weldable to aluminized multilayer	2. Alinement for installation critical
	3. Bond bottom of multilayer to vehicle skin	3. Difficulty in bonding to aluminized multilayer	3. System not readily removable or replaceable

PROPOSED FASTENING METHODS

Section 4
ANALYSIS OF VARIOUS APPLICATION TECHNIQUES

The literature search and design workshop sessions produced a collection of potential thermal-insulation attachment methods. Over 40 suppliers throughout the country were contacted to obtain their recommendations for attachment techniques or materials which might be utilized in the thermal-control composite system. Since there is a scarcity of data available on adhesives which are usable in temperature and vacuum environments to be encountered in our application, the majority of suppliers contacted were manufacturers of adhesives.

All candidate attachments were evaluated and screened with respect to design constraints imposed by intended application for the thermal-control composite system. Attachment methods were analyzed in relation to their performance capability within the application envelope outlined as follows:

a. Ability to withstand
   1. Atlas-Agena random and sinusoidal vibration;
   2. Launch acoustic levels;
   3. Spin normal acceleration and acceleration due to longitudinal thrust of spacecraft while boosted into orbit;
   4. Shock due to boosted ignition and engine-cutoff perturbations;
   5. Thermal-vacuum environment between temperature extremes in space of -100 to 800°F.
b. Materials of construction and assembly must be nonmagnetic.
c. Fabrication procedures for components of composite must be developed so that manufacturing personnel can assemble system using existing state-of-the-art techniques.
d. Materials of construction must have low thermal conductivity.
e. Composite system must be easy to install and have capability of removal for access to vehicle substrate or replacement of damaged components.
f. Composite system must be usable on cylindrical and flat shapes.

Although not stated in the RFP, consideration was given to presence of penetration or cutouts in the composite system to allow for antenna booms or sensors.

Basic materials selected for use in the composite system were second-surface mirrors (optical solar reflectors) and multiple-layer insulation. The second-surface mirrors are approximately 1 inch squares consisting of metallic silver (10^{-5} cm. thick) vapor-deposited on one side of fused silica 0.015 cm. thick, nominal). The silver is over-coated with a thin (5×10^{-6} cm.), vacuum-deposited coating of inconel for corrosion protection. The multiple-layer insulation system consists of a series of doubly aluminized polyimide film (0.0013 cm. thick) separated by glass-fiber spacers (0.0015 cm. thick).

For clarity, overall problems of attaching the thermal-control composite to the spacecraft was subdivided into four areas. Discussion will deal with each problem area and then the system. Figure 4-1 shows individual attachment problems and lists the major performance parameters required for the thermal-control composite.

4.1 SECOND-SURFACE MIRRORS TO A SUBSTRATE

4.1.1 Mechanical Attachment

Attachments such as tracks, clips, and tabs were studied as potential methods for retaining mirrors to a metallic substrate. None of these methods were promising because of expansion and contraction of metallic elements due to thermal gradient. If the mirrors were held tightly in position, expansion of the metallic holding device would cause the mirrors to crack. If the mirrors are loosely restrained, they would tend to move around during ground handling and boost-phase operations and thus be susceptible to breakage.

Primary disadvantage of any mechanical schemes lay in necessity for large spacing between mirrors so that they may be held in place. Any tab or track arrangement would cover a portion of the mirror surface and thus optical degradation, in direct proportion to amount of mirror surface covered, would occur.

Design Constraints

1. Completely removable for access to vehicle
2. Nonmagnetic materials in construction
3. Low thermal conductivity
4. High-temperature performance
5. Structural integrity: must withstand conditions of Atlas-Agena launch

Attachment Problems

1. Mirrors to substrate
2. Substrate materials
3. Mirror-substrate assembly to vehicle
4. Multilayer assembly
5. Multilayer assembly to vehicle skin

Configuration

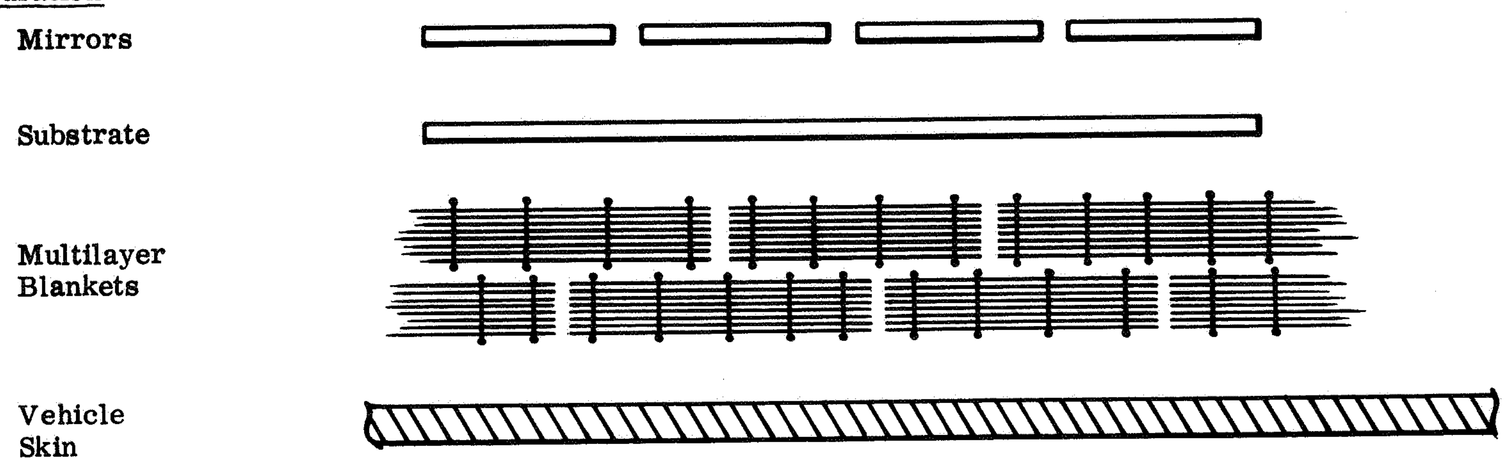


Figure 4-1. Design constraints and attachment problems for thermal-control composite system

4.1.2 Welding to Inconel Mirror Backing

This technique was studied with unfavorable results. Two factors which tend to make most welding techniques unworkable are

a. Inconel backing on mirrors is of insufficient thickness to effect a bond. Increased thickness of inconel could be provided by the manufacturer, but this would add to cost of second-surface mirrors. In the timespan allotted to the performance of this study contract, it was apparent that mirrors could not be fabricated and delivered in time for evaluation.

b. Most welding or brazing techniques require that pressure be applied to the two elements being joined, or that a vacuum autoclave be employed. Neither of these techniques are considered practical when working with fragile mirrors of 0.015 cm. thickness. Additionally, these techniques normally require concentrated heat in the joining zone, and this causes local thermal gradients which may either crack the mirrors or detrimentally affect reflective properties of the silver/inconel backing.

4.1.3 Ultrasonic Welding

An attempt to bond gold wire to the silver/inconel backside of second-surface mirrors using ultrasonic bonding techniques was made. The gold wire, once attached to the mirror backside then could be attached mechanically to a screen substrate. The mechanical bond obtained would be stable in any temperature range up to the melting point of the joining metals. Unfortunately, all attempts to bring about a bond between the gold wire and the mirror backside were unsuccessful. Although experience utilizing this technique is limited, it was evident that the inconel thickness was not sufficient to permit fusion of gold into the inconel backing. Increased inconel thickness, which might permit brazing or ultrasonic welding, could be provided by the manufacturer of the second-surface mirrors. However, modified mirrors could not be prepared and delivered in time for evaluation during the timespan allotted to the performance of this study contract.

4.1.4 Adhesive Bonding

The major portion of Phase I investigations was spent in evaluating candidate adhesive systems for use in attaching second-surface mirrors to metallic substrates. Although there are literally hundreds of adhesive systems that are advertised for use in the 500 to 800°F. range, testing was restricted to systems which are available commercially. In many cases, responses from vendors to our inquiry about a particular product advertised in a recent trade journal have indicated that they were in the process of determining additional property data before marketing the product. Over 30 adhesive systems were evaluated during the Phase I portion of the study. A comprehensive explanation of individual tests performed, as well as mixing ratios and cure cycles used for the adhesive systems, is given in Appendix A of this report.

Initial evaluation of a candidate adhesive system's usefulness consisted in determining its ability to maintain good bonding strength at temperatures in the 600 to 800°F. range. The adhesive was applied to glass cover slides and metallic substrates and then exposed to elevated temperature. If adequate bonding strength was noted, second-surface mirrors were substituted for cover slides and the entire system subjected to high temperature while under vacuum. Testing experience indicated that these tests must be performed in vacuum because the mode of failure for some of the adhesive systems, as well as their effect on the mirror's silver backing, is different when exposed to a vacuum environment.

4.1.4.1 Ceramic/Silicate Systems. Because the ceramic and silicate systems showed promise in retaining their bonding strength at temperatures in excess of 800°F., LMSC attempted to modify them by adding fillers, such as aluminum oxide. It was anticipated that the addition of such materials might reduce the tendency of the silicates to migrate through the protective inconel layer and attack the silver and fused-silica substrate. However, the silvered surface of the second-surface mirrors was degraded whenever brought into contact with the modified silicate/ceramic adhesive systems. Figure 4-2 shows effects of two candidate adhesives on the solar absorptance of second-surface mirrors. In one case, the metallic side of the optical solar reflector was coated with a water-based, alkali-silicate adhesive. A silicone-adhesive system was applied to the second mirror. Both samples were exposed to 750°F. for 6 hours in a vacuum of

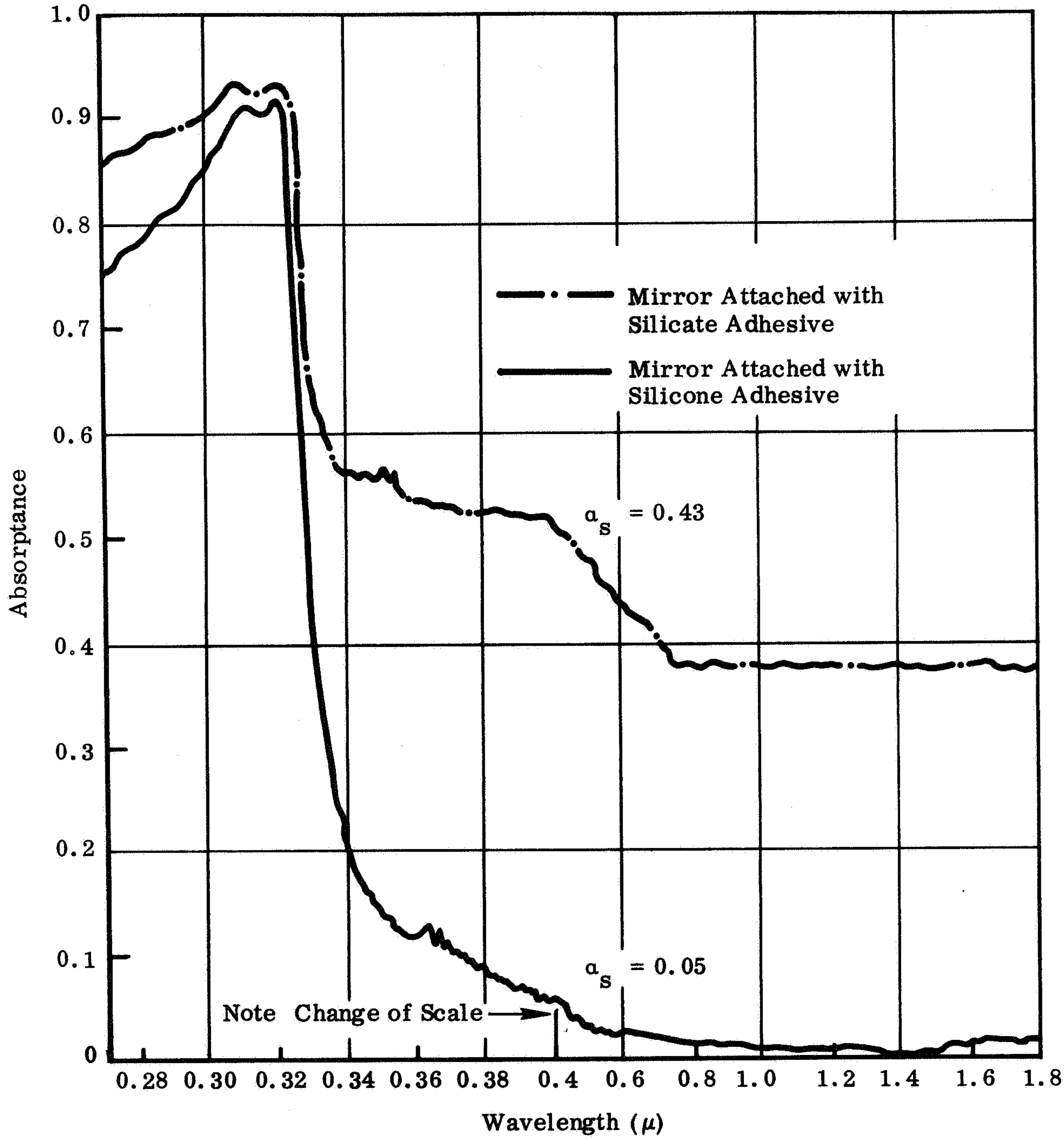


Figure 4-2. Solar absorptance of second-surface mirrors

approximately 10^{-4} torr and allowed to cool slowly to room temperature. The spectral reflectance of each mirror was measured subsequently from 0.275 to 1.8 μ (microns) on the Cary spectrophotometer. Solar absorptance was calculated from the integration of the Cary trace, which is adjusted for variations in solar flux at various wavelengths. No increase in solar absorptance was noted for the second-surface mirror attached with silicone adhesive. However, the silicate system attacked the silvered surface, causing an increase in solar absorptance to 0.43 from the original value of 0.05. The optical degradation of the mirror exposed to the silicate adhesive is attributed to chemical attack of the reflective silver by the caustic nature of the liquid silicate adhesives.

4.1.4.2 Silicone Systems. The adhesive system which showed the most promising performance characteristics at elevated temperatures and vacuum conditions was a Dow Corning Company silicone under the trade name of Dow Corning DC 92-024 Aerospace Sealant. This adhesive is a one-part system and is relatively easy to apply to a uniform film thickness 0.003 to 0.004 inch. It has shown no corrosive effect on the silver, and exhibits excellent bonding strength during exposure to vacuum conditions and temperatures in excess of 700°F. It should be noted that very little bonding strength is required actually in our particular application. The adhesive must be able only to hold the weight of the 1-inch-square mirror (approximately 0.30 grams) to the substrate.

To determine an upper temperature limit for DC 92-024 silicone adhesive a second-surface mirror was attached to an aluminum panel with the adhesive. A weight (17 grams) was attached to the mirror and allowed to pull the bondline in tension. The specimen was placed in a bell jar and exposed to temperature (800°F.) and vacuum (10^{-4} torr). After 14 days of continuous exposure to temperature and vacuum environment, the mirror and weight separated from the substrate. Inspection of the adhesive after removal from the bell jar revealed that all cohesive qualities of the silicone system were destroyed; the material was powdery in appearance. Another specimen was prepared and a weight attached in the same manner as above. The specimen was continuously exposed to high temperature (710°F.) and vacuum (10^{-4} torr) for 30 days. Examination of the specimen after removal from the bell jar revealed some crazing at the bondline, but there was no reason to suspect the ability of the bondline to withstand continued exposure to high temperature and vacuum conditions. Because this test placed loads on the bondline which are far in excess of those to be encountered during actual application, suitable performance for the Dow-Corning adhesive system in vacuum applications where continuous service temperatures do not exceed 650-700°F. is predicted.

Visual observation during vacuum-temperature testing of the silicone adhesive showed that the adhesive outgasses (releases lower molecular weight, high vapor pressure fractions) heavily at approximately 275°F. A sample for thermal decomposition/ volatilization testing was prepared in order to determine if preconditioning at elevated temperature reduces outgassing from the silicone adhesive system.

Four 1-inch square glass cover slides were bonded to a 2-inch square aluminum substrate using DC A-4094 primer and DC 92-024 adhesive and cured for 4 hours at 300°F. in an oven at ambient pressure. The sample was mechanically mounted to an aluminum plate so that the cover slides were facing a-front-surface aluminized mirror mounted at the opposite end of a cylindrical chromium-plated chamber as illustrated in Figure 4-3. The entire system was enclosed in a vacuum bell jar and the pressure reduced from ambient to 3×10^{-4} torr. The test sample was heated to 350°F. within 4 minutes and held at temperature for 30 seconds by means of a tungsten filament radiant lamp array mounted external to the vacuum chamber. The sample-mirror configuration assured that all thermal decomposition-volatilization products evolved during heating would condense on the water-cooled front-surface mirror. A Beckman Spectrophotometer was used to measure changes in spectral reflectance of the optically clear front surface mirror before and after exposure to the heated sample. At a wavelength of .23 microns, where the most severe optical degradation normally occurs, the spectral reflectance of the mirror had been reduced 6.7%. At longer wavelengths the effect was minimal.

The test specimen was subsequently placed inside another vacuum system and its temperature raised to 700°F. Visual observation revealed a significant decrease in the amount of volatiles that were emitted by the preconditioned sample in comparison to other specimens which had been cured at room temperature. Although the preconditioning significantly reduced the amount of outgassing, it did not prevent outgassing from

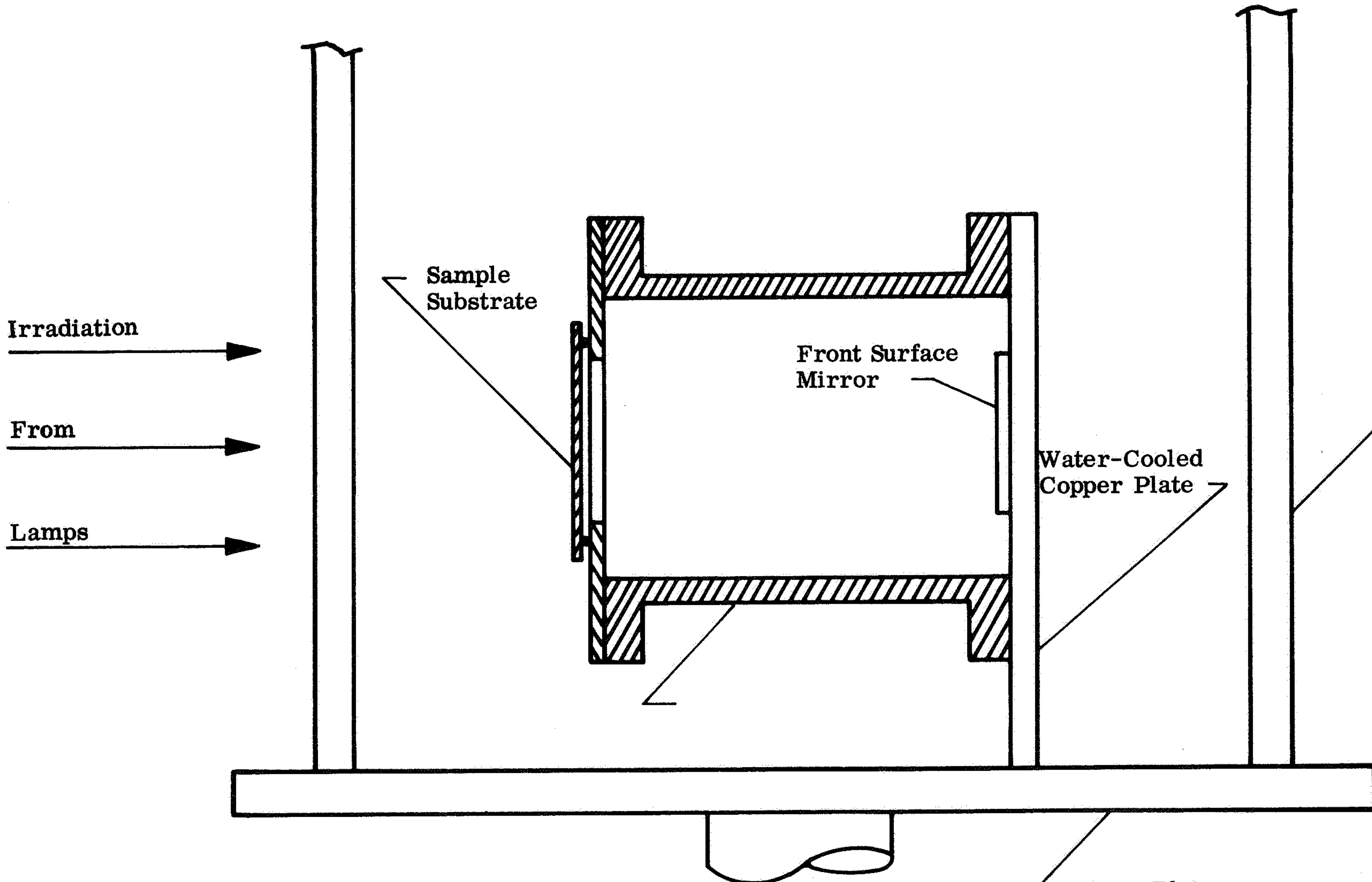


Fig. 4-3 Diagram of Thermal Decomposition – Volatilization Test Apparatus

occurring at higher temperatures. Additionally, it should be noted that pressures to be encountered in space will be much less that is obtainable with simulation techniques, so an analysis of effects that could result from outgassing must be completed for each specific design. In certain applications, there may be no optical surfaces positioned in the path of molecules released by the adhesive system. If this is not the case, then each material within the spacecraft must be preconditioned to remove any possibility of outgassing during the spacecraft mission. Generally, this requirement is derived from the specific spacecraft mission, as well as its configuration. If no outgassing is permissible, then an extensive investigation into the length of exposure at elevated temperature and vacuum that are required for each material is necessary.

4.1.4.3 Double-Backed Polyimide Tape Systems. LMSC also investigated the use of a double-backed, polyimide tape system for applying the second-surface mirrors to substrates. The tape, produced by the Permacel Tape Company under the trade designation of ST-6962, consisted of polyimide film coated on both sides with approximately 0.001 inch thickness of a silicone adhesive. The adhesive system provides a good bond at temperatures below 600°F. but at higher temperatures the tape begins to discolor and the bond line degrades. A second-surface mirror was attached to an aluminum substrate with the tape system and exposed the specimen to high temperature (710°F.) and vacuum (10^{-4} torr.) in a bell jar. A weight (17 grams) was attached to pull the bondline in tension. After 30 days continuous exposure, the mirror and weight separated from the polyimide film and the test was stopped. Examination of the specimen revealed that the polyimide film was severely charred and very little adhesive remained on either side of the tape.

The same double-backed tape was used successfully during repeated temperature cycling in vacuum between -108 and 500°F. (reference 6). It offers a significant application advantage over conventional one or two-part silicone adhesives because the tape system can be applied easily to curved surfaces and requires no additional curing. However, its tackiness does not permit realignment once the tape is set.

One problem was noted during an in-house development effort to qualify the tape for use on an Air Force-sponsored program. The adhesion of the silver/inconel backing on the fused silica of the second-surface mirror is not as good as the adhesion of the silver/inconel backing to the silicone adhesive used on the polyimide film. When second-surface mirrors were applied to an aluminum dome and cycled between approximately -200 and 140°F., the edges of the mirrors tended to lift away from the adhesive film. When this happened, some of the silver and inconel pulled from the fused silica and remained with the adhesive on the polyimide film. The particular dome section used for temperature cycling had a dual curvature. Second-surface mirrors were positioned in a fixture, transferred to the double-backed tape system, and pressed into position by using a rubber roller. It was necessary to allow the mirror edges to remain lifted rather than attempt to conform the mirrors to the curvature of the underlying substrate. Stresses induced during the rolling process were sufficient to overcome the adhesive's bond strength during expansion and contraction of the underlying substrate.

4.1.4.4 Epoxy and Phenolic Systems. The epoxy-adhesive system evaluated during Phase I attacked the silver surface of the mirror and also cracked the mirror. Epoxy and phenolic systems have an inherent lack of elasticity and their resistance to high temperature for prolonged periods is poor. For these reasons, no further experimentation with epoxy or phenolic adhesive systems with respect to mirror application was attempted.

4.2 MIRROR SUBSTRATE TO MULTIPLE-LAYER INSULATION OR TO VEHICLE SKIN

Only two alternatives were available for attaching second-surface mirrors to the thermal control composite; either apply the mirrors onto the top layer of the multilayer blanket, or to a substrate mounted to standoffs which pierce through that multilayer blanket and are attached to the vehicle skin by mechanical or adhesive bonding techniques.

4.2.1 Direct attachment to Multilayer

During Phase I studies, it was concluded that the added weight of mirrors, statically and dynamically supported by blankets, would cause the multilayer blankets to sag when placed in a vertical position. Additionally, it was felt that the multilayer blanket attachments would be overstressed due to the added weight of the mirrors. Point of failure was predicted to occur either at the attachment point between the multilayer blanket and the vehicle, or within the multilayer blanket itself (at the button-top layer attach points). This conclusion was based on previous experience wherein low-strength, low thermal-conductivity materials (nylon or teflon) were used to hold multilayer blankets together (reference 7).

Because direct attachment of mirrors to a blanket top layer would considerably reduce subsequent installation problems, a test specimen in which cover slides (approximately the same weight and dimensions as second-surface mirrors) were bonded to the top layer of a 20 layer insulation blanket, was prepared. There was no evidence of sag when the composite system was mounted to an aluminum substrate and held in the vertical position. However, a failure occurred during subsequent exposure to sinusoidal vibration forces typical for an Agena flight. The complete cover slide-polyimide film assembly separated from the blanket at all top layer attachment points. It was obvious that the weight of the cover slides had caused the glass fiber thread, which was used to hold the multilayer blankets together, to shear at the points where the thread looped through the blanket top layer.

Additional experimentation performed during Phase II resulted in the design of a system whereby second-surface mirrors could be applied directly to the blanket top layer. This effort is reported in Section 5 of this report.

4.2.2 Attachment to Metallic Substrate

Attachment of second-surface mirrors to a rigid metallic substrate was considered to offer considerable flexibility for a variety of applications. Access to the vehicle skin as well as to both the mirrors and the insulation blanket could be accomplished if the mirrors were adhesively bonded to a removable metallic substrate. Techniques wherein the mirrors would be adhesively bonded to a metallic substrate and then subsequently attached to standoffs which pierce through the multilayer blanket were investigated. The standoffs could be attached to the vehicle skin by either mechanical fastening or adhesive bonding techniques.

It was recognized that attachment posts to which the mirror substrate is connected provide an undesirable conductive heat path through the multilayer to the vehicle skin. However, the heat leak is minimized by fabricating attachment posts from low thermal conductance materials such as ceramic or pyrex glass. Plastic materials were considered for use as posts, but they are unable to withstand high temperatures that will exist directly beneath the mirror substrate.

Initially, metallic Velcro fasteners were investigated as a possible means of attaching a mirror substrate to standoffs. One portion of the metallic Velcro pads would be welded or brazed to the underside of the mirror substrate and the other half bonded to the standoffs. Positive attachment would be made by pressing the two mating halves of the Velcro pads together. A sample of the metallic-fastener material was tested for magnetism by Ames at our request. Test results indicated that level of magnetism for a 1-inch square fastener was far in excess of what is permissible for vehicles currently under consideration by NASA/Ames. Although the manufacturer is investigating the use of nonmagnetic materials, this modification is only in the developmental stage. Attempts to pursue this attachment technique were abandoned when it became apparent that fasteners fabricated from nonmagnetic materials would not be available for purchase before mid-1968.

Two additional techniques for attaching the mirror substrate to standoffs were studied. The first technique utilized small, hat-shaped, aluminum clips which were welded to the underside of the mirror substrate. These clips served as guides for stainless steel wires which were threaded through the clips and into holes drilled into standoffs which pierce through the multilayer insulation. The wire was twisted around the standoffs to provide a positive lock which secured the mirror substrate in position. Because clearance between the top of the multilayer and the bottom of the mirror substrate is only 1/4 inch, the threading technique was found to be relatively difficult to install. However, both the mirror substrate and multilayer system could be removed separately by merely clipping the attachment wire. This would free the mirror substrate from the standoffs, and the multilayer could be lifted away from the vehicle skin.

To alleviate the above-mentioned installation problem, another technique was investigated. Aluminum snaps or clips, joined to the mirror-substrate underside, would be press-fitted over the free end of the standoffs. Although numerous attempts were made, no satisfactory method of modifying the tie-down technique could be designed. Thermal expansion coefficient differences between metallic snaps and ceramic standoffs precluded the possibility of snap-on attachments; during exposure to high-temperature environments, the metallic snap would loosen from the ceramic standoff. Additionally, the brittle nature of ceramic materials would prevent subsequent removal of the mirror substrate once it was snapped in place. If metallic standoffs were substituted for low-thermal conductance materials such as pyrex or ceramic, the excessive heat leak through the standoffs would tend to negate the use of the multilayer insulation system. Calculations of the ratio of heat transfer through metallic standoffs to that through the multiple layer insulation indicated that the use of metallic standoffs could not be tolerated from a thermal viewpoint. If four titanium standoffs (0.156-inch diameter) were used for every square foot, the ratio of heat transfer through the standoffs to that through the multilayer is 26-to-1. If aluminum were substituted, the ratio increases to approximately 433-to-1.

4.3 MULTILAYER INSULATION

4.3.1 Cylindrical or Longitudinal Wrap

This technique is applicable for large cryogenic tanks but not practical in applications where access to the substrate being covered by the blanket is necessary. Additionally, for configuration where cutouts for boom penetrations are required, this method of attaching multilayer insulation is undesirable from an assembly viewpoint.

4.3.2 Sewing or Stitching Blankets

This method for holding the multilayer together also is considered unfeasible with respect to the requirement for ease of removal and replacement. Sewing tends to compress the multilayer system and degrade its performance characteristics in high-temperature applications.

4.3.3 Teflon Buttons and Thread

The technique of forming blankets consisting of layers of aluminized mylar with glass-fiber spacers in between and held together with low conductive teflon pins and buttons was developed under a Lockheed-sponsored program (reference 8). Buttons and pins allow fabrication of blankets prior to actual installation onto a vehicle skin and also tend to negate handling problems associated with handling fragile multilayer blankets. Unfortunately, temperature limitations of teflon (maximum continuous operating temperature of 500°F.) prevent its use in the attachment problem presented in this study.

4.3.4 Polyimide Film Buttons and Glass-Fiber Thread

This system is similar in construction to that presented above except that 0.005-inch-thick polyimide film is used as button material, and glass-fiber thread (0.017-inch diameter) is used as the thread or pin. Both of these materials are capable of withstanding the highest temperature (800°F.) anticipated for the upper layer of the insulation system. The glass fiber is threaded through the multilayer and polyimide button and is secured at the bottom of the blanket by a knot. This method of holding the multilayer system together was used successfully during the study and showed no damage due to handling or environmental test conditions.

4.3.5 Laminate and Thread

A modification to the above technique was devised in order to allow the second surface mirrors to lie flat when placed on the top layer of the multilayer blanket. Buttons were eliminated by looping thread through the top-layer and laminating another piece of polyimide film over the entire surface with silicone adhesive. This eliminated all humps due to the looped thread, and provided a flat surface for mirror attachment. A comprehensive description of the fabrication technique is presented in Section 6.

4.3.6 Ceramic Studs and Aluminum Push-Nuts

This modification of the button and thread technique substitutes ceramic studs for the polyimide button/glass fiber attachment method. T-shaped ceramic studs

(Figure 4-4) are pierced through the multilayer blanket and are held in position by aluminum push-nuts installed onto the bottom of the stud located at the underside of the blanket (Figure 4-5). It was anticipated that the number of studs required to hold the multilayer blanket together would be considerably less than required for the polyimide button/glass fiber attachment. This assumption was verified during experimentation and the stud-push nut combination offered a more rapid manner of blanket assembly than the looped thread configuration. No change to multilayer blanket integrity was noted when the stud-push nut attachment technique was used on blankets subjected to vibration excitation.

4.4 MULTILAYER TO VEHICLE SKIN

This juncture was not as difficult to treat as the aforementioned attachment problems because of the moderate temperature environment (70 to 120°F.) encountered at the vehicle skin.

4.4.1 Bonding of Multilayer to Vehicle Skin

Use of an adhesive system to bond the bottom of the multilayer blanket onto the vehicle surface is impractical and does not permit removal of the system without destroying the blankets themselves.

4.4.2 Snap or Clip Fasteners

Snaps or clips fabricated either from metallic or nonmetallic material secured to the underside of the multilayer blanket were eliminated as a possible means of providing attachment to the vehicle skin. Problems associated with this technique are twofold: (1) difficulty in maintaining alinement of multilayer blanket clip or snap with respect to receptacle located on vehicle surfaces; and (2) clip or snap must be bonded to the bottom of a multilayer blanket, and most bond lines would be damaged by repeated flexes of blanket which occur during handling, installation, and removal.

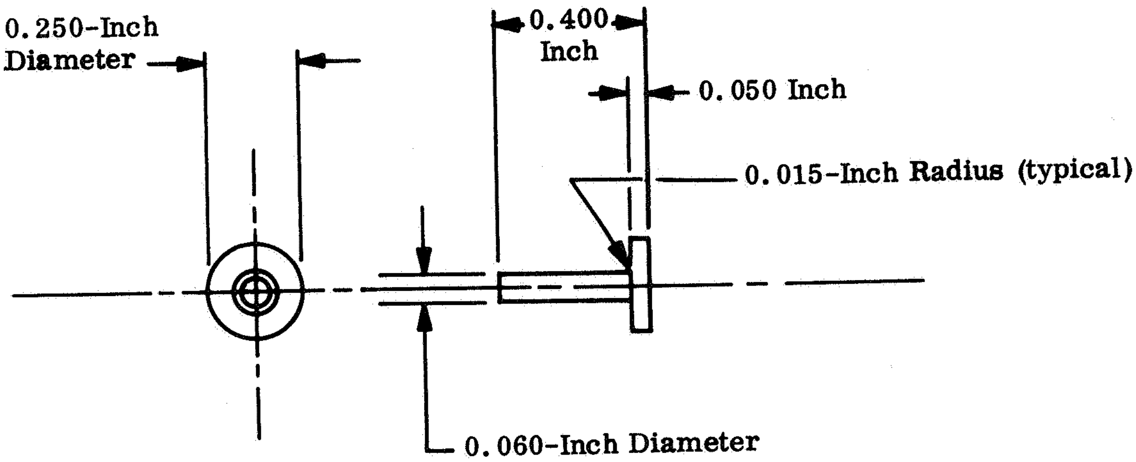


Figure 4-4. Attachment stud

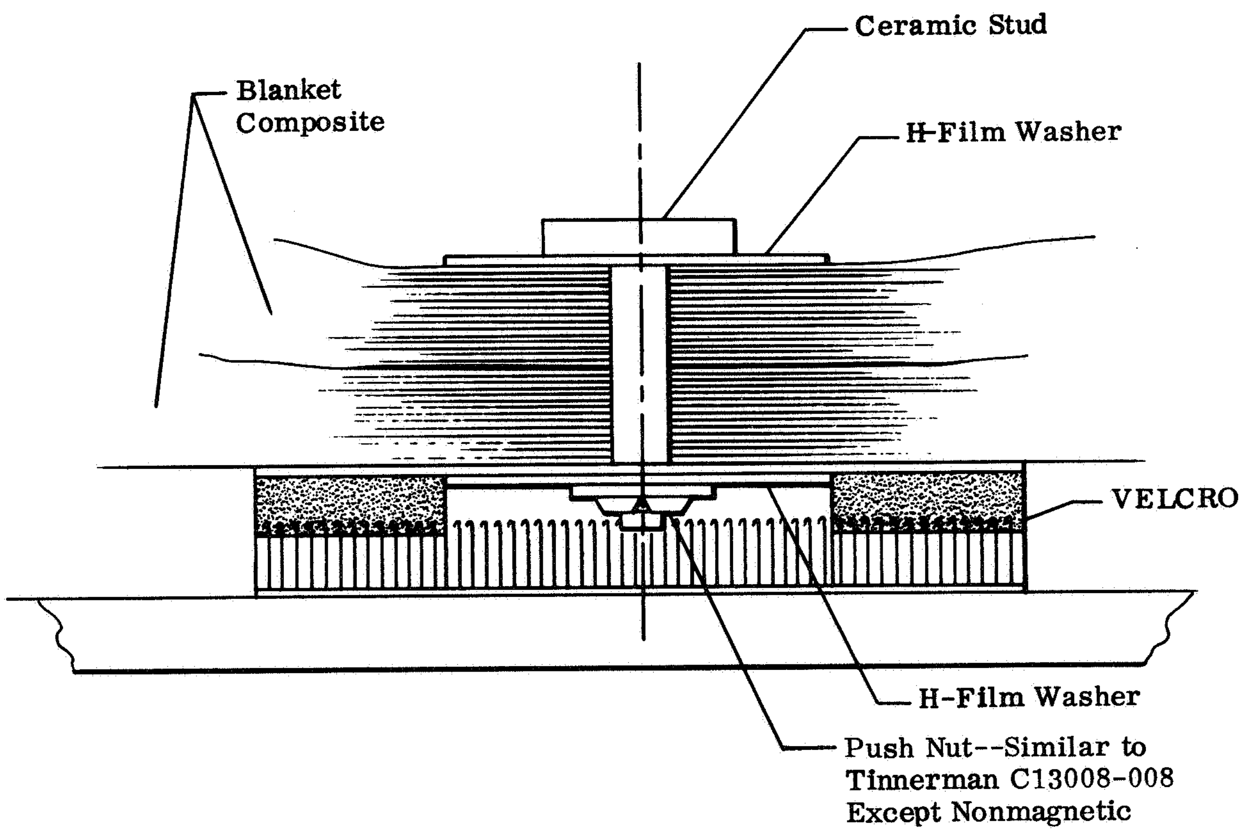


Figure 4-5. Ceramic stud-metallic pushnut attachment for multilayer

4.4.3 Velcro Fasteners

Nylon Velcro fasteners are composed of two separate sections: a hook portion and a loop (pile) segment. When mated, the two segments enmesh and form a bond which has a tensile separation strength on the order of 7 p.s.i. The hook portion of the fastener is adhesively bonded to vehicle surface in positions to mate with pile portions which are attached to the underside of the multilayer blanket by the glass-fiber thread or ceramic stud described in 4.3.4 and 4.3.6. Exact alinement is not required to provide a good bond between mating portions of the fastener because each tiny hook mates with a portion of the pile half of the Velcro. Also the hook portion, which is bonded to the vehicle skin, could be twice the size of the pile half so as to accommodate any misalinement which might occur during blanket installation. This Velcro fastening technique has been used successfully by Lockheed on NASA and company-funded developmental programs (references 7, 8, and 9). An epoxy adhesive is used to bond the hook portion of the Velcro pad to the vehicle surface. This adhesive provides excellent bonding performance in the temperature range to be encountered on the vehicle surface (70-120°F.).

Section 5
SELECTION OF MOST FEASIBLE ATTACHMENTS

Selection of methods deemed most feasible for attaching a thermal-control composite to cylindrical and flat surfaces is based on the experimental results obtained during this study.

The discussion given below presents the basis for selecting two different types of attachment techniques for environmental and development testing.

5.1 SECOND-SURFACE MIRRORS TO A SUBSTRATE

This element of the composite was segregated into two temperature regimes: a high temperature application (600-800°F.) and a lower-temperature design (less than 600°F.). Dow Corning silicone 92-024 is the best adhesive for the higher-temperature application and the double backed polyimide tape (Permacel ST6962) appears to be promising for use in designs which do not exceed a maximum temperature of 600°F.

Our experience with DC 92-024 silicone adhesive indicates that the performance characteristics of the adhesive system degrades at a lower temperature in an air oven than when exposed in a vacuum environment. The material showed no detrimental effects on appearance or bond-line strength after 72 hours at 800°F. or 30 days at 710°F. in a vacuum of 10^{-4} Torr. However, the same material showed embrittlement and crazing after 8 hours exposure to 650°F. in an air oven. Apparently, the silicone adhesive is oxidized when exposed to high temperature in an environment which includes oxygen. Alkyl or aryl groups in the siloxane molecule are attacked by the oxidation process. In general, the larger the alkyl or aryl groups attached to the silicone atom, the more readily the polymer is oxidized. The combination of oxygen and high temperature cause a chemical reaction in which water is released and the silicone begins to decompose. Crazing of the bond line is the first indication of the decomposition process.

In a vacuum environment the lack of oxygen prevents the oxidation process from occurring, and thus the mode of bond-line degradation is thermal depolymerization or scission. Without oxygen, the temperature must be of sufficient magnitude to overcome the bond energies between silicon and oxygen atoms within the molecular structure of the polymer. When this occurs, the molecule is thermally cracked into smaller, more volatile, segments which may either outgas or continue to crosslink and form other products.

Application of second-surface mirrors to double-backed polyimide tape appears to be feasible as long as the temperature exposures do not exceed 600°F. Because this study was directed toward the higher temperature regime, double-backed polyimide tape was not utilized during the environmental tests conducted.

5.2 MIRROR SUBSTRATE SELECTION

Second-surface mirrors could only be applied as part of the composite system in one of two manners; to the top of the multilayer blanket or to a substrate which was subsequently attached to the vehicle skin. For reasons outlined in paragraph 4.2.2, initial efforts were concentrated toward finding a suitable, lightweight metallic substrate which could be used for mirror attachment.

5.2.1 Metallic Screen Substrate

Expanded-metal screen, fabricated from 1145 aluminum alloy, was selected for use as the mirror substrate for the silicone-adhesive system. Screen provides an excellent surface for attaching mirrors with silicone adhesive. The adhesive squeezes through the screen openings and is entwined around the backside of the screen so that an excellent bond is established after curing. The screen offers added advantages when compared with foil substrates because of reduced weight and elimination of air-entrapment problems associated with adhesive application. Aluminum was chosen because it is a lightweight, nonmagnetic material. Expanded metal may be procured in a variety of mesh sizes, and in thicknesses ranging from 0.002 to 0.010 inch. To minimize weight, 0.005-inch thick material weighing 0.030 pound per square foot was selected for initial evaluation. Subsequent exposure to forces resulting from sinusoidal vibration revealed this thickness to be insufficient for carrying loads imposed by the second-surface mirrors and adhesive. Another aluminum material of 0.005-inch thickness, but with less openings and a weight of 0.039 pound per square foot, was used successfully during development tests performed during the program.

5.2.2 Multilayer Substrate

Application of mirrors onto the multilayer substrate was determined to be feasible. However, a method for providing a smooth top-layer surface had to be developed so that the mirror surfaces would lie in the same plane. If a mirror were raised, the adhesive bond-line would be exposed to incident solar radiation. Exposed adhesive would absorb a high percentage of incident solar radiation, and the resultant temperature increase could result in failure of the adhesive bond-line.

Primary candidate techniques for holding the multilayer blanket together required the use of thread and buttons. The thread was looped through buttons located on the topside of the blanket, and were knotted into Velcro pads positioned at the underside. Buttons and thread caused the top of the blanket to be uneven because humps were formed wherever they were located. These humps resulted in cocked mirrors whenever the mirrors were subsequently applied onto the blanket with adhesive.

The above-mentioned problem was corrected by developing a technique whereby the blanket top-layer would become a laminate. A piece of polyimide film was laminated (with silicone adhesive) over the buttons and thread, thus providing a smooth surface for mirror attachment. A description of the fabrication process for such a multilayer assembly is given in Section 6.

5.3 MIRROR SUBSTRATE ATTACHMENT

For composite systems in which mirrors were applied onto the blanket top-layer, the mirror substrate was attached during the assembly of the multilayer blanket. In the alternate technique, the expanded metal screen was attached through the use of retaining tabs, wire, and standoffs, as described in paragraph 4.2.2. Both of these attachment methods were proven to have adequate structural integrity during the development tests conducted during the study.

Attachment of the metallic-screen substrate using press-fit techniques was discarded because no suitable method could be devised. All methods utilizing the press-fit technique required metallic standoffs which resulted in excessive heat leak through the thermal-control composite system. Thermal analyses of high-temperature multilayer systems and heat losses anticipated for fastening techniques were performed. These data, presented in Appendix B indicate that use of low thermal conductance materials is mandatory in order to provide a thermally efficient composite system.

Some preliminary investigations into the possible use of metallic fastening systems which would be drilled, screened, or riveted to the spacecraft skin were accomplished. However, thermal analyses dictated that only ceramic or pyrex be used as standoffs. Heat transfer through metallic standoffs would excessively degrade the efficiency of the composite system.

5.4 MULTILAYER SYSTEMS

The basic system developed for fabricating high-temperature multilayer blankets consists of alternate layers of doubly aluminized polyimide film and Tissueglass spacers which are held together with polyimide buttons and quartz fiber thread. In cases where the multilayer blanket is used as the mirror substrate, the quartz fiber thread is reinforced with silicone adhesive and looped between two laminated sheets of 0.005 inch-thick polimide film. The laminate is then used as the top layer of the blanket assembly.

Single-strand, unreinforced, glass fiber thread was determined to be incapable of carrying the weight of the mirrors during sinusoidal vibration tests completed in Phase II of the study effort. While the quartz fiber thread had good tensile strength, its resistance to flexure was poor. During sinusoidal excitation imposed along the x-axis of a multilayer-mirror composite, a shearing action occurred due to displacement of the blanket top-layer in relation to the stationary position of the Velcro attachments. The entire weight of the mirrors was carried by the thread. Repeated flexure during vibration tests caused the thread to fray, and eventually break completely.

Numerous materials were investigated for use as thread material. Titanium (0.005-inch-thick) and copper (0.003) wire was obtained as possible candidates. It was determined that materials which tend to cold work, and thus fail during repeated flexure, generally have low thermal conductivities. While copper was undesirable from a thermal-conductivity standpoint, it is relatively unaffected by flexure. By using two metals which represent extremes (tendency to cold-work and thermal-conductivity), the feasibility of using any type of metallic thread could be determined. Additionally, because failure of the quartz fiber resulted from fraying, an attempt was made to reduce this tendency by coating the quartz thread with both a silicone and a polyimide adhesive.

Sample mirror-multilayer composites were prepared which utilized single and multiple-strands of copper wire, titanium wire, and silicone-reinforced quartz fiber thread. Polyimide adhesive increased the brittleness of quartz fiber, and was eliminated as a possible candidate. Each of the composite samples was subjected to sinusoidal vibration excitation. Only samples prepared with multiple strands of copper and silicone-reinforced quartz thread survived the vibration environment. The silicone-reinforced quartz thread was selected as the better attachment technique because of its low thermal-conductivity characteristics.

Investigations into the use of ceramic studs in lieu of quartz threads (described in paragraph 4.3.6) revealed this technique would only be applicable in cases where the mirrors would be applied to a metallic substrate which would be subsequently attached to the vehicle skin. Experience with multilayer blanket fabrication dictated that spacing between blanket attachments should not exceed 8 inches due to handling and installation problems. During experimentation it was determined that polyimide buttons and quarz thread could be used on 8-inch centers. A switch to the proposed ceramic studs on 8-inch centers would have resulted in a large increase (a factor of 12) in the heat transfer through the multilayer blanket due to fasteners. The ceramic stud-pushnut attachment technique was eliminated from further consideration.

Section 6
COMPOSITE FABRICATION

Fabrication techniques for producing a thermal-control composite system utilizing second-surface mirrors and multilayer insulation were developed for each of the two systems originated during this program. A description of the assembly techniques for the blanket, and then for the individual composite systems follows.

6.1 MULTILAYER ASSEMBLY

Manufacturing plans for fabrication of the test specimens were based on criteria from several sources. These include results of Phase I experimentation efforts and experiences from previously fabricated blanket systems for cryogenic applications. The primary objective of the plan was to fabricate the test specimens in an effective economical manner, and at the same time develop the knowledge for full-scale fabrication.

6.1.1 Thread-Button Attachment

The multilayer blanket system selected for use in the program consisted of 0.0005 inch-thick, doubly-aluminized polyimide film, 0.001 inch-thick Tissueglass spacers, and 0.017 inch-diameter quartz fiber thread. Buttons, 0.5-inch diameter, were punched from singly-aluminized, 0.005 inch-thick, polyimide film.

Blankets were prepared by stacking alternate sheets of aluminized polyimide film and Tissueglass spacers over a layup fixture of the desired contour. The layup fixture consisted of plywood whose outside radius represented the contour required for the inside mold line of the blanket assembly. For flat specimens, the fixture was merely a flat section of plywood. Rolls of aluminized polyimide and Tissueglass were positioned in a rack above the plywood fixture, and alternate sheets of the two materials were stacked to obtain the desired blanket configuration. In this program, all blankets consisted of 20 sheets of aluminized polymide, each separated with a sheet of Tissueglass.

Holes were predrilled in the plywood mounting fixture to accomodate the desired hole pattern. For example, in systems where retaining buttons were located on 8-inch centers, the hole pattern would be accordingly spaced in the mounting fixture.

After the layers were properly stacked, a hollow needle was used for installing the thread. One end of the thread was inserted into the needle, and the needle was pierced through the layers from the underside of the mounting fixture. After penetrating the top of the blanket, the needle was looped through a 1/2-inch-diameter button and inserted back through the blanket from the topside. After repeating this procedure at all desired button locations, the blanket was turned over and the thread looped through a one inch-square pile section of nylon Velcro fasteners. The thread was knotted at the center of the Velcro pad, and some air-drying epoxy adhesive was placed over the knot to prevent slippage.

After allowing the epoxy adhesive to cure (approximately a one-hour, room-temperature cure), the blanket assembly was trimmed to the desired dimensions, and stored in a clean polyethylene bag. White nylon gloves were used to contact the multilayer system during all assembly and handling operations. It was determined that the maximum distance between button locations that would permit handling was 8 inches. If larger button spacings were used, the blankets would be damaged during handling and installation procedures. The quartz fiber thread and polyimide button retainers serve two important functions. They permit assembly of the individual layers into blankets before they are installed onto the spacecraft skin. They also provide the structural support needed during high load conditions and prevent relative movement of the individual shields and spacers.

Although most of the blankets prepared for this study were flat, one 20 layer system was prepared to cover a 1-foot-long by 1-foot-diameter cylinder. To prevent excessive heat leak through the point where the ends of the multilayer blanket came together, a ship-lap joint was employed. The ship-lap technique provided a 4-inch spacing between butt-joints, and the maximum gap between joints was approximately 0.050 inches. Mating halves of the blanket were connected by lacing quartz thread around button retainers.

6.1.2 Thread-Laminate Attachment

The above procedure was modified for composite systems in which second-surface mirrors were applied onto the blanket top-layer. A glass cloth-polyimide-adhesive laminate was employed as the top layer of the blanket, and twisted strands of silicone-reinforced quartz fiber was used as thread.

Figure 6-1 depicts the assembly sequence. A sheet of 0.005-inch-thick aluminized polyimide film was primed and coated with a thin film (approximately .002 inch) of DC A-4094 primer and DC 92-024 silicone adhesive. A fine-weave glass cloth (.003 inch-thick) was placed on top of the adhesive layer, and the adhesive was worked through the glass cloth mesh by pressing the cloth into the adhesive with a wooden dowel Fig. 6-1(a). While the adhesive was still wet, silicone-reinforced, braided glass thread was looped through the polyimide-glass cloth laminate at the desired attachment locations. (Four-inch spacing between attachments was determined to be required during vibration testing.) Because the looped thread resulted in an uneven surface, another piece of 0.005 inch-thick polyimide film was laminated over the glass cloth-polyimide layer Fig. 6-1(b).

Before proceeding, it should be noted that silicone-reinforced, braided glass thread was prepared prior to initiation of the laminate assembly. Individual strands of 0.017-inch-diameter quartz thread were primed by soaking the thread in DC 1200 primer (DCA-4094 primer was also determinized to be acceptable), and allowed to air-dry for one hour at room temperature. The strands were then coated with DC 92-024 adhesive by drawing the thread through a die coated with adhesive. Four coated strands were then twisted together to form a braided thread assembly. The completed thread-assembly was then allowed to cure at ambient conditions for 24 hours before use in the multilayer blanket assembly.

After encapsulating the silicone-reinforced glass thread into the laminate, the laminate was installed as the top layer of a multilayer blanket. Ends of the silicone-reinforced thread were inserted into hollow needles and pierced through layers of aluminized polyimide and Tissueglass positioned on a mounting fixture Fig. 6-1(d).

FOLDOUT FRAME 1

FOLDOUT FRAME 2

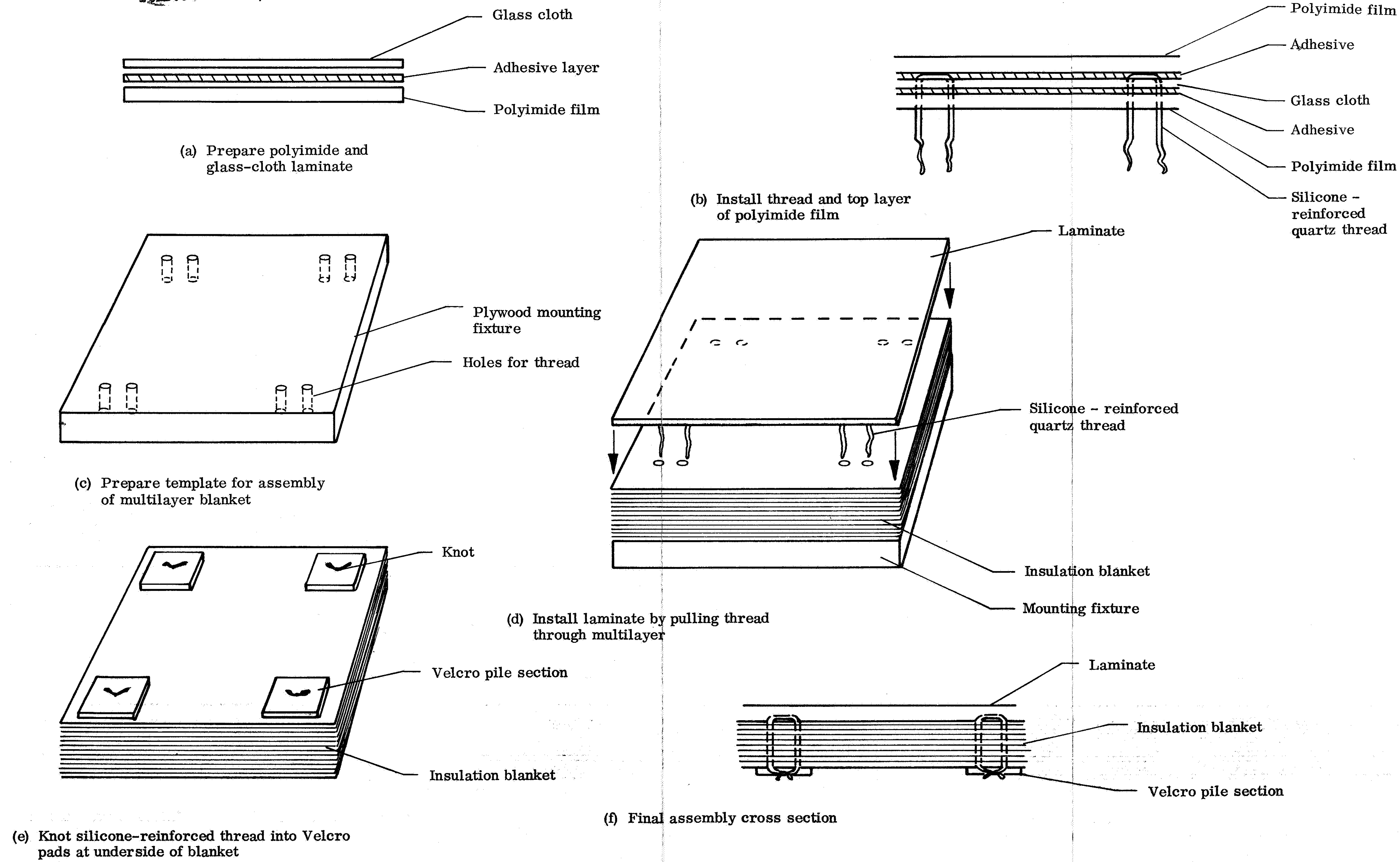


Fig. 6-1 Sequence for Laminate-Multilayer Blanket Assembly

The thread was drawn through positioning holes located in the mounting fixture. Completion of assembly operations consisted in turning the blanket over, piercing through Velcro pile sections (1 inch-squares), and knotting the thread together at the center of the Velcro pads Fig. 6-1(e). Some DC 92-024 silicone adhesive was placed over the knot to prevent slippage.

Figure 6-1(e) shows a cross-section of the completed assembly which was used for thermal-control composites in which mirrors were applied to the blanket top-layer. The laminated top-layer provided a smooth surface for mirror attachment, and thus eliminated the posssibility of cocked or raised mirrors. Glass cloth strengthened the attachment locations, and prevented the silicone-reinforced glass thread from tearing through the polyimide film whenever tangential loads were applied. Overall thickness for the top-layer laminate (including thread) was approximately 0.048 inches. Blankets fabricated with a laminated top-layer retained their ability to sustain flexure, and were found to be adaptable to curved and flat surfaces.

6.2 MIRROR APPLICATION

Second-surface mirrors were applied to multilayer and screen-substrates with DC 92-024 adhesive and DC A-4094 or 1200 primer. Both the backside of the mirrors, and the substrate surface were primed prior to positioning the mirrors. Silicone adhesive was spread over the primed surface (either the backside of the mirror or the top of the substrate) to a thickness of approximately .005 inches. Mirrors were individually applied to the substrate by starting at the upper left-hand corner, and placing the mirrors side-by-side until the row was complete. The second row was then started, and the same sequence repeated for each remaining row. Adhesive was allowed to cure at ambient conditions for 24 hours, although after six hours the adhesive sets up sufficiently that the assembly may be handled. Excessive adhesive is removed by wiping with a toluene-soaked tissue, or by lightly scraping the mirror surface with a teflon-coated spatula.

A technique developed by LMSC, but not employed during this program, is recommended for large surfaces. A vacuum device with contour to accomodate the outside mold of the mirror substrate is fabricated from metallic or plastic materials. Holes (1/16-inch-diameter) are drilled on 1-inch centers to coincide with the desired mirror spacing. A valve is provided for attachment to a vacuum pump. The valve is opened to the vacuum pump and mirrors are placed over each hole with the inconel backing facing outward. The mirrors can be easily aligned until the desired placement is obtained. The mirror substrate is primed and coated with DC 92-024 silicone adhesive and placed into contact with the mirrors. The assembly is allowed to remain in position for 6 to 12 hours, and then the vacuum is cut off and the mirror assembly removed. This technique is less time-consuming than the individual mirror application technique. Special care must be taken during fabrication to make certain that the surface of the vacuum-holding device is smooth.

6.3 COMPOSITE ASSEMBLY

Techniques for installing the thermal-control composite system onto a metallic substrate were developed during the study effort, and are described below.

6.3.1 Mirrors-to-Expanded Metal Technique

The attachment method in which the mirrors were adhesively bonded to expanded-metal screen required bonding ceramic standoffs to the simulated vehicle skin. LMSC designed attachment posts (Fig. 6-2) which could be fashioned from a low thermally conducting material such as pyrex or ceramic.

Ceramics can be obtained which offer excellent structural strength, and are recommended for use in full-scale production applications. However, pyrex was substituted during the developmental tests because of the relatively long (6-8 weeks) procurement time and high initial investment required for the ceramic parts. Ceramic posts would be made by an outside vendor, and initial tooling requirements for a mold would be on the order of $500. Posts would only cost about 20 cents each once the mold was prepared, however there was no assurance that the post configuration selected represented the optimum design. Pyrex posts, which were machined to the desired dimensions, were procured from a local supplier.

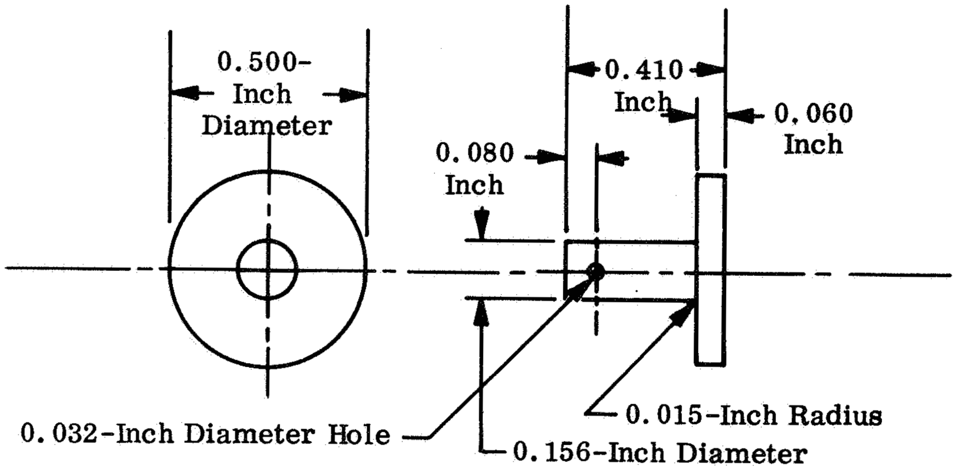


Fig. 6-2 Attachment Post

Application of the composite system required that first the multilayer blanket and then the expanded metal-mirror combination be installed. A 12-inch by 18-inch flat aluminum plate was the first specimen to be prepared. Hook portions of the nylon Velcro pads were bonded with epoxy adhesive to the plate surface. Position of the pads was dictated by the position of the mating halves located on the underside of the multilayer blankets, e.g., if pile sections were attached at 4-inch centers on the multilayer blanket, the hook sections would be attached at 4-inch centers on the aluminum plate. Four pyrex posts were bonded to the panel with a two-part epoxy system, and allowed to cure for 4 hours at room temperature. The multilayer blanket was placed over the posts, and a hole punched through the blanket. The blanket assembly was then placed over the posts and the mating Velcro halves brought into contact.

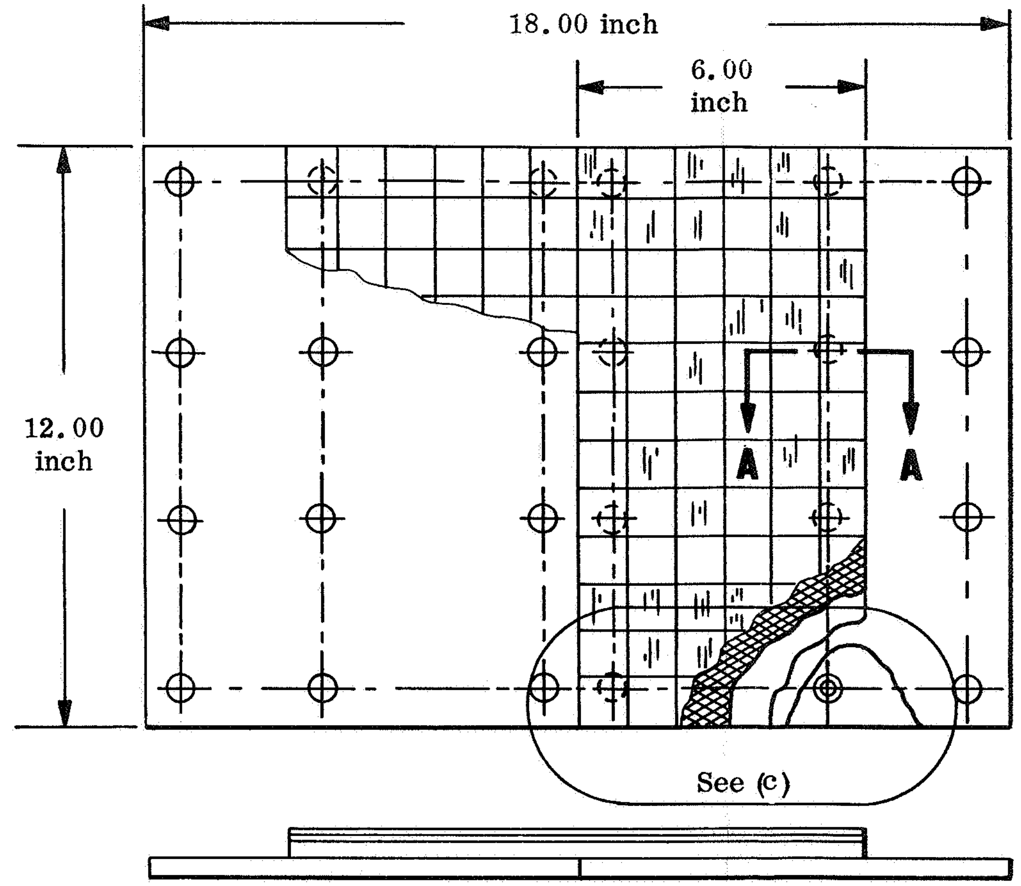
After installation of the multilayer blanket the expanded metal was attached to the pyrex posts by threading wire through retaining tabs located at the underside of the expanded metal. The retaining tabs were spot-welded to underside of the expanded metal prior to mirror application. The rectangular tabs (0.5-inch by 2 inches) were made from 0.010 inch-thick aluminum alloy, and were channeled at the center to permit 0.028-inch diameter stainless steel wire to pass through. The wire was threaded through one of the pyrex standoffs, through the two retaining tabs, and through the second standoff. The ends of the wire were twisted around the base of the pyrex posts to lock the screen into position. The same procedure was repeated for the other two standoffs and tabs. On each wire strand, two electrical splices were crimped onto the strand to prevent the panel from sliding along the wire.

Figure 6-3 depicts the completed assembly. The wire was threaded through the standoffs and retaining tabs by the use of a pair of long-nose, needle pliers. Excess wire was clipped with a pair of side cutters. If the panel is to be removed, the wire is clipped, and a new piece of wire is used for reinstallation. Because the mirror panel was fragile, special care was taken during installation procedures to avoid contact with the top surface. Similar installation techniques were employed for constructing the cylindrical test specimen, except that two panels were employed. The edges of the panels were permitted to overlap by approximately 1/4-inch to prevent incident solar radiation from reaching the underlying multilayer blanket.

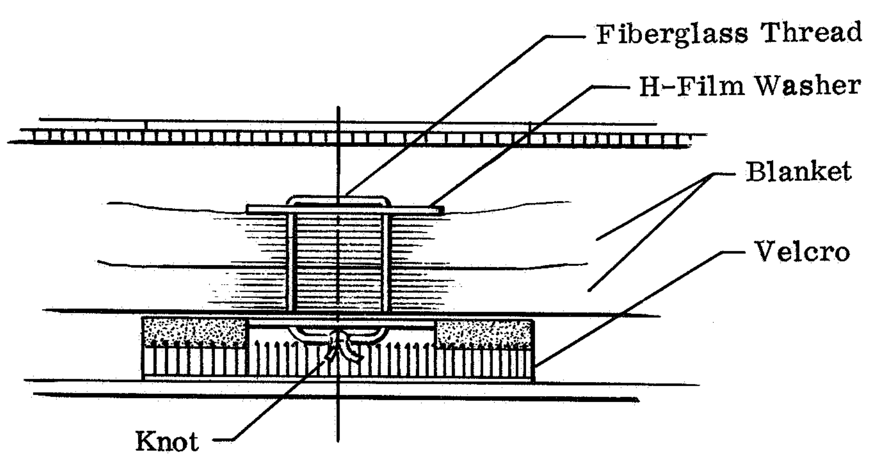
Although the threading technique offered good structural integrity, the installation process was difficult and time-consuming. Clearance between the top of the multilayer and the bottom of the mirror substrate was only 1/4-inch, and this did not permit easy access for threading wire into the attachment posts. Additionally, ceramic standoffs bonded to the spacecraft skin could present an operational restraint because of their susceptibility to damage during vehicle test and prelaunch handling operations. If an attachment post is broken or damaged, a fixture must be available for holding the replacement post in position until the epoxy adhesive cures. If the attachment posts could be inserted into receptacles which have been previously welded or riveted into the spacecraft frame, then the attachment posts would be readily removable and replaceable. However, during this study it could not be assumed that drilling or riveting to the spacecraft was permissible in all potential applications for the composite thermal-control system. For this reason, efforts were concentrated toward the development of attachment techniques which require no structural modification to the spacecraft skin.

6.3.2 Mirrors-to-Multilayer Technique

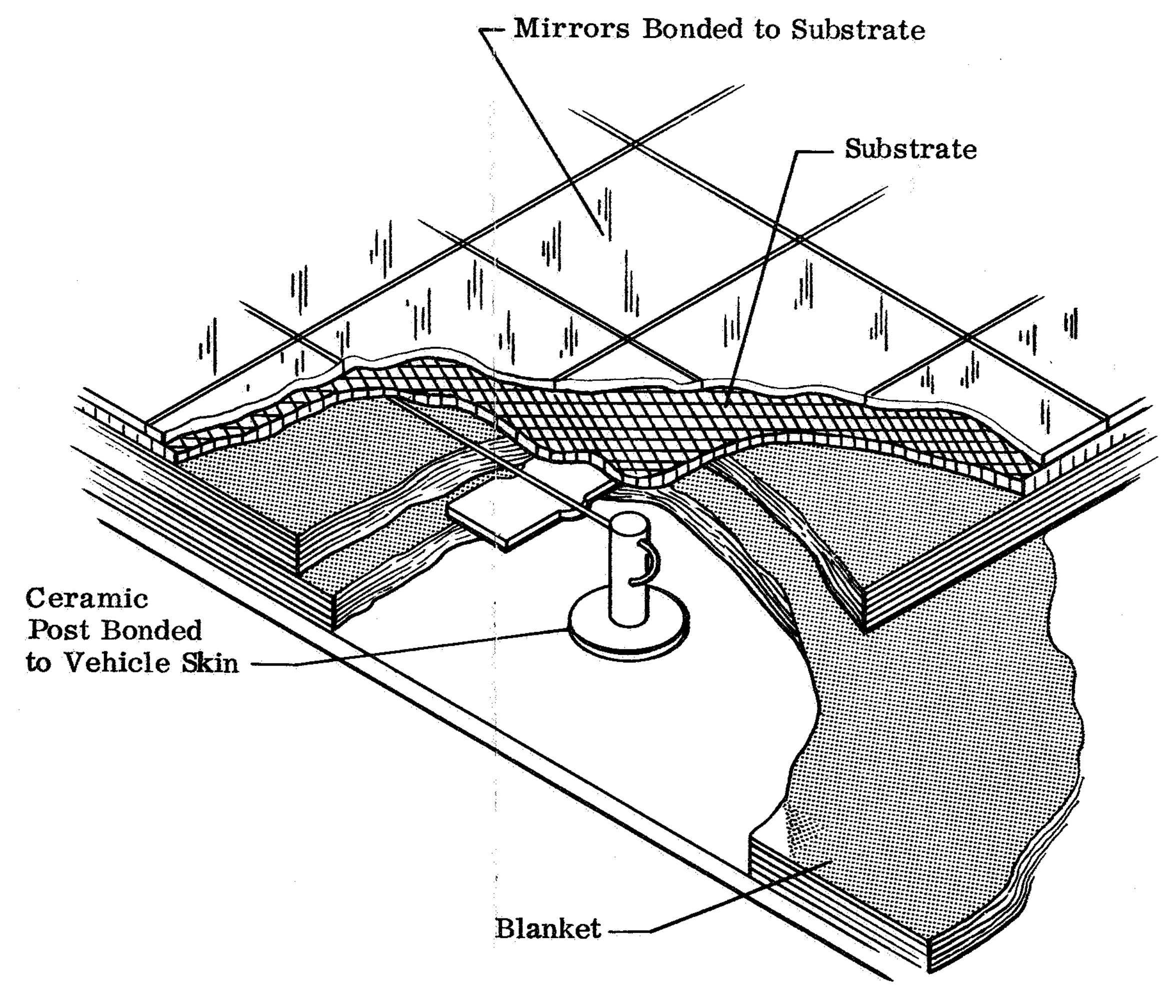
Installation of mirror-multilayer composites merely required bonding the mating Velcro hook portions to the desired substrate, and pressing the composite into place. Care was taken to apply pressure over a large area to prevent cracking the mirrors. The composite system was locked into position when the Velcro halves were mated. Clean nylon gloves were used when handling the composite to prevent contamination of the optical surface. Figure 6-4 depicts a mirror-multilayer composite.



(a) Plan and side views

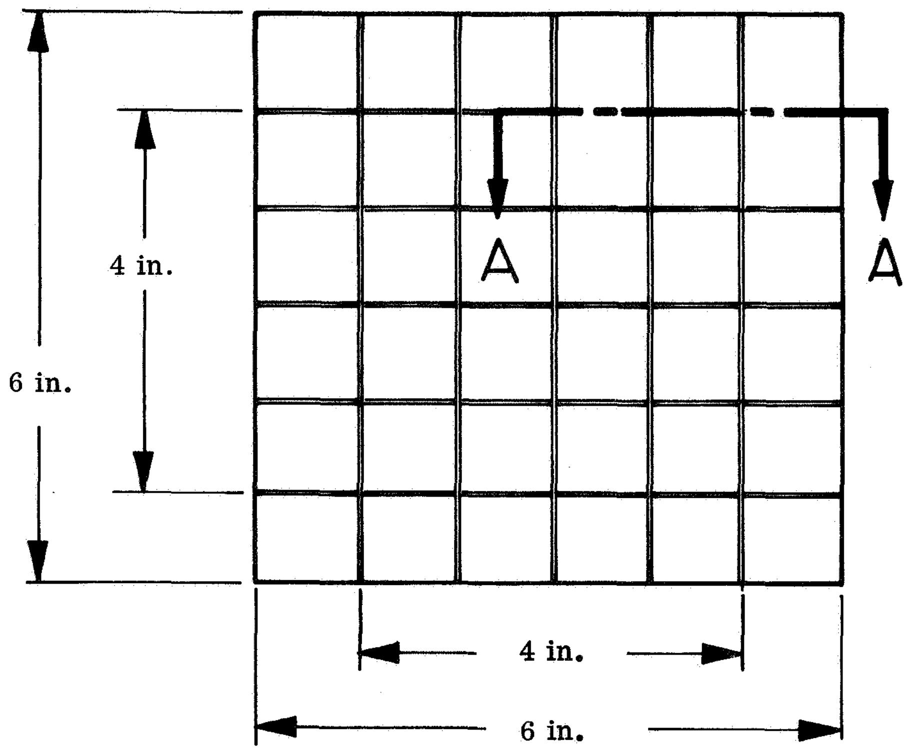


(b) Section A-A. Method of tying blanket composite with buttons and fiberglas thread

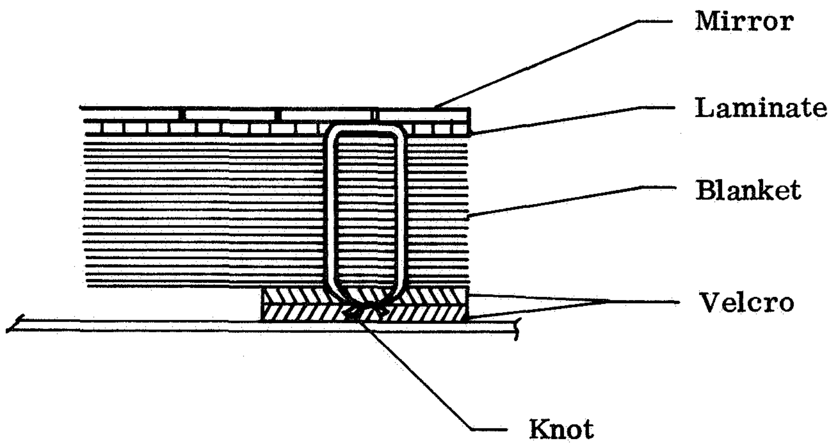


(c) Method of mirror-substrate assembly to vehicle skin

Fig. 6-3 Expanded Metal-Multilayer Composite Configuration



(a) Configuration Plan View



(b) Section A-A

Fig. 6-4 Mirror-Multilayer Composite Configuration

Section 7
ENVIRONMENTAL TESTING

During Phase I of the study, attachment methods which appeared to be the most promising for use on spacecraft systems were selected. Phase II efforts were devoted to modifying and evaluating the candidate systems in order to establish their ability to withstand the anticipated spacecraft launch and orbit environments. This section describes the environmental tests performed in support of the Phase II effort. Table 7-1 describes the configurations tested. Specimen designations assigned in Table 7-1 (e.g., Specimen No. 1 etc.) are continued throughout the text for clarity. Table 7-2 summarizes the type of environmental test performed on each candidate composite system.

LMSC obtained approval of a program test plan from the contract technical monitor prior to initiation of developmental testing. The program plan defined testing parameters necessary to evaluate credibility of attachment methods for thermal-control composite systems. Purpose of the development series of tests was to determine compatibility of attachment techniques with critical environments to be encountered during use of a passive thermal-control system for a spacecraft. Specific environments to which the candidate composite were exposed are:

- Rapid pumpdown
- Thermal-cycling
- Acceleration
- Vibration (both sinusoidal and random)
- Acoustical noise
- Shock

7.1 RAPID PUMPDOWN

During the ascent phase of the spacecraft mission, rapid decrease from atmospheric to vacuum conditions can cause ballooning of the multilayer blanket due to air escaping from within individual blanket layers. Previous test experience indicated that,

Table 7-1

COMPOSITE TEST CONFIGURATIONS

Specimen Number	Description
1	6 in. x 12 in.; polyimide buttons and quartz thread on 4 inch centers; cover slides bonded to .016 in. thick stainless steel screen; phenolic standoffs.
2	Same as No. 1 except ceramic studs and aluminum pushnuts used in lieu of polyimide buttons and quartz thread.
3	Same as No. 1 except cover slide attached to .002 in. thick stainless steel foil.
4	12 in. x 18 in.; polyimide buttons and quartz thread on 4 inch centers; cover slides and mirrors attached to 0.005 in. thick aluminum expanded metal; pyrex standoffs.
5	12 in. x 18 in.; polyimide buttons and quartz thread on 4 inch centers; cover slides and mirrors bonded to top of mulitlayer blanket.
6	1 ft. long x 1 foot dia. cylinder; other components same as No. 4.
7	3 in. x 6 in.; single strand, .005 in. diameter titanium wire looped through top-layer laminate on 4 inch centers; cover slides bonded to top-layer laminate.
8	Same as No. 7, except twisted 3 strands of titanium together for use as thread.
9	Same as No. 8, except titanium foil placed in laminate to act as reinforcement.
10	3 in. x 6 in.; twisted strands of copper wire (.015 in. thick) looped through top-layer laminate on 4 inch centers; cover slides bonded to top-layer laminate
11	3 in. x 6 in.; 4 strands of silicone-reinforced quartz-fiber thread braided together and looped through top-layer laminate on 4 inch centers; cover slides bonded to laminate.
12	Same as No. 11 except silicone built up around thread to flatten surface.
13	Same as No. 12.
14	Same as No. 12 except sheet of .005 inch thick polyimide film laminated over thread to provide smooth surface for cover slides.
15	12 in. x 18 in.; polyimide buttons and quartz thread on 8 inch centers; cover slides bonded to .013 in. thick expanded-metal; aluminum standoffs.

Table 7-2

DEVELOPMENT TESTS PERFORMED ON CANDIDATE COMPOSITE SYSTEMS

Test	Candidate System														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rapid Pumpdown	Yes	-	-	-	Yes	-	-	-	-	-	-	-	-	-	-
Thermal Cycling	-	-	-	Yes	-	-	-	-	-	-	-	-	-	-	-
Acceleration	-	-	-	Yes	Yes	-	-	-	-	-	-	-	-	-	-
Vibration															
Random (boost)	Yes	Yes	Yes	-	Yes	Yes	-	-	-	-	-	-	Yes	Yes	Yes
Random (flight)	-	-	-	-	Yes	Yes	-	-	-	-	-	-	Yes	Yes	Yes
Sine (boost)	-	-	-	-	Yes	Yes	-	-	-	-	-	-	Yes	Yes	Yes
Sine (flight)	-	-	-	Yes*	Yes*	Yes*	Yes*	Yes*	Yes*	Yes	Yes	Yes	Yes	Yes	Yes
Acoustical Noise	-	-	-	Yes	-	-	-	-	-	-	-	-	Yes	Yes	-
Shock	-	-	-	Yes	-	-	-	-	-	-	-	-	Yes	Yes	-

*Denotes failure

depending on the blanket configuration and pumpdown rate, this ballooning effect can be of sufficient magnitude that the button retaining system and Velcro attachments could be compromised. Because the mirrors and their substrate will be positioned just above the multilayer blankets, the ballooning could cause deflections in the mirror substrate which result in breakage of the mirrors. To determine whether ballooning would be a problem for candidate composite systems, decompression tests were conducted on specimens 1 and 5.

Specimen 1 was placed in an altitude chamber and the pressure reduced from ambient pressure to 0.6 psia in 50 seconds. A scale, calibrated in tenths and sixteenths of an inch, was used as reference against which blanket deflection was measured. An external light source was used to illuminate the test specimen through a viewing port of the chamber. Upon evacuation of the chamber to 0.1 psia, the blanket expanded approximately 0.3 inch. Since the clearance between the top of the multilayer and the bottom of the aluminum screen was 0.2 inch, a slight deflection of the screen was noted. The chamber was allowed to return to atmospheric pressure, and the pumpdown was repeated. Identical test results were obtained during the second evacuation.

The test specimen was then removed from the altitude chamber and tape was applied over 3/4 of the edge area to reduce the available vent path. The screen was removed so that taping could be accomplished, and was not reinstalled. The specimen was placed into the chamber and pumpdown tests, at the same rate noted above, were repeated. Expansion of the blanket did not exceed 0.2 inch during decompression. The blanket deflection for this configuration was less than noted during the previous tests because the tape tended to limit the amount of expansion possible. Visual inspection of the buttons and Velcro fasteners after all tests revealed no detrimental effects to fastener integrity.

Similar tests were performed on specimen 5, and the maximum deflection was approximately 0.2 inch with all edges free, and 0.1 inch with two 18-inch edges taped down. One cover slide was slightly cracked during the test in which two edges were taped. No damage to the attachments was revealed.

It was concluded that decompression during ascent would not affect blanket or composite integrity. Adequate vent paths exist along the edges of the composite to permit escape of entrapped air. The type of multilayer blanket system utilized for the composite system, i.e., button and thread technique, offers an advantage over sewn or wrapped systems in which vent paths for escaping air are closed off. Also, additional venting areas result from the use of ceramic standoffs which pierce through the multilayer blankets.

7.2 THERMAL-CYCLING

Specimen 4, which utilized expanded-metal as the mirror substrate, was subjected to thermal-cycling between -100 and 700°F at 10^{-4} Torr. The test specimen was heated by means of a resistance heater which radiated onto a flat stainless steel plate in order to avoid the use of quartz lamps. Quartz lamps would have required water-cooling because of the test duration, and quartz lamps tend to burn out during long operation at high temperature. Because of its spectral distribution, radiation emitted from the underside of the stainless steel plate was determined to be as readily absorbed by second-surface mirrors as glass cover slides.

Figures 7-1, 7-2, and 7-3 depict the test set-up. The specimen was mounted inside an insulation box to reduce power requirements for the resistance heater and to prevent excessive heat loss. The insulation box was fabricated from an asbestos material (Johns-Manville "transite"). A shroud of 1 inch-thick Dexiglass, encased in aluminized polyimide flim, was attached to the outside of the insulation box. Thermocouples were attached in various locations (Table 7-3) within the composite for temperature measurement. Cooling to -100°F was provided by circulating liquid nitrogen through coils attached to the bottom of the radiator plate.

Two temperature cycles, consisting of holding at -100°F for 2 hours and holding at 700°F for 4 hours were completed. Examination of temperature readings (Table 7-4), obtained from thermocouples placed at various locations under the specimen surface, revealed significant temperature gradients across the panel surface during the high-temperature portions of the test. While temperature readings of 700°F were obtained on a mirror located in the center of the test specimen, only 400-500 degree readings

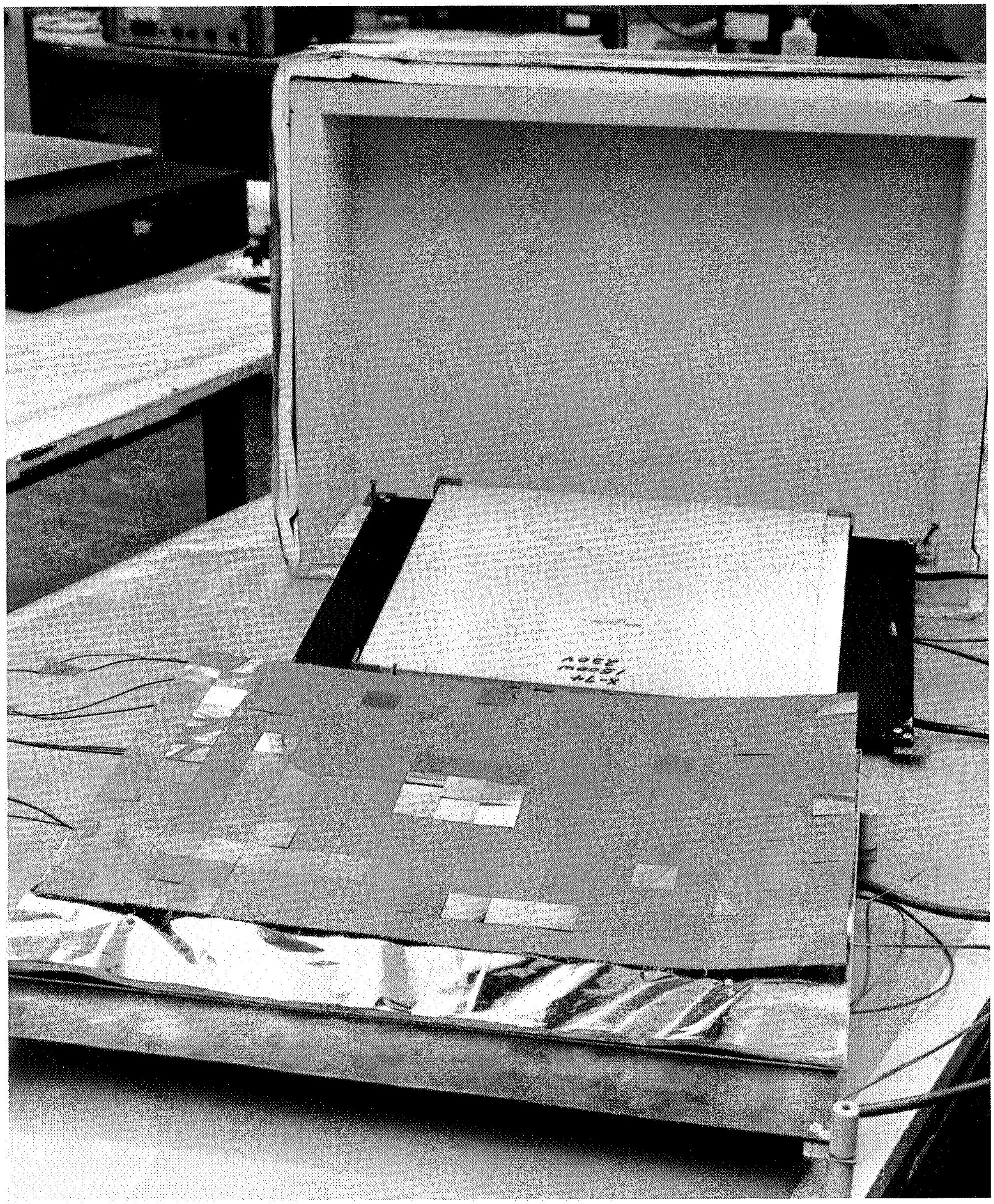


Figure 7-1. Configuration for thermal-cycling test

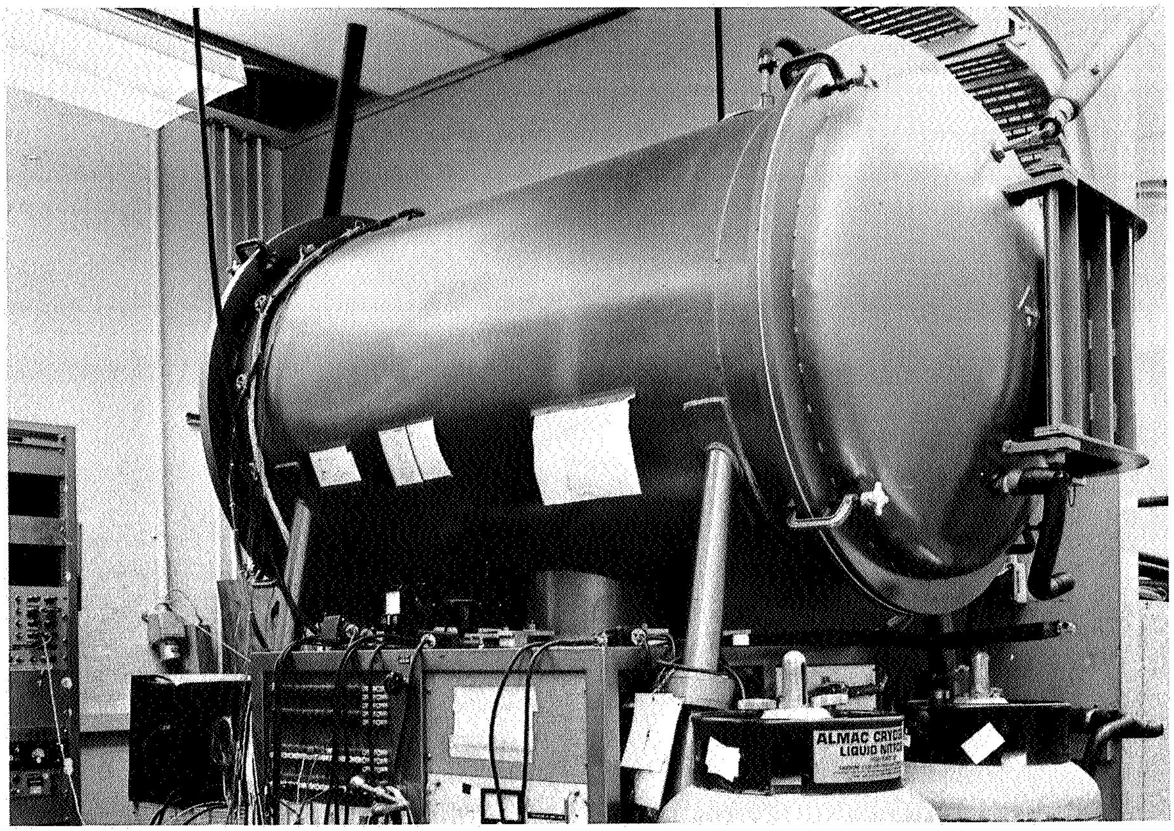


Figure 7-2. Thermal-vacuum test chamber

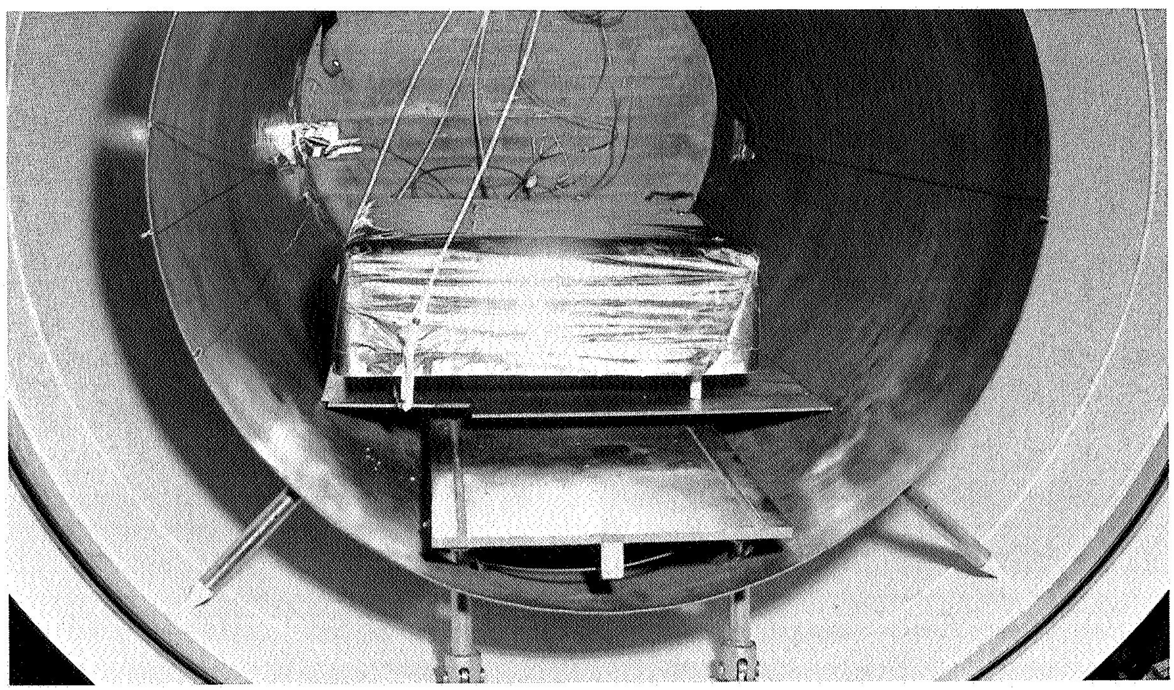


Figure 7-3. Specimen and insulation box mounted in vacuum chamber

Table 7-3. Thermal-cycling test data

Time	Thermocouple Readings ($^oF.$)											
	1	2	3	3A	3B	3C	4	4A	4B	5	6	7
	First Run											
10:00	75	75	---	---	---	---	---	---	---	---	---	---
11:00	-50	100	---	---	---	---	---	---	---	---	---	---
12:00	-100	100	---	---	---	---	---	---	---	---	---	---
13:00	-100	100	---	---	---	---	---	---	---	---	---	---
14:00	-110	100	-112	---	---	---	-85	---	---	---	---	---
15:00	200	100	125	125	100	100	200	125	100	90	75	75
16:00	700	100	600	500	225	150	675	375	190	425	275	390
17:00	700	100	625	500	350	250	700	450	300	475	300	390
18:00	700	100	600	550	390	250	700	450	350	450	---	---
19:00	700	100	600	575	400	275	700	500	350	450	---	---
20:00	700	100	600	575	425	290	700	500	350	450	---	---
	Second Run											
08:00	42	60	---	---	---	---	---	---	---	---	---	---
09:00	-90	100	---	---	---	---	---	---	---	---	---	---
10:00	-100	100	-110	---	---	---	-86	---	---	---	---	---
11:00	0	100	---	---	---	---	---	---	---	---	---	---
12:00	400	100	275	250	125	100	390	150	125	175	---	---
13:00	700	100	600	550	340	250	690	350	300	440	300	375
14:00	700	100	600	550	390	---	700	350	350	450	---	---
15:00	700	100	600	550	400	---	700	375	375	450	---	---
16:00	700	100	600	550	400	---	700	375	350	450	---	---
	Third Run											
11:00	730	100	704	632	545	---	682	607	490	673	583	659
12:00	725	100	698	628	549	---	685	600	512	683	585	698
13:00	720	100	695	628	550	---	685	590	510	680	585	696
14:00	745	100	730	661	569	---	716	635	524	712	610	702
15:00	725	100	700	632	552	---	698	609	510	695	592	686
16:00	700	100	675	603	530	---	657	595	495	667	555	654
17:00	650	100	632	590	522	---	622	564	455	615	528	613

Table 7-4. Thermocouple positions

Thermocouple Number	Location
1	Attached at center of radiator plate
2	Attached at center of specimen base-plate
3	Exact center of panel; attached at OSR-screen interface
3A	Exact center of panel; attached beneath 4 layers of blanket
3B	Exact center of panel; attached beneath 10 layers of blanket
3C	Exact center of panel; attached beneath 15 layers of blanket
4	Left-center of panel; attached at OSR-screen interface
4A	Left-center of panel; beneath 4 layers of blanket
4B	Left-center of panel; beneath 10 layers of blanket
5	Right-hand edge of panel; attached at cover slide-screen interface
6	Right-hand upper edge of panel; attached at cover slide-screen interface
7	Upper edge of panel; attached at cover slide-screen interface

were obtained at other locations on the specimen surface. It was determined that temperature gradients of 200^{O}F were occurring on the blackened stainless steel radiator plate itself. This was due to heat losses through the cooling coils located on the underside of the radiator plate.

The cooling coils were cut away from the radiator plate and the entire specimen re-exposed to 650-700^{O}F in the altitude chamber for 6 hours. Temperature readings obtained during the third run (Table 7-3) were in close agreement (within 20-25^{O}F). These temperature variations across the surface are probably due to irregularities in the flatness of the test specimen surface resulting from thermocouple positioning. Additionally, some sag occurs at the unsupported center of the test specimen.

Examination of the composite and its attachments, after the cycling tests, revealed no damage had occurred to any of the materials. No evidence of change to bond line integrity or elasticity was apparent. A brown discoloration of the gray silicone adhesive was detected. The discoloration was attributed to vacuum-induced release of binders and coloring agents comprising the insulation and jacketing which surrounded the thermocouple leads. No such discoloration had occurred during previous testing of the adhesive system at high temperature (800^{O}F) in vacuum.

7.3 ACCELERATION

Rotary-motion tests on specimens 4 and 5 were conducted on a centrifuge (Fig. 7-4) which provided g levels anticipated for the composite system attached at a radius to simulate a 3 ft. diameter spacecraft rotating at 60 revolutions per minute. The test was performed for 2 hours to demonstrate the ability of the composite to withstand spin modes anticipated during spacecraft operation. Orientation of specimens was changed 90^{O} to simulate longitudinal loading experienced during an Atlas-Agena boost phase. Rotation of the centrifuge and positioning of the specimens was accomplished to provide a 13.7 g force along the x-axis of the specimens. Test duration was 4 minutes. No visible signs of damage to the mirror surfaces or attachment points were evident at the conclusion of the test.

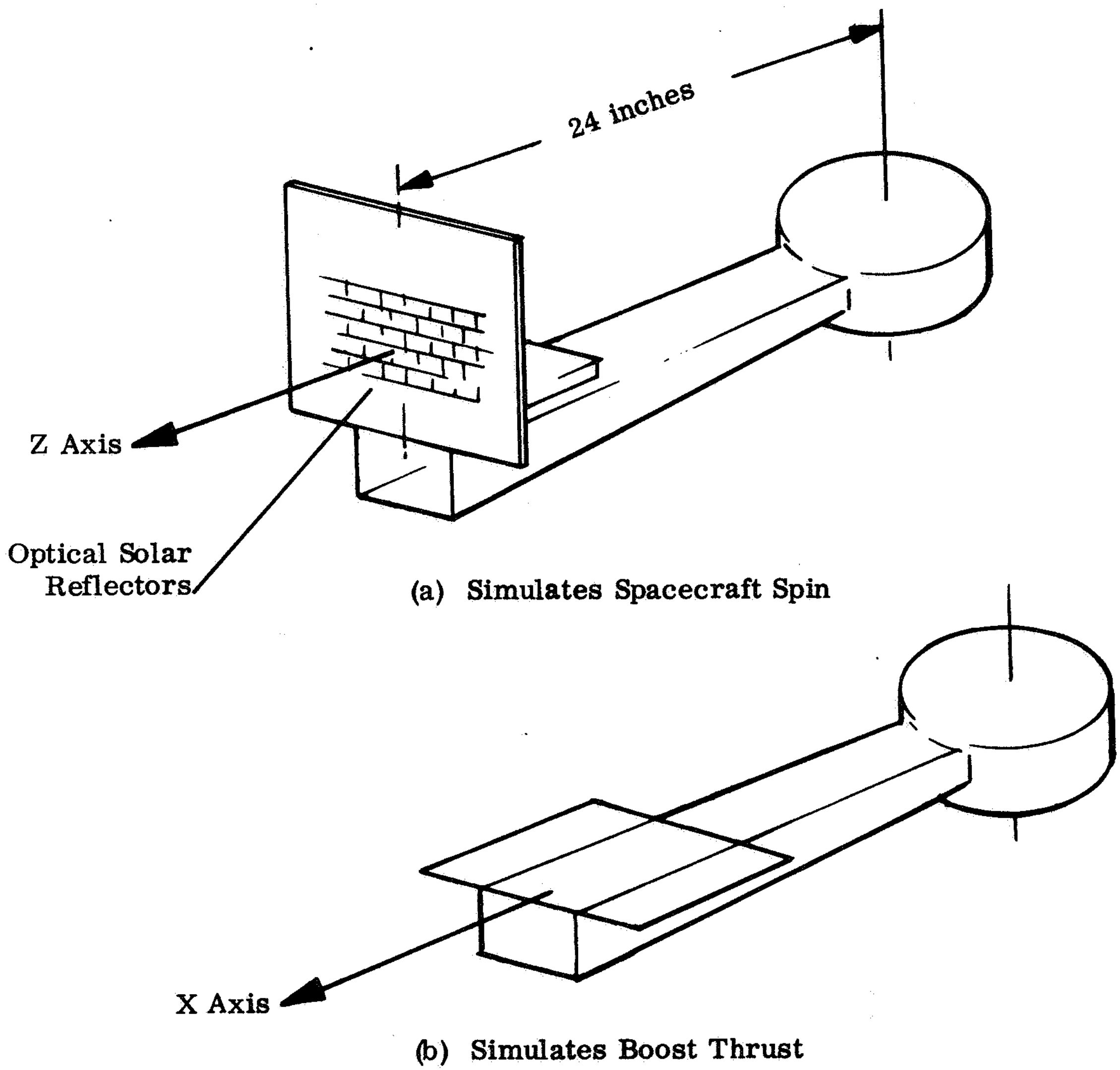


Fig. 7-4 Acceleration-Test Configuration

7.4 VIBRATION

Composite specimens were subjected to both sinusoidal and random vibration forces along the x-axis only. Vibration parameters were qualification levels used for components located within the payload enclosure during an Atlas-Agena mission. Testing levels are given below.

Sinusoidal (boost):

Frequency Range (Hz)	g Level
5-15	0.17 inches peak-to-peak
15-400	2.0 inches peak-to-peak
400-2000	7.5 inches peak-to-peak

Sinusoidal (flight):

Frequency Range (Hz)	g Level
5-17	0.50 inches peak-to-peak
17-22	7.0 inches peak-to-peak
22-2000	5.0 inches peak-to-peak

(Sweep rate for each test was from 5 to 2,000 cps in 25 minutes.)

Random (boost):

Frequency Range (Hz)	Spectral Density (g^2/Hz)
20-400	.05
400-2000	.12

Random (flight):

Frequency Range (Hz)	Spectral Density (g^2/Hz)
20-400	.003
400-4000	.010

(Duration for each test was from 20 to 4000 cps in 5 minutes.)

Specimen 1, 2 and 3 were subjected to boost phase random vibration levels. Specimens 5, 6, 13 and 14 were subjected to both boost and flight-phase excitation.

Figure 7-5 shows a composite specimen mounted on top of the shaker table for vibration testing. Holes were drilled in the specimen's aluminum base plate and attachment to the shaker was effected by screwing bolts through the base plate into holes pre-drilled in the shaker mounting table. No effect to mirrors or attachments was noted after completion of random-vibration tests.

Considerable difficulty was encountered during sinusoidal-vibration tests. Failures occurred to the attachment techniques used for specimens 4, 5, 6, 7, 8 and 9 during flight-phase sinusoidal excitation. Specimens 5 and 6 had passed random (boost and flight) and boost-phase sinusoidal vibration tests prior to flight-phase exposures. Failure for both systems occurred during the sine flight phase between 14-17 cps at 0.5-1 inch displacement. It was determined that at these parameters, the specimens were exposed to a 7.0 g level, at a displacement of 0.5 inch. Thus, the specimens were being subjected to both flexure and g-loading at a relatively long period of time per cycle. At higher frequencies, the specimens were exposed to g-loading for a shorter period of time per cycle, and the tendency to flex was precluded due to the shorter displacement.

Figure 7-6 shows the failure that occurred to specimen 4. Tabs which held the expanded metal-mirror substrate to the pyrex standoffs were pulled loose from the screen. Additionally, the heads of the pyrex standoff had ruptured the expanded metal at locations where the expanded metal contacted the heads of the standoffs. Specimen 6 failed in a similar manner.

Figure 7-7 shows the result of exposing specimen 5 to flight sinusoidal vibration amplitudes. Quartz fiber thread was sheared at all button-attach points. Displacement of the panel at 14-17 cps was 0.5 inch. This displacement permitted the blanket top-layer (with mirrors attached) to move relative to the stationary Velcro pads. Repeated movement caused the single-strand quartz thread to break at every attachment point.

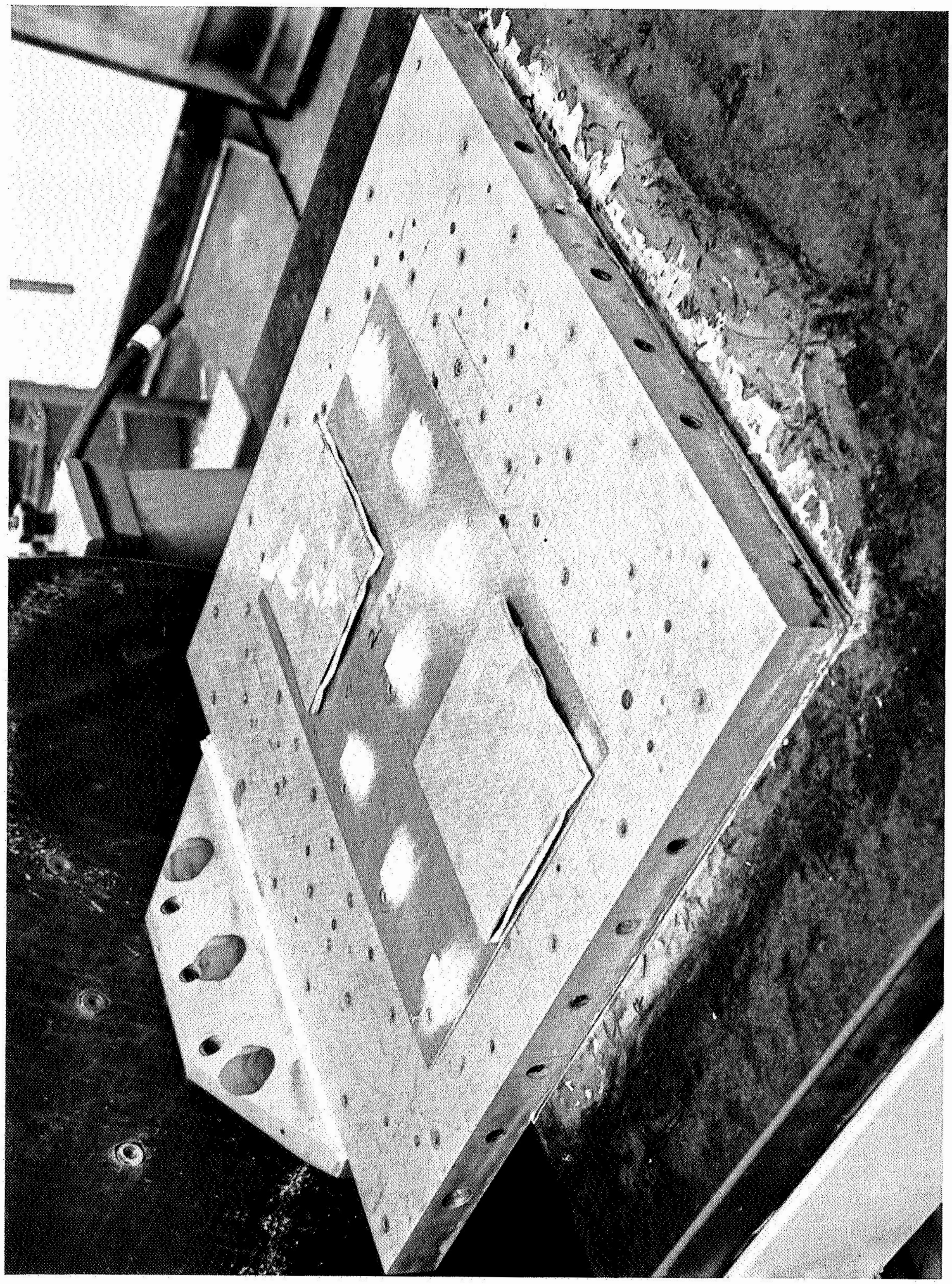


Figure 7-5. OSR-multilayer composite mounted on shaker table

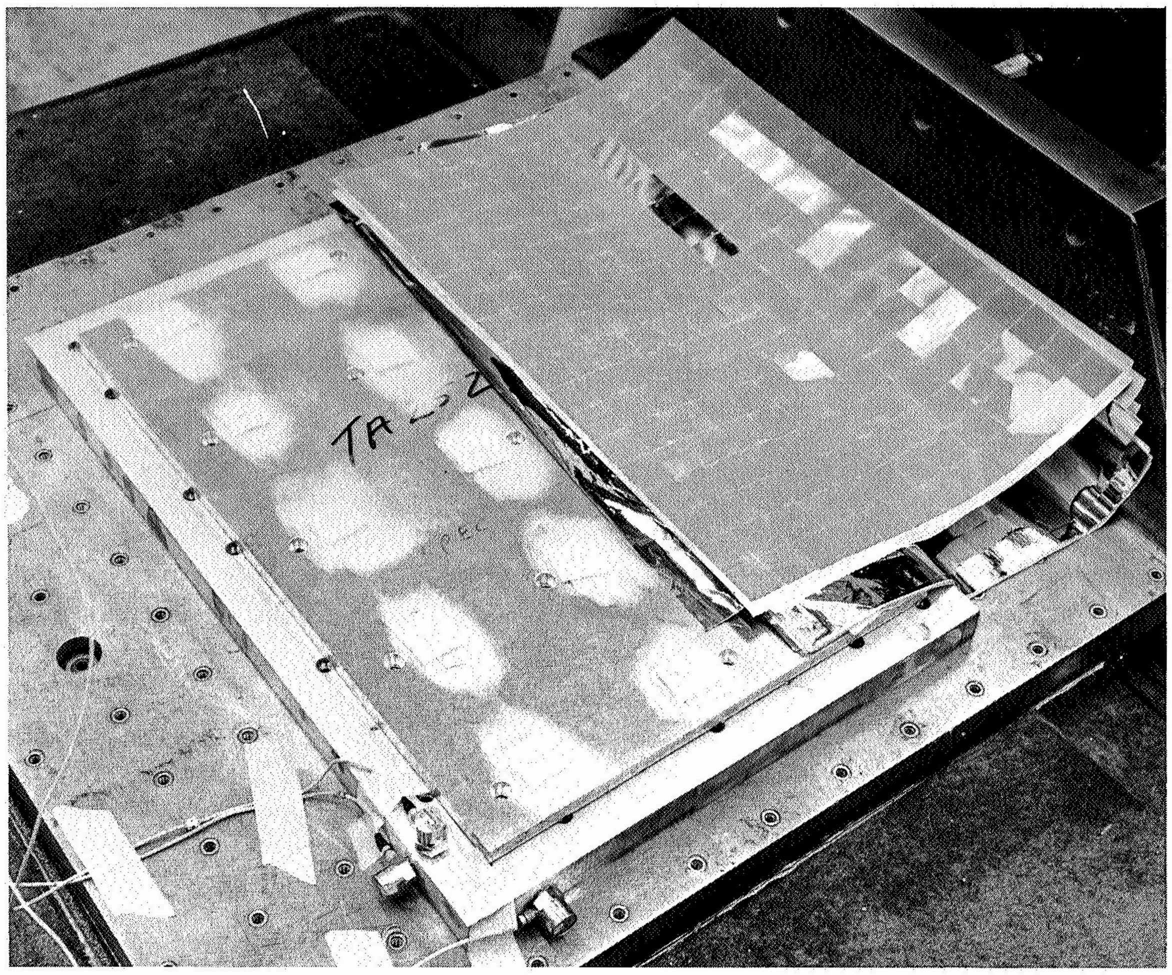


Figure 7-6. OSR-multilayer composite failure. Single-strand, quartz-fiber thread sheared during vibration testing

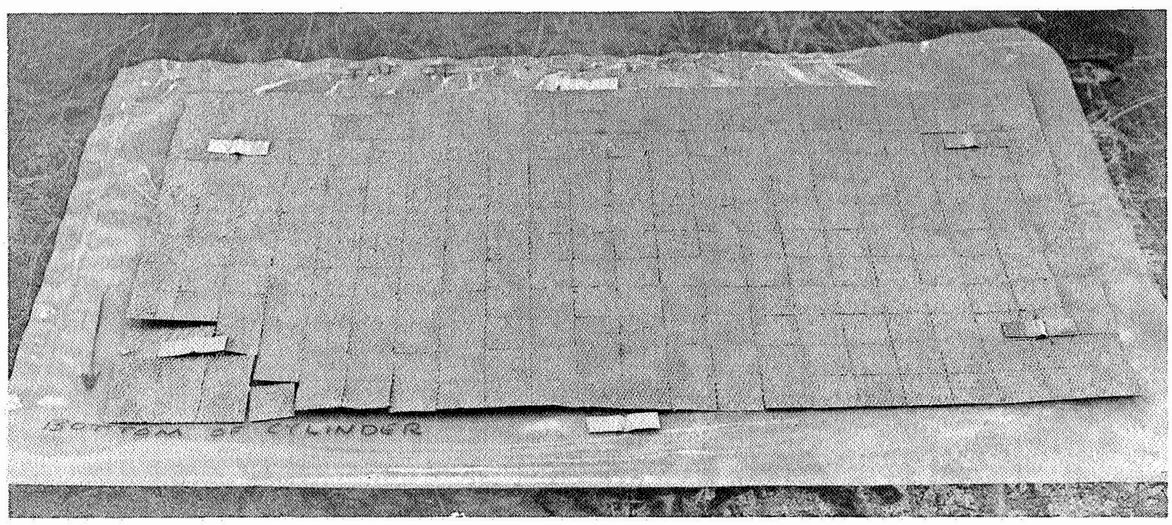


Figure 7-7. Expanded metal-OSR composite failure. Retaining tabs pulled loose from expanded metal during vibration testing

A program to correct attachment deficiencies was undertaken by LMSC. Specimens 7, 8, 9, 10, 11, and 12 were prepared, utilizing various materials (copper wire, titanium wire, and silicone-reinforced glass fiber) as thread. Specimens were subjected to flight-phase sinusoidal vibration amplitudes. Specimens 7, 8, and 9 failed at 14-17 cps and 0.5-inch displacement; all other specimens survived. Specimens 10, 11 and 12 were then carried to destruction by increasing the displacement and g level. Specimen 10 failed at a displacement of 0.5 inch and 15 g's. Specimens 11 and 12 failed at a displacement of 0.7 inch and a loading of 25 g's.

Aluminum expanded metal, 0.013 inch-which, was obtained for use as the mirror substrate for specimen 15. Four pyrex standoffs were bonded to the base plate, and the composite attached with wire. The specimen was subjected to flight sinusoidal vibration. At approximately 15 cps and a load of 5 g's two pyrex attachment posts sheared. The posts cracked at the points where the tee met. Aluminum rivets, of the same dimension as pyrex posts, were substituted for the pyrex posts. The specimen and attachments were re-exposed to the flight sinusoidal vibration environment. No damage to the composite occurred. The specimen was then subjected to boost phase sinusoidal and random (boost and flight) vibration excitation. No cover slides or attachments were damaged. Figures 7-8, 7-9, 7-10, 7-11 depict the vibration environment encountered by specimen 15.

LMSC is confident that ceramic standoffs, with properly designed stress-relief at the tee where the post and head meet, would withstand the vibration environment. The pyrex standoff was machined from raw stock, and no adequate provision was made for filleting at point where the post meets the head of the standoff. Aluminum standoffs are not recommended for spacecraft applications because they permit excessive heat transfer from the external composite surface.

Specimens 13 and 14 were prepared by using silicone-reinforced glass thread and a laminated top-layer (paragraph 6.1.2) as part of the attachment system. Both specimens survived the boost and flight, sine and random, vibration test levels shown in Figures 7-12, 7-13, 7-14 and 7-15. No damage to mirrors or attachments was detected after conclusion of the tests.

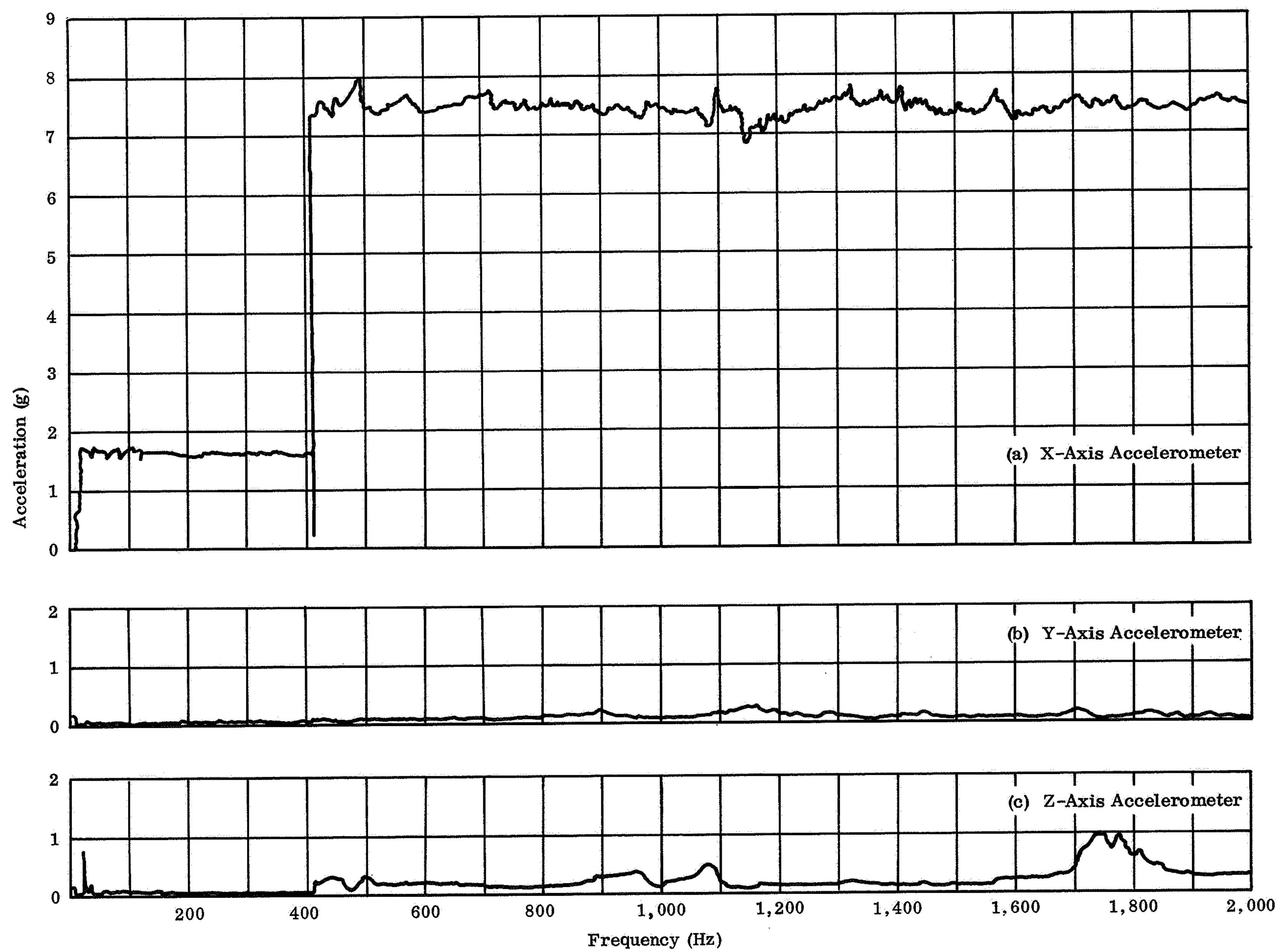


Figure 7-8. Boost-Phase sinusoidal-vibration levels on expanded-metal and multilayer composite

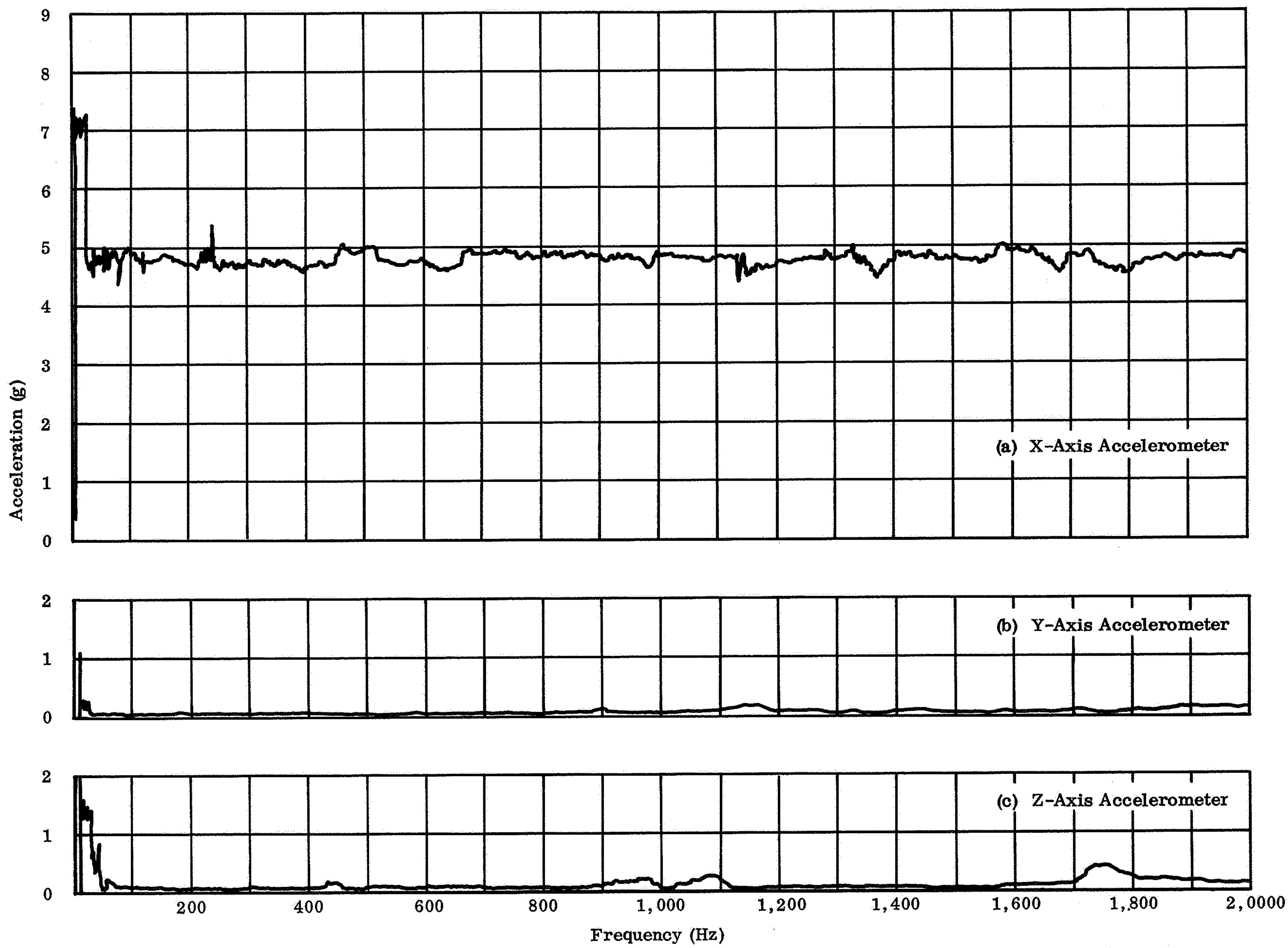


Figure 7-9. Flight-phase sinusoidal-vibration levels on expanded-metal and multilayer composite

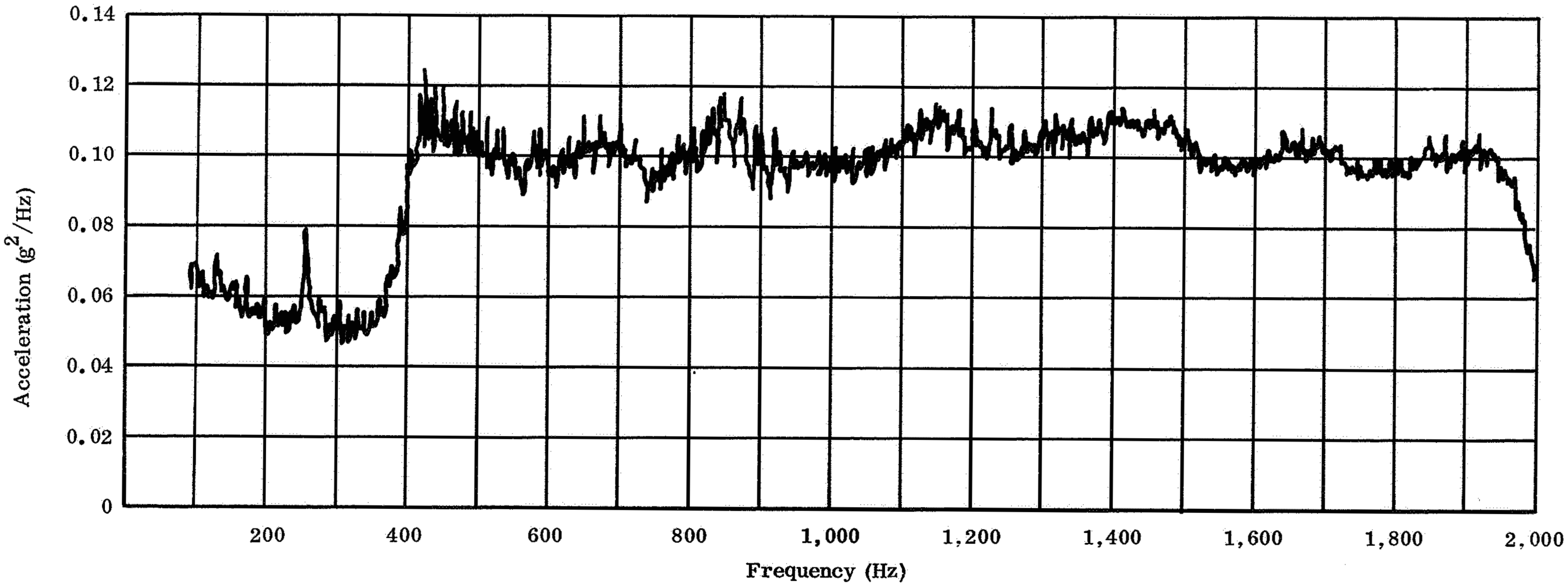


Figure 7-10. Boost-phase random-vibration levels on expanded-metal and multilayer composite per X-axis accelerometer

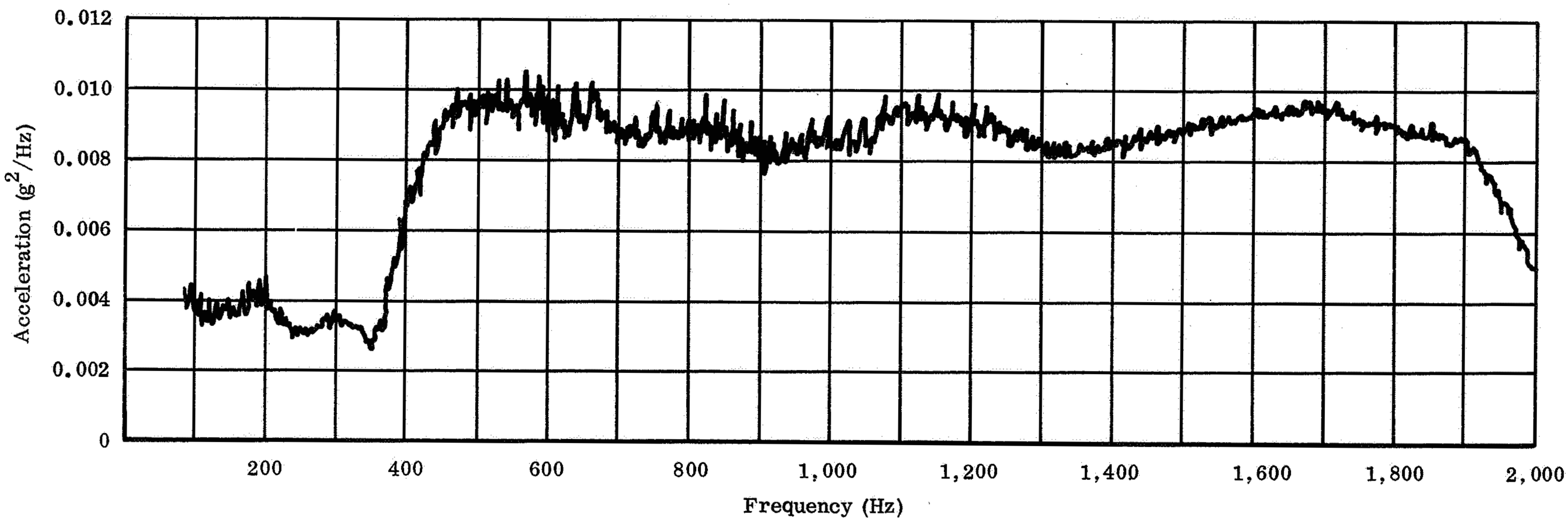


Figure 7-11. Flight-phase random-vibration levels on expanded-metal and multilayer composite per X-axis accelerometer

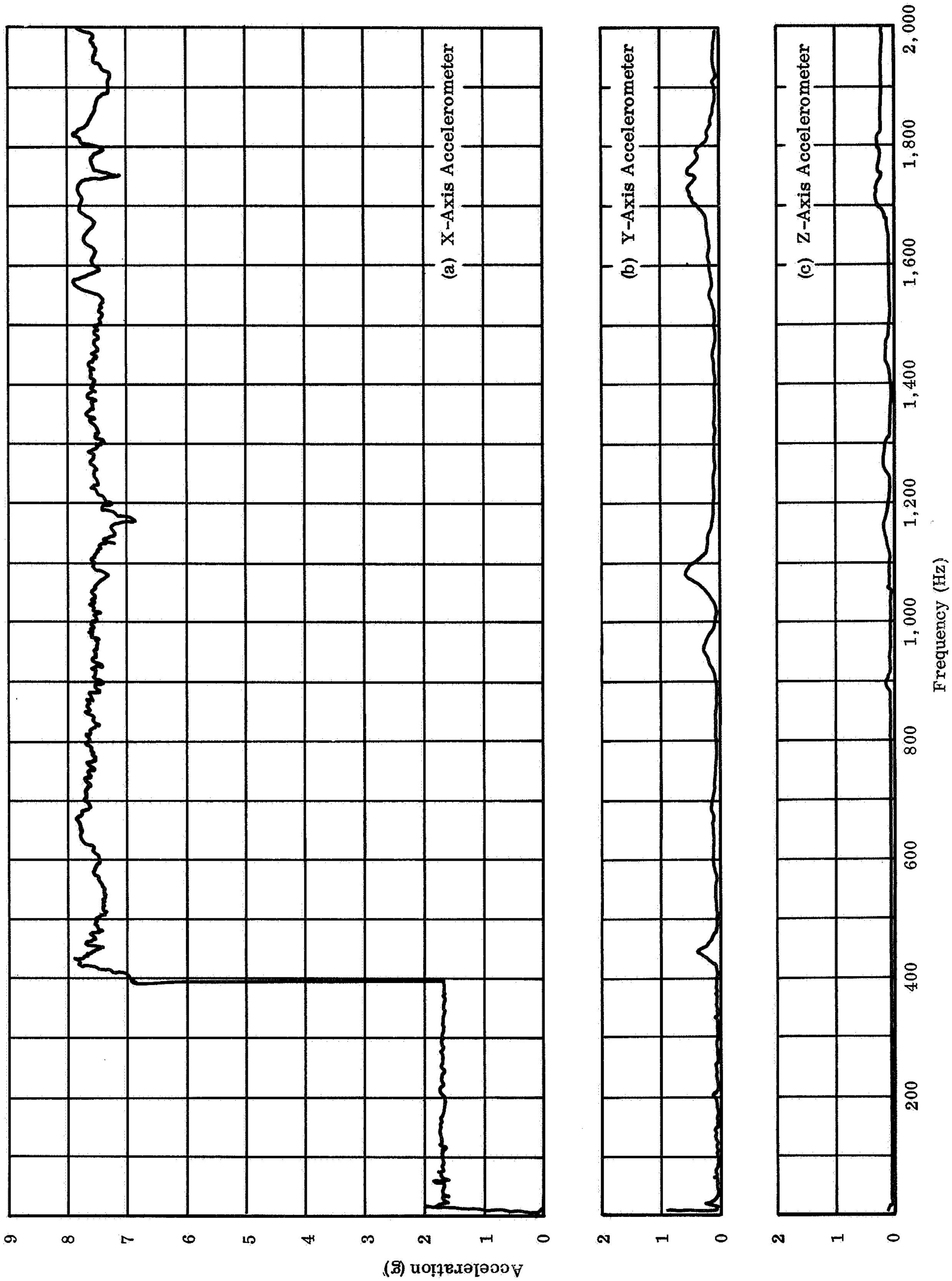


Figure 7-12. Boost-phase sinusoidal-vibration levels on OSR-multilayer composite

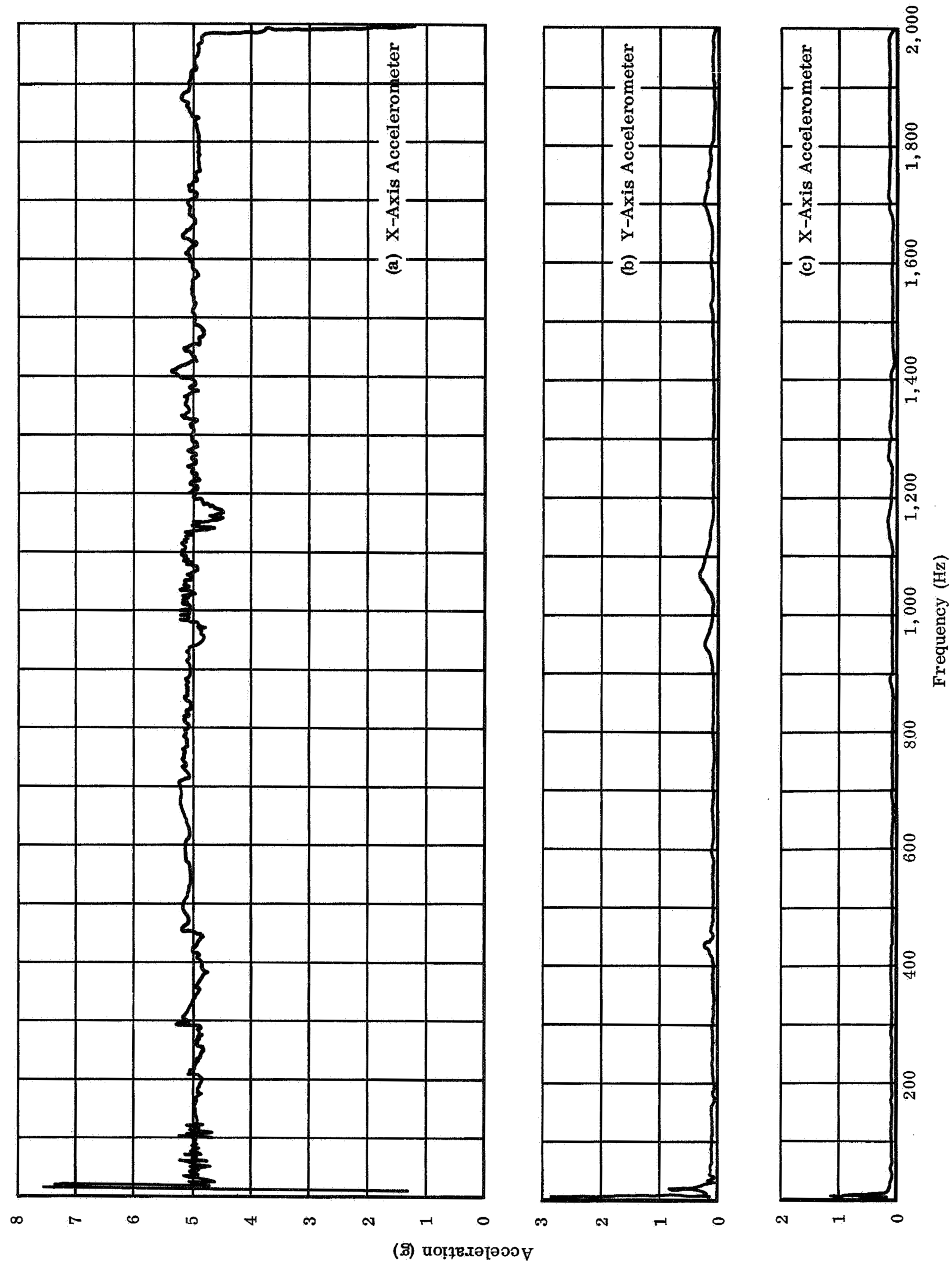


Figure 7-13. Flight-phase sinusoidal-vibration levels on OSR-multilayer composite

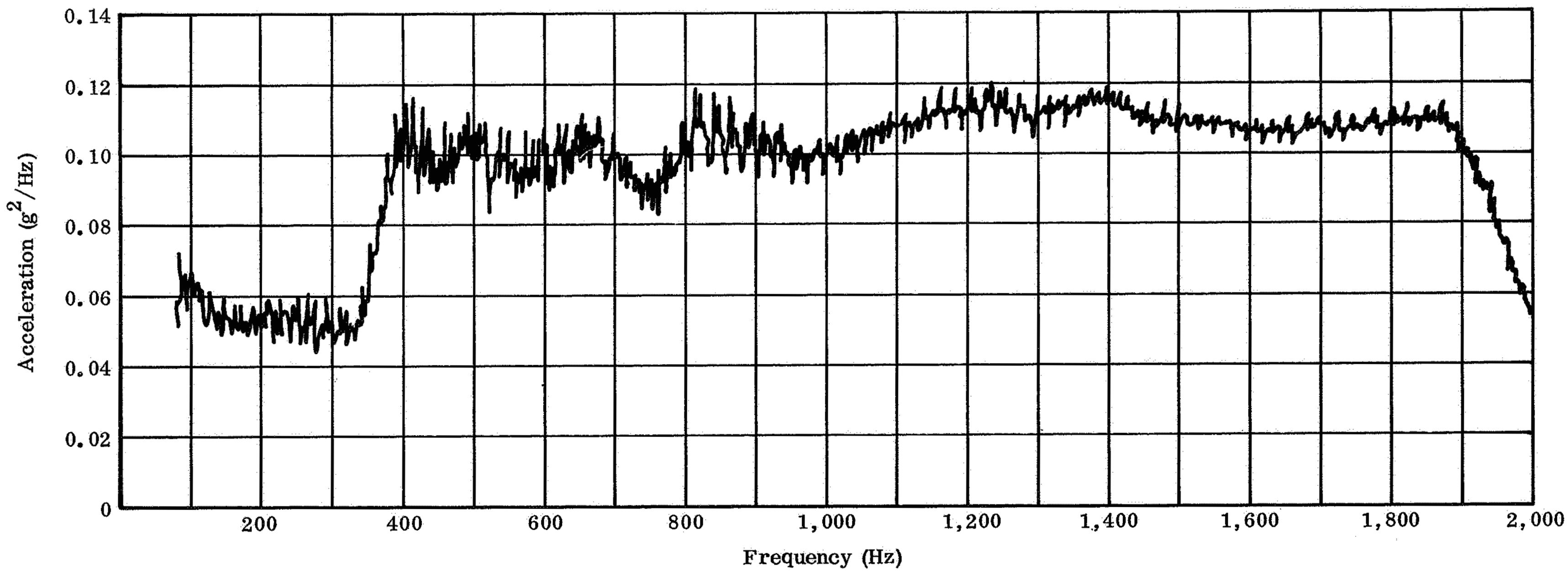


Figure 7-14. Boost-phase random-vibration levels on OSR-multilayer per X-axis accelerometer

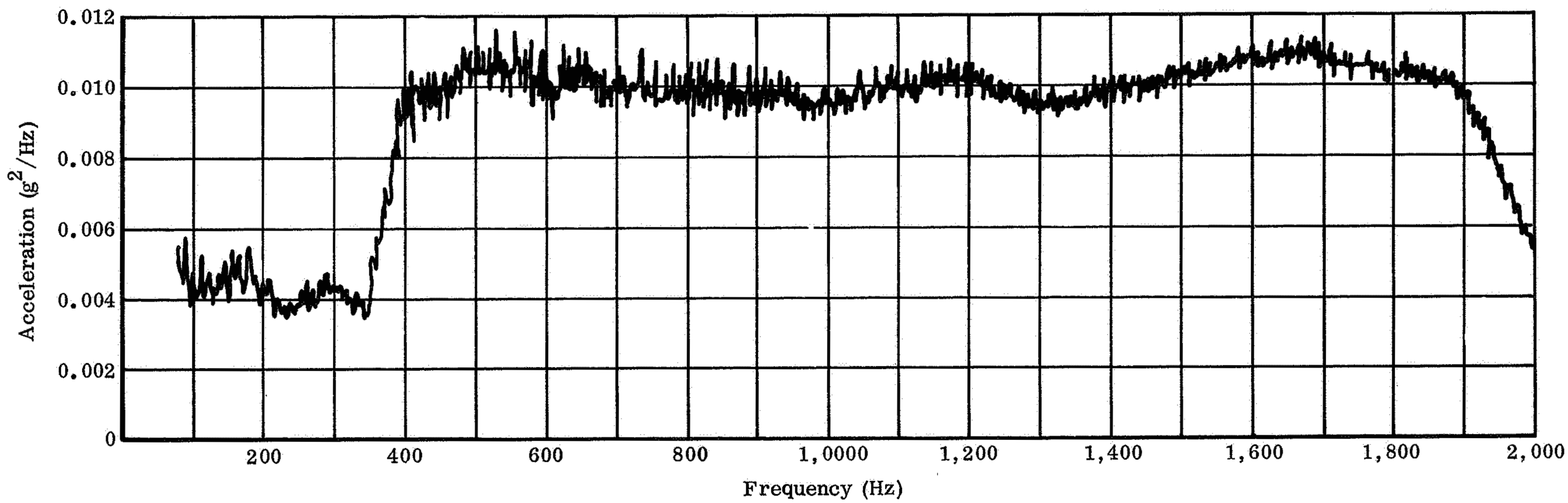


Figure 7-15. Flight-phase random-vibration levels on OSR-multilayer per X-axis accelerometer

7.5 ACOUSTICAL NOISE

Specimens 4, 13 and 14 successfully survived the random, acoustic-excitation levels shown in Figure 7-16 for a period of 5 minutes each. No damage to mirrors or attachments was detected by visual inspection after test.

7.6 SHOCK

Specimens 4, 13 and 14 were mounted to a pendulum-shock apparatus (Figure 7-17) by inserting bolts through holes in the specimen base plate, and screwing the bolts into threaded receptacles located on the mounting fixture. Each specimen was subjected to two 30-g shock runs for 8 milliseconds by releasing the pendulum arm from a predetermined height. Shock produced by the pendulum arm striking the table was verified through the use of accelerometers and an oscilloscope. Figure 7-18 is typical of traces obtained during testing. The 30-g shock loading was representative of shocks to be experienced during Atlas-Agena launch and the Agena ignition/burn phases.

No cover slides or mirrors were cracked during the test, and there was no evidence of damage to the multilayer or attachments. It had been postulated that the pyrex standoffs on specimen 4 might be sheared during shock-testing, but neither the adhesive bond line nor the standoffs were detrimentally affected.

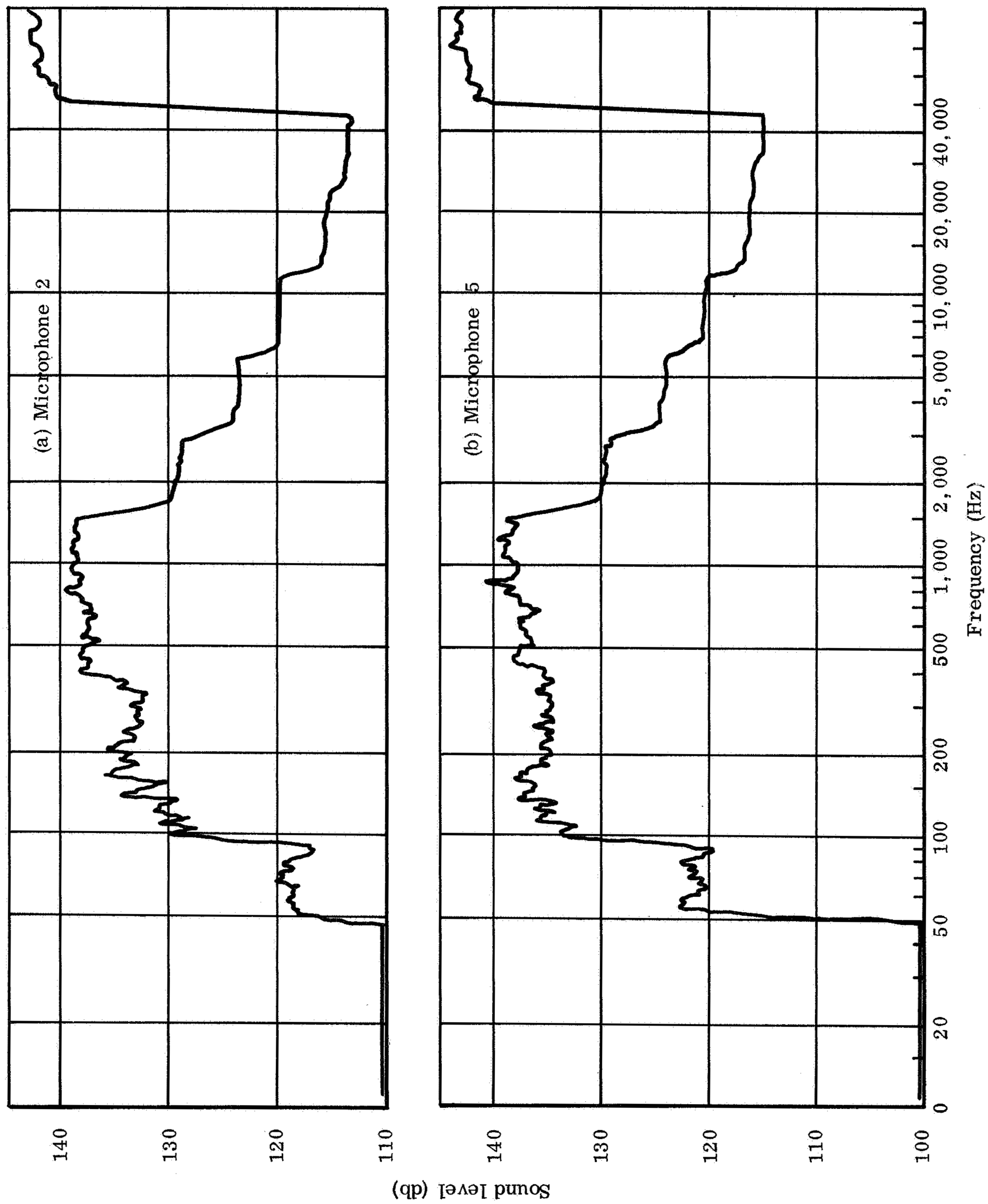


Figure 7-16. Acoustic noise level

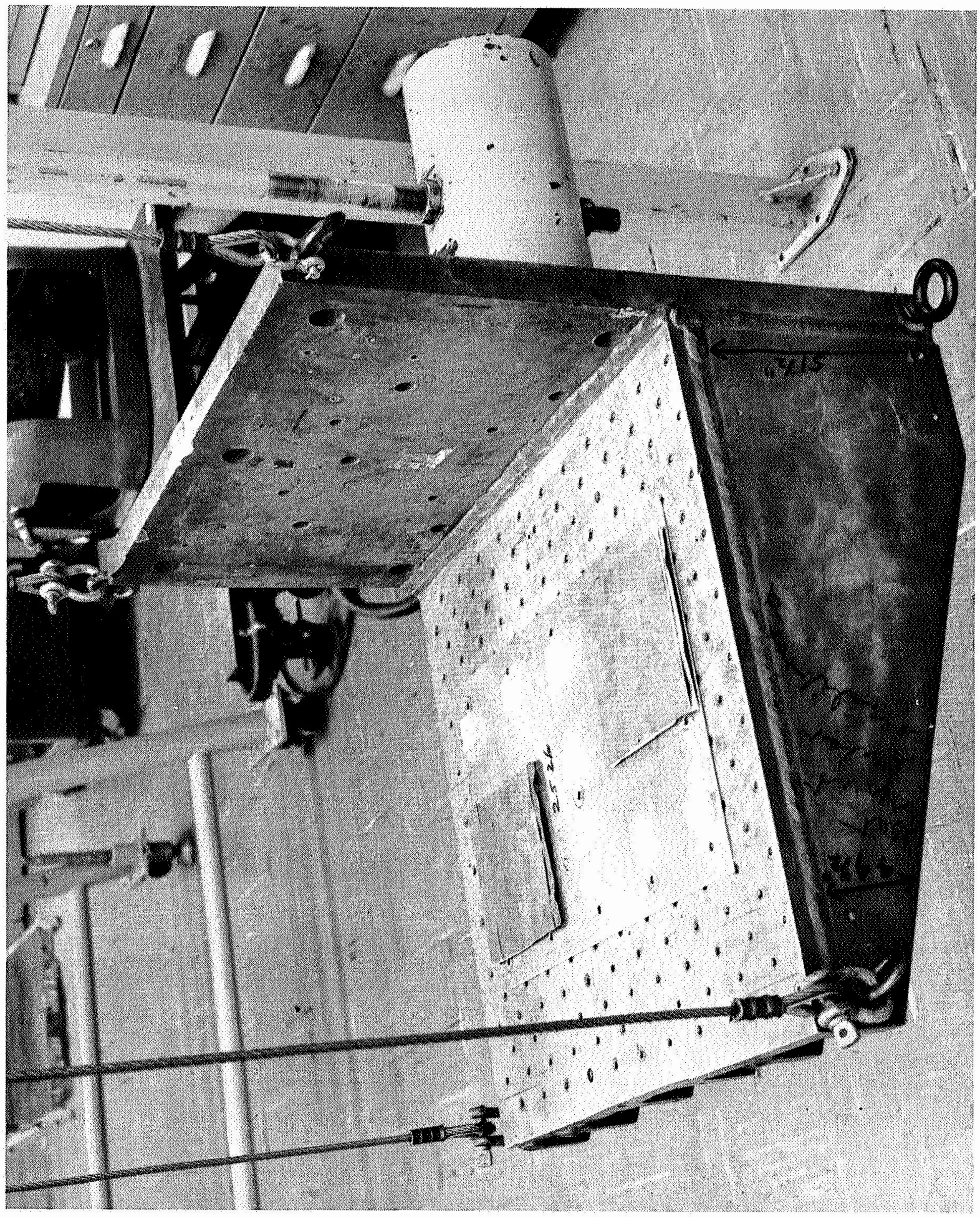


Figure 7-17. OSR-multilayer composite mounted on pendulum-shock apparatus

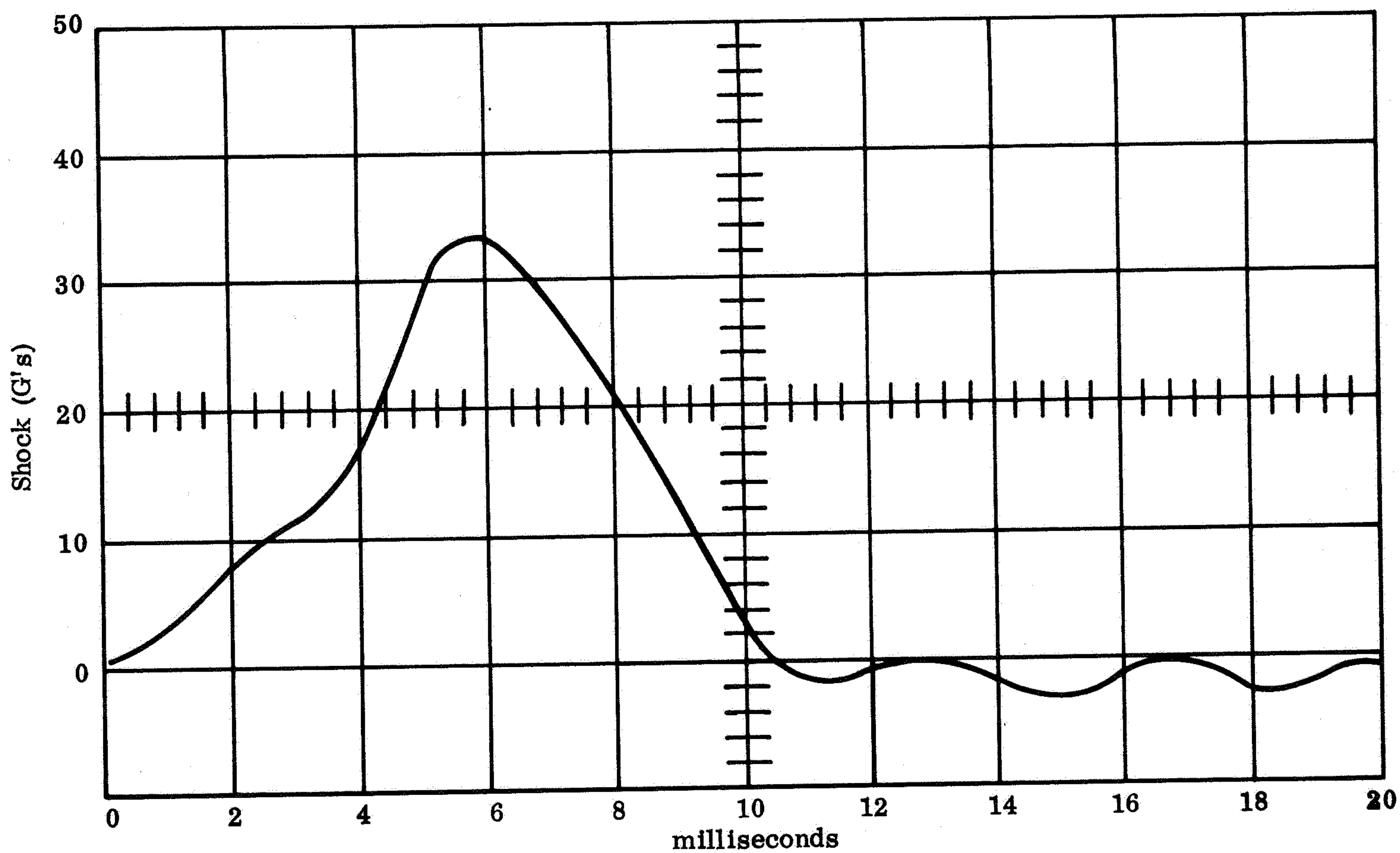


Figure 7-18 Oscilloscope Trace of Shock Applied Along X-Axis of Test Specimen

Section 8
CONCLUSIONS AND RECOMMENDATIONS

Composite systems developed during this program will successfully withstand environmental conditions anticipated during launch and orbit conditions of a near-solar spacecraft mission, and offer potential for use as thermal protection of storage tanks for cryogenic propellants or areas adjacent to stabilization or propulsion rockets. The thermal-control materials (second-surface mirrors and multilayer insulation) and attachment techniques will withstand forces imposed by an Atlas-Agena launch and orbit sequence, and can operate successfully in the temperature range of -100 to 700°F.

This study disclosed that each potential application for the composite thermal-control system will dictate the particular attachments required No single attachment technique is universally acceptable, as the geometry of the underlying substrate, the permissible heat leak, and the allowable weight penalty associated with the composite system dictate which attachments may be utilized Two thermal-control composite systems, each with different attachment techniques, were developed In one system, second-surface mirrors are adhesively bonded to the reinforced top-layer of a multilayer-blanket assembly The second system requires that the mirrors be adhesively bonded to an expanded metal material which is subsequently attached to standoffs connected to the vehicle substrate In the latter system, the multilayer-blanket assembly is positioned over the standoffs before attachment of the expanded-metal substrate. Choice between the two systems is dependent upon the intended application. As an example, if edges of the multilayer blanket would be directly exposed to solar radiation in a particular application, the resultant increase in parallel conductivity through the multilayer might dictate that an overhang of mirrors to shield the blanket edges be employed. In this case, a modification to the expanded-metal attachment concept could be effected. No such modification to the multilayer-mirror concept is immediately feasible.

Escape of entrapped air within multilayer blanket assemblies during vehicle ascent operations has no detrimental effect on either the second-surface mirrors or the blanket attachments. Experimental results obtained during rapid pumpdown tests conducted during this study indicate adequate vent paths exist along the circumferential edges of systems attached to cylindrical substrates to prevent excessive ballooning of the multilayer. The problem is minimized further for flat-plate applications, as four edges are available for venting.

Optimization of attachment techniques for both thermal-control composites should be accomplished with respect to weight reduction and ease of installation. For composites which utilize the mirror-to-multilayer concept, it may be possible to remove the glass-cloth reinforcement on the blanket top-layer. This could be verified by sample preparation and environmental testing. The objective in using the glass cloth was to prevent attachment thread from tearing through the polyimide top-layer at the attach points. However, observation of the specimen during environmental testing indicates that the silicone adhesive, placed inside the top-layer laminate, may provide sufficient reinforcement to prevent threads from tearing through at the attach points. Installation procedure for composites utilizing the expanded metal-mirror concept is difficult because of lack of clearance between the bottom of the metal and the top of the multilayer. If thermal analyses for a particular application indicate that metallic standoffs could be tolerated, a press-fit type of attachment could be readily designed. Such a system would employ metallic standoffs, bonded or welded to the vehicle skin, and metallic snaps welded to the underside of the mirror substrate. Snaps and standoffs would be fabricated from the same metal to prevent incompatible thermal-expansion rates.

It is recommended that anticipated thermal performance of both composite systems be verified by conducting a high-intensity, solar-irradiation test. This test would result in thermophysical property data which could be used by the thermal designer. The additional effort would verify the acceptability of the composite systems for use on specific spacecraft applications. The recommended test program was beyond the scope and level of effort provided for this study.

Section 9

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9. Final Report, Thermal Protection System for a Cryogenic Spacecraft Propulsion Module, Report No. CR-54789, Contract No. NAS 3-4199, Nov. 1966.

Appendix A

ADHESIVE CANDIDATE EVALUATIONS

Material and Manufacturer	Test and Evaluation
1. Sauereisen 6 Sauereisen Cement Co. Pittsburgh, Pa. 2. Sauereisen 7 3. Sauereisen 8 4. Sauereisen 31 5. Sauereisen 66 6. Sauereisen 70 7. Sauereisen 78	1. Applied 1-mil coat to aluminum substrate. 2. Attached mirror to substrate. 3. Dried at 150^{o}F. for 1 hr. 4. Slowly heated to 800^{o}F. in air. Adhesion was good for all except No. 66. 5. Cooled slowly to room temperature. 6. Mirror surface attacked and separated from aluminum panel.
8. MR-1 Lithafrax Carborundum Co. Latrobe, Pa. Potassium silicate Kasil 88 Philadelphia Quartz Co. Chicago, Ill.	192 grams lithafrax 114 grams Kasil 88 250 cc water 1. Applied 1-mil coat to aluminum substrate. 2. Attached mirror to substrate. 3. Dried at 150^{o}F. for 1 hour. 4. Heated slowly to 800^{o}F. 5. Cooled slowly to room temperature. 6. Adhesion good at 800^{o}F.; separated during cooling to room temperature.
9. MR-2 Same ingredients as MR-1	192 grams Lithafrax 192 grams Kasil 88 1. Same procedure and observations as MR-1.
10. Alumina 33 I Norton Co. Santa Clara, Calif. Kasil 88 Philadelphia Quartz Co. Chicago, Ill.	10 g Kasil 88 10 g Alumina 33 I 1. Applied 1-mil coat to aluminum substrate with spatula. 2. Attached mirror to substrate. 3. Heated 1 hr. in air at 150^{o}F. 4. Heated slowly to 800^{o}F. in air; adhesion good. 5. Adhesive attacked mirror surface.

Appendix A (Continued)

Material and Manufacturer	Test and Evaluation
11. Potassium silicate Philadelphia Quartz Co. Chicago, Ill.	1. Applied 1-mil coat to aluminum substrate. 2. Attached mirror to substrate. 3. Heated 1 hr. in air at 150°F. 4. Heated slowly to 800°F.; adhesion fair. 5. Mirror separated from substrate when cooled to room temperature.
12. Potassium silicate Kasil 88 Philadelphia Quartz Co. Chicago, Ill. Silica	10 g Kasil 88 10 g Silica 1. Mixed above ingredients and applied 1-mil coat to aluminum panel and attached mirror. 2. Heated 1 hr. in air at 150°F. 3. Heated slowly to 800°F.; adhesion good. 4. Cooled slowly to room temperature; mirror separated from panel.
13. Potassium silicate Kasil 88 Philadelphia Quartz Co. Chicago, Ill. Alumina Kastite refractory Pyro Engineering Co. Alhambra, Calif.	10 g Kasil 88 10 g Kastite refractory 1. Mixed above ingredients and applied 1-mil coat to aluminum panel and attached mirror. 2. Heated 1 hr. in air at 150°F. 3. Heated slowly to 800°F.; adhesion good. 4. Cooled slowly to room temperature in air; mirror separated from panel.
14. Potassium silicate Kasil 88 Philadelphia Quartz Co. Chicago, Ill. Alumina 1139 Norton Co. Santa Clara, Calif.	10 g Kasil 88 10 g Alumina 1139 1. Mixed above ingredients and applied 1-mil coat to aluminum screen. 2. Heated 1 hr. in air at 150°F. 3. Heated slowly to 800°F. in air; adhesion good. 4. Cooled slowly in air to room temperature. 5. Adhesive attacked mirror surface; removed silver from glass.

Appendix A (Continued)

Material and Manufacturer	Test and Evaluation
15. Potassium silicate Kasil 88 Norton Co. Santa Clara, Calif. Zirconia Yttrium oxide	10 g Kasil 88 5 g Zirconia 1 g Yttrium oxide 1. Mixed above ingredients and applied 1-mil coat to aluminum panel. 2. Heated 1 hr. in air at 150°F. 3. Heated slowly in air to 800°F.; adhesion good. 4. Cooled slowly to room temperature; mirror separated from panel.
16. Kellundite 371W Electo Refractories and Abrasives Buffalo, N. Y.	1. Applied thin coat of adhesive to aluminum panel. 2. Air dried 1 hr. at 150°F. 3. Heated slowly to 800°F. in air; adhesion good. 4. Cooled slowly in air to room temperature; adhesive attacked mirror surface.
17. Potassium silicate Kasil 88 Philadelphia Quartz Co. Chicago, Ill. Stainless-steel pigment Williams Co. Emeryville, Calif. Triton X-100 Rohm & Haas Philadelphia, Pa.	5 g Stainless-steel pigment 5 g Kasil 88 1 Drop Triton X-100 1. Mixed above ingredients and applied thin coat to mirror and aluminum screen. 2. Air dried 1 hr. at 150°F. 3. Heated in air to 700°F.; adhesion good, mirror cracked.
18. Potassium silicate Kasil 88 Philadelphia Quartz Co. Chicago, Ill, Stainless-steel pigment Williams Co. Emeryville, Calif. Triton X-100 Rohm & Haas Philadelphia, Pa.	10 g Stainless-steel pigment 10 g Alumina 1139 20 g Kasil 88 1 Drop Triton X-100 1. Mixed above ingredients and applied thin coat to mirror and aluminum screen. 2. Air dried 1 hr. at 150°F. 3. Heated slowly to 800°F.; adhesion good.

Material and Manufacturer	Test and Evaluation
18. (Continued) Alumina 1139 Norton Co. Santa Clara, Calif.	4. Cooled slowly in air to room temperature; adhesive attacked mirror surface.
19. Silicone 92-024 Dow Corning Co. Midland, Mich.	1. Applied Dow 1200 primer to mirror and screen. 2. Air dried at room temperature for 1 hr. 3. Applied thin coat of silicone to mirror. 4. Air dried 1 hr. at room temperature. 5. Heated to 700°F. in air; adhesion good although bondline showed signs of embrittlement and crazing. 6. Repeated procedures 1 through 4. 7. Heated to 800°F. in vacuum; adhesion good but heavy outgassing at approx. 275°F. 8. Repeated procedures 1 through 3. 9. Air dried 1 hr. at room temperature. 10. Air-oven dried 1 hr. at 300°F. 11. Subjected to 800°F. in vacuum; adhesion good. Outgassing considerably diminished. 12. Attached 20 gram weight to mirror, allowed to stand 72 hr. in vacuum at 800°F. 13. Good adhesion; no sign of bondline degradation. 14. Repeated processes 1 through 4 except attach to flat aluminum substrate. 15. Attached 17 gram weight to mirror, allowed to stand for 30 days in vacuum at 710°F. 16. Good adhesion; no sign of bondline failure.

Material and Manufacturer	Test and Evaluation
19. (Continued)	17. Applied Dow-A4094 primer (interchangeable with No. 1200) to aluminum substrate and 4 cover slides, air dried for 1 hr. at room temperature. 18. Applied thin coat of adhesive to cover slides and cured for 4 hours at 300°F. 19. For thermal decomposition-volatilization test at 350°F. and noted slight outgassing occurred. 20. Subjected specimen described in 17 and 18 to 700°F. and vacuum. Noted some outgassing occurred at approximately 500°F. 21. No evidence of bondline degradation. 22. Subjected aluminum expanded metal-mirror combination to cycling between -100°F. and 700°F. in vacuum chamber. Mirrors attached with DC 1200 primer and DC92-024 adhesive. Held at -100°F. for 2 hours and held at 700°F. for 4 hours. Cycle repeated twice. 23. No evidence of bondline degradation.
20. Silicone 93-067 Dow Corning Co. Midland, Mich.	1. Applied Dow 1200 primer to mirror and screen; air dried 1 hr. at room temperature. 2. Mixed 93-067 with catalyst on a 10:1 weight ratio. 3. Air dried 1 hr. at 150°F. 4. Heated in air to 800°F. 5. Adhesion good to 600°F.; separated at 800°F. 6. Heated in vacuum to 700°F. 7. Removed from vacuum and cooled slowly to room temperature. 8. Adhesive bondline embrittled.
21. Epoxy 1206-2 Adhesive Eng. Co. San Carlos, Calif.	1. Mixed Epoxy 1206-2 with catalyst on a 1:1 weight ratio. 2. Adhesive set up too rapidly; could not spread it evenly on substrate.

Material and Manufacturer	Test and Evaluation
22. Silicone EP 5909 EP 5910 Imperial Chemical Industries Ltd. Stevenston, Eng.	1. Mixed EP 5909 and EP 5910 on a 1:1 weight basis. 2. Applied to mirror and screen. 3. Silicone very fluid and difficult to control. 4. Air dried at 270°F. for 1 hr. 5. Adhesion was fair at 700°F. in air.
23. Epoxy BR-600 William Bean Co. Detroit, Mich.	1. Mixed components A, B, and C and placed mix under refrigeration. 2. Applied mix to screen and mirror. 3. Epoxy too fluid and difficult to control. 4. Heated 2 hr. in air at 270°F. 5. Adhesion was good to 600°F. 6. Mirror shattered at 625°F. 7. Mirror surface attacked by adhesive.
24. Lead oxide Mallinckrodt Chem. Co. St. Louis, Mo. Glycerol J. T. Baker Co. Phillipsburg, N. J.	1. Mixed lead oxide and glycerol on a 3:1 weight basis. 2. Applied thin film of above ingredients to screen and glass slide. 3. Heated at 250°F. for 1 hr. in air. 4. Glass slide separated from screen at 250°F.
25. Epoxy BR-600 William Bean Co. Detroit, Mich. Nickel-powder General Chem. Co. New York, N. Y.	1. Mixed Epoxy and nickel on a 1:1 weight ratio. 2. Applied thin film to glass slide and screen. 3. Heated in air at 250°F. for 2 hr. 4. Heated in air at 800°F. 5. Adhesion good to 700°F.; separated at 800°F. and attacked mirror surface.
26. Silicone 92-010 Dow-Corning Co. Midland, Mich.	1. Applied thin film of adhesive to glass slide and aluminum screen. 2. Dried in air at 150°F. for 1 hr. 3. Heated in air to 800°F.

Material and Manufacturer	Test and Evaluation
26. (Continued)	4. Adhesion good to 650°F.; mirror separated from substrate at 800°F. 5. Material difficult to apply because of fluidity.
27. Astroceram American Thermocatalytic Co. Mineola, N. Y.	1. Applied to both glass slide and mirror and attached to aluminum screen. 2. Air dried 1 hr. at 150°F. in air. 3. Heated to 800°F. in air. 4. Glass slide adhesion good at 800°F. 5. Adhesive attacked mirror surface and separated from screen.
28. Astroceram American Thermocatalytic Co. Mineola, N. Y. Stainless-steel pigment Williams Co. Emeryville, Calif.	10 g Astroceram 5 g stainless-steel powder 1. Mixed above ingredients and applied thin film to mirror and screen. 2. Heated for 2 hrs. in air at 210°F. 3. Heated to 800°F. in air: at 700°F., mirror attacked by adhesive; at 800°F., mirror separated from screen.
29. Polyimide - polyimide 150 Amoco Chem. Co. Chicago, Ill.	1. Cured adhesive at 270°F. for 2 hr. 2. Adhesive was too fluid and would not adhere to surfaces. 3. Pressure and vacuum required for curing operation.
30. Double-backed polyimide tape ST6962 Permacel Tape Co. New Brunswick, N. J.	1. Applied tape to mirror and aluminum. 2. Heated to 800°F. in air. 3. At 600°F., tape discolors; adhesion fair. 4. At 700°F., tape turning black; adhesion fair. 5. At 800°F., tape degraded completely; removed from mirror and aluminum panel.

Material and Manufacturer	Test and Evaluation
30. (Continued)	6. Applied tape to mirror and aluminum. 7. Attached 17 gram weight to mirror. 8. After 30 days at 700°F. in vacuum polyimide film charred and little adhesive left.
31. Scotchcast SK351	1. 10 g Scotchcast resin 2. Unable to apply to mirror and substrate; material requires high temperature and pressure for cure.

Appendix B

THERMAL CONSIDERATIONS

B.1 THERMAL PERFORMANCE OF HIGH TEMPERATURE MULTILAYER INSULATION

An analysis of data presented in technical reports submitted in support of a NASA-funded study (reference 3), was made in order to predict the temperature profile in the multilayer insulation system for various boundary conditions. Since the temperature variation through the insulation is to be quite large in the intended application, it was proposed to vary, in the thickness direction, the attachment or reinforcement materials in a manner consistent with the temperature profile and applicable material properties. It, therefore, became desirable to make a determination of the temperature profile in the insulation. The temperature profile will of course be affected by the attachments, but hopefully the effect will be small.

In the analysis which follows it is assumed that the heat transport across the multilayer can be described by the usual differential equation governing a material with variable conductivity. A solution is obtained by assuming a simple power function variation of conductivity with temperature. The solution yields a nonlinear temperature profile with exponents which may be evaluated from observed conductivity data.

ANALYSIS

<u>Nomenclature</u>

C_1, C_2	integration constants
K	thermal conductivity
L	thickness of multilayer
n	exponent defined by eq 2a
q	heat flux
T	temperature
x	thickness direction coordinate
τ	reduced temperature $= T/T_o$

Subscripts

o	reference and/or value at an insulation boundary
1, 2	value at a boundary
e	effective

The differential equation for one dimensional steady state heat conduction is

$$\frac{\delta}{\delta x}\left(K \frac{\delta T}{\delta x}\right) = 0 \tag{1}$$

where

$$K = K(T) \tag{2}$$

and for simplicity let

$$K = K_o \left(\frac{T}{T_o}\right)^n \tag{2a}$$

combining (1) and (2a) yields

$$\frac{\delta}{\delta x}\left\{K_o \left(\frac{T}{T_o}\right)^n \frac{\delta T}{\delta x}\right\} = 0$$

or

$$K_o \left(\frac{T}{T_o}\right)^n \frac{\delta T}{\delta x} = C_1 \tag{3}$$

integrating (3) yields

$$\frac{K_o}{T_o^n} \frac{T^{n+1}}{n+1} = C_1 x + C_2 \tag{4}$$

a new variable, τ , is introduced such that

$$\tau = T/_{T_o}$$

and (4) becomes

$$\frac{K_o T_o \tau^{n+1}}{n+1} = C_1 x + C_2 \tag{4a}$$

at $x = 0 \quad \tau = 1$, so that from (4a)

$$C_2 = \frac{K_o T_o}{n+1} \tag{5}$$

also evaluating (3) at $x = 0$ yields

$$K_o \left.\frac{\delta T}{\delta x}\right/_{x=o} = q = C_1 \tag{6}$$

substituting for C_1 and C_2 in (4a)

$$\frac{K_o T_o}{n+1} \left(\tau^{n+1} - 1\right) = qx \tag{7}$$

at $x = L \quad \tau = \tau_1$ so that from (7)

$$\frac{K_o T_o}{n+1} \left(\tau_1^{n+1} - 1\right) = qL \tag{7a}$$

eliminating q between (7) and (7a) yields the temperature profile

$$\frac{\tau_1^{n+1} - 1}{\tau^{n+1} - 1} = \frac{L}{X} \tag{8}$$

It would be useful to obtain an expression between k_o and the reported values at effective conductivity, k_e. The effective conductivity, k_e, is defined as

$$K_e = \frac{qL}{T_1 - T_o} = \frac{qL}{T_o(\tau - 1)} \tag{9}$$

eliminating q between (9) and (7a) yields

$$K_o = \frac{\left(n+1\right)\left(\tau_1 - 1\right)}{\tau_1^{\,n+1} - 1} K_e \tag{10}$$

Since the conductivity data is available as a function of warm side temperature for a constant cold side temperature, it would be useful to have an expression which involved this data such that the exponent n could be determined. Letting $K_e = K_{e1}$ at $\tau = \tau_1$ and $K_e = K_{e2}$ at $\tau = \tau_2$, then from (10) there is obtained

$$\frac{K_{e2}}{K_{e1}} = \frac{\left(\tau_1 - 1\right)\left(\tau_2^{\,n+1} - 1\right)}{\left(\tau_2 - 1\right)\left(\tau_1^{\,n+1} - 1\right)} \tag{11}$$

Using equation (11) the exponent, n, was evaluated for the several insulation systems tabulated in Table 5-1. Note that there is very good agreement amongst the various systems in the value for n, particularly for the Tissueglass data. Also, tabulated in Table 5-1 is the value for room temperature conductivity obtained from equation (2a) and the appropriate value for n. Plotted in Fig. B-1 are several temperature profiles calculated from equation (8) with n equal to 2.54 which corresponds to the average value for the three Tissueglass systems. Curve A represents the temperature distribution for an aluminized polyimide film-Tissueglass multilayer blanket with an outer boundary (mirror) temperature of 800°F., and a constant, 70°F., inner (equipment) temperature. Curves B and C represent the distribution for outer boundary temperature of 600 and 400°F. respectively, and a constant, 70°F. inner temperature.

Table B-1. Reduced Thermal Conductivity Data

Spacer Material: Type	Spacer Material: Layers Per Spacer	Layer Density ($inch^{-1}$)	△ Reference	Calculated Values: n*	Calculated Values: Room Temperature ($70^{o}F.$) Conductivity BTU/hr $ft^{o}R. \times 10^{4}$
Dexiglas	1	60	3	2.17	1.6
	3	20	3	2.76	2.0
Tissueglass		60	3	2.58	.63
		120	3	2.5	.43
		150	3	2.58	.40

△ For references, refer to Section 9 of this report.

*Average value obtained by averaging the three values obtained from the three combinations of the three data points available for each system.

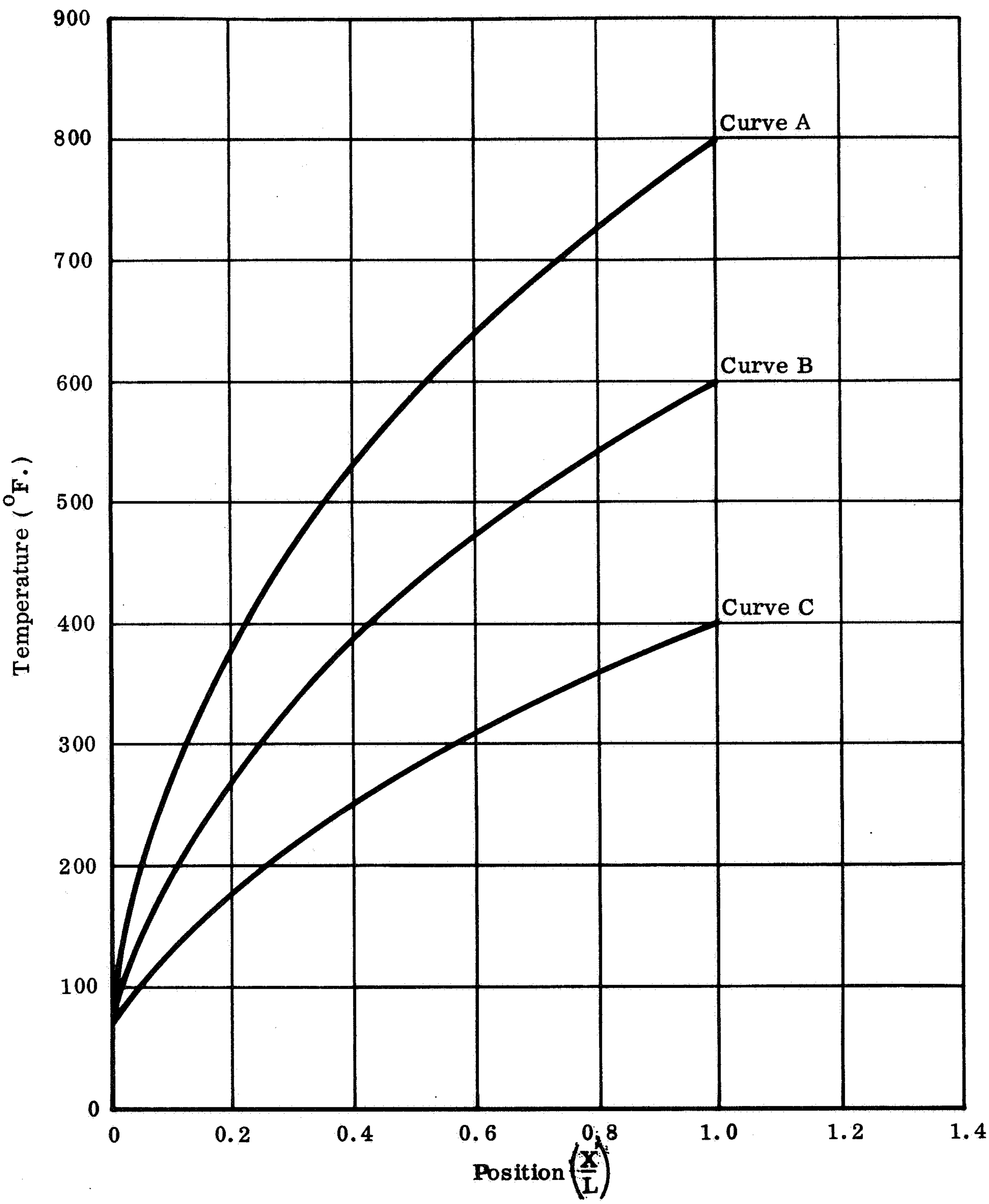

Fig. B-1 Probable Temperature Profiles in Aluminized Polymide Film-Tissueglass Multilayer for Several Boundary Conditions

Inspection of the curves presented in Fig. B-1 shows that no significant drop in temperature occurs through the top half of the multilayer blanket. For an 800°F. outer boundary temperature condition, the temperature halfway through a multilayer blanket is approximately 640°F., hence materials for attaching multilayer insulation must be capable of withstanding the high temperature environment unless located at the bottom of the multilayer blanket.

B.2 HEAT TRANSFER EFFECTS IN FASTENERS FOR MULTILAYER INSULATION

In order to provide a basis for making simple estimates of the effect on overall heat transfer through a multilayer insulation blanket resulting from fastener or attachment post penetrations, a technique for calculating the ratio of heat transfer through the fasteners (or attachments) to that through the multiple layer insulation was devised.

When an insulation blanket is penetrated by a fastener, a parallel heat path to the one through the insulation is created. Further, there will be a heat exchange between the fastener and insulation. If the fastener diameter is small (less than 1/16 inch) this latter effect may be neglected and the heat transfer through the fastener and insulation analyzed independently. Fig. B-2, where the ratio of fastener to insulation heat transfer is plotted versus fastener diameter for various ratios of fastener to insulation conductivity, has resulted from such an analysis.

Listed below are approximate values for the thermal conductivity of several candidate fastener materials for the temperature range of interest.

Material	Thermal Conductivity (BTU/hr ft °R)
Titanium-Chromium	8.7
Titanium-Aluminum	5.5
Stainless Steels	8.5-10
Quartz/Glass	1.0
Ceramic	3.0
Aluminum	100.0

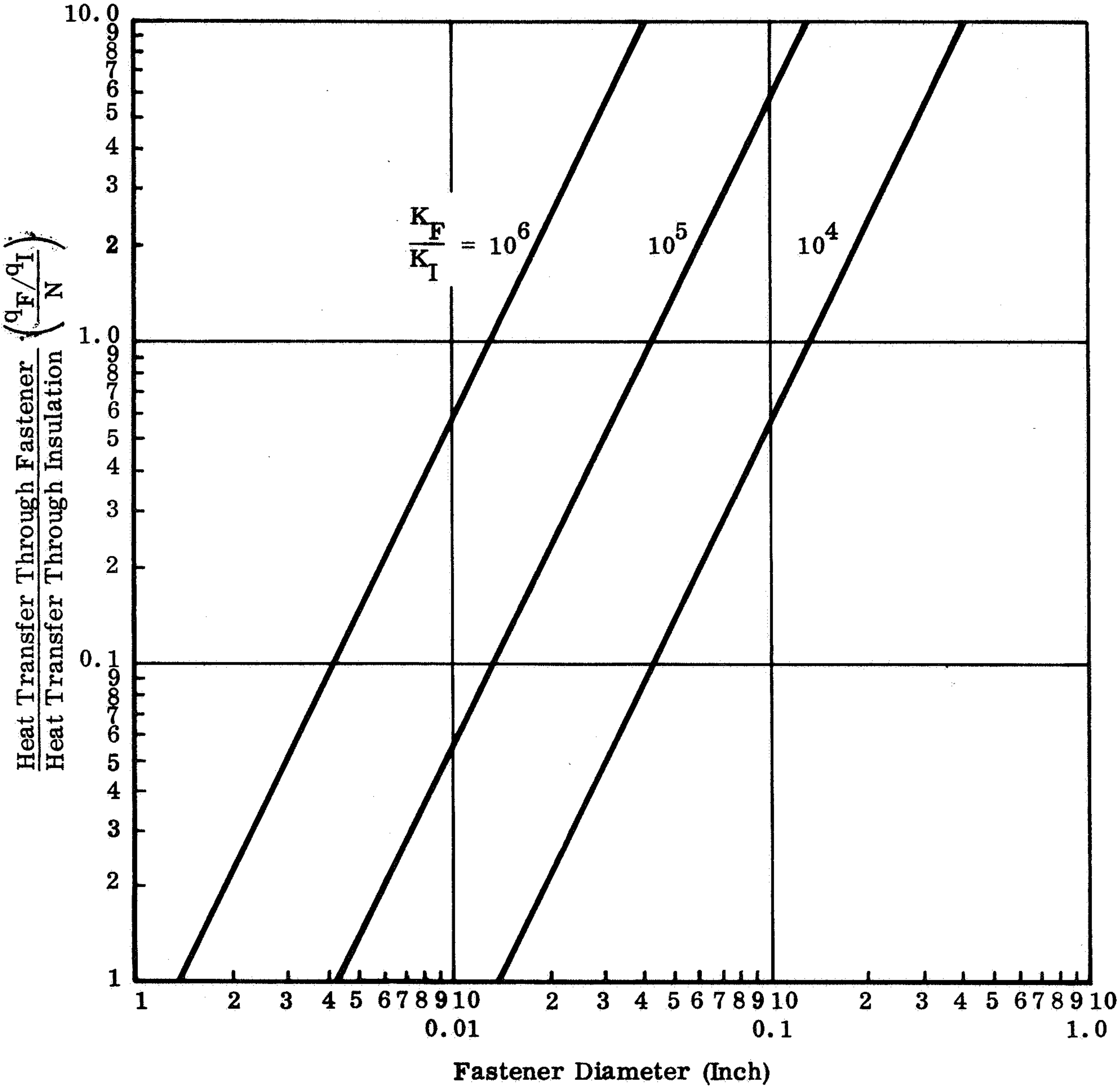

Fig. B-2 Heat Transfer Effects in Multilayer Insulation Resulting From Fasteners

Several example calculations of the ratio of fastener heat transfer to multilayer insulation heat transfer for systems evaluated in this study are presented below.

Example 1. What is the ratio of the heat transfer through the fasteners to that through the insulation for a 12-inch by 18-inch module consisting of aluminized H film and Tissueglass having a layer density of 150 layers/inch with 4 single-strand (looped) glass fiber threads (0.017-inch-diameter) and 4 pyrex glass attachment posts (0.156-inch-diameter)? The outer surface temperature of 600^{o}F. and the inner surface is at 70^{o}F.

SOLUTION

Nomenclature

d	diameter
K	thermal conductivity
N	number of penetrations per square foot

Subscripts

e	effective or average value
F	fastener
I	insulation
O	reference and or value at a boundary

From Table B-1, the room temperature conductivity of the multilayer is 0.40×10^{-4} BTU/hr $ft^{o}R$ and $n = 2.58$. The effective thermal conductivity over the temperature range of interest is calculated with the aid of equation (10) from page B-4.

$$K_e = \frac{\tau_1^{n+1} K_o}{(n+1)\,(\tau_1 - 1)} = \frac{\left(\frac{460 + 600}{460 + 70}\right)^{2.58+1} - 1}{(2.58 + 1)\left[\frac{460 + 600}{460 + 70} - 1\right]} \left(.40 \times 10^{-4}\right)$$

$$= 1.2 \times 10^{-4} \text{ BTU/hr ft}^{o}\text{F}$$

but from paragraph B.1

$$K_F = 1 \text{ Btu/hr ft}^{\circ}\text{F.}$$

so that

$$\frac{K_F}{K_I} = \frac{1}{1.2 \times 10^{-4}} = .83 \times 10^4$$ (for both the glass fiber thread, and the pyrex attach posts)

from Figure B-2, at a fastener diameter of 0.156 inch for the pyrex attach posts and $K_F/K_I = 10^4$

$$q_F/q_I/N = 1.35$$

so that for

$$K_F/K_I = .83 \times 10^4$$

$$q_F/q_I/N = \frac{.83 \times 10^4 \ (1.35)}{10^4} = 1.12$$

but

$$N = \frac{4}{1.5} = 2.67$$

so that

$$q_F/q_I = 2.67 \times 1.12 = 3$$

For the glass fiber threads, at $d = 0.017$, and $K_F/K_I = 10^4$ on Figure 5-2,

$$q_F/q_I/N = 0.18$$

so that for

$$K_F/K_I = .83 \times 10^4$$

$$q_F/q_I/N = \frac{.83 \times 10^4 \; (.018)}{10^4} = .015$$

but

$$N = \frac{8}{1.5} = 5.33$$

so that

$$q_F/q_I = 5.33 \times .018 = .096 = 9.6\%$$

Total heat transfer of the fasteners in relation to the multilayer equals

$$\frac{q_F \text{ (attach posts)} + q_F \text{ (quartz thread)}}{q_I \text{ (insulation)}} = 3 + .096 = 3.096$$

In other words, the heat transfer through the fastening system would be slightly over 3 times that transferred through the multilayer. The contribution of the glass fiber thread is negligible with respect to that through the pyrex attachment posts.

Example 2. What is the ratio of the heat transfer for the same system and boundary conditions as above, but with aluminum ($K = 100$ Btu/hr ft$^\circ$F) attach posts in lieu of pyrex?

SOLUTION

For the glass fiber thread

$$q_F/q_I = 9.6\%$$

for the aluminum attach posts

$$\frac{K_F}{K_I} = \frac{100}{1.2 \times 10^{-4}} = 83 \times 10^4$$

from Figure B-2

$$q_F/q_I/N = 1.35$$

so that for

$$K_F/K_I = 83 \times 10^4$$

$$q_F/q_I/N = \frac{83 \times 10^4 \ (1.35)}{10^4} = 112$$

$$N = 2.67 \text{ (from previous example)}$$

so that

$$q_F/q_I = 2.67\ (112) = 300$$

The heat transfer through the aluminum attachment posts is 300 times that transferred through the multilayer. Thus the fasteners tend to negate the benefits obtained by the use of the multilayer insulation.

Example 3. What is the ratio of the heat transfers for a 6-inch by 6-inch module consisting of aluminized H-film and tissueglass having a layer density of 150 layers/inch with 4 twisted strands of silicone-reinforced glass fiber thread (.036 total diameter) attachments? The outer surface temperature is 600°F. and the inner surface is at 70°F.

SOLUTION

From B-7

$$K_F = 1 \text{ Btu/hr ft}^{\circ}\text{F}.$$

so that

$$\frac{K_F}{K_I} = \frac{1}{1.2 \times 10^{-4}} = .83 \times 10^4$$

from Figure B-2, at a fastener diameter of 0.036 inch, and $K_F/K_I = 10^4$

$$q_F/q_I/N = .075$$

so that for

$$K_F/K_I = .83 \times 10^4$$

$$q_F/q_I/N = \frac{.83 \times 10^4 \, (.075)}{10^4} = 0.062$$

but

$$N \text{ for module} = \frac{4 \times 2}{0.5} = 16$$

so that

$$q_F/q_I = 16 \times 0.062 = .99 = 99\%$$

Heat transfer through the silicone-reinforced glass thread is approximately equal to that through the multilayer insulation. However, the effective cross-sectional area of the multifilament quartz thread is likely to be 70 percent of that for a solid cross section. Therefore, the above ratio may be about 30 percent higher than the actual case. Heat transfer through the silicone may be neglected inasmuch as the conductivity is one-tenth the value of glass, and total thickness is approximately 0.002 inch.