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STUDY OF ATTACHMENT METHODS FOR ADVANCED SPACECRAFT THERMAL-CONTROL MATERIALS

PHASE I SUMMARY REPORT

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FOREWORD

This report summarizes progress in the selection and design of attachment methods for a thermal-control composite system consisting of second-surface mirrors (optical solar reflectors) and multiple-layer insulation. The work is being conducted by Lockheed Missiles & Space Company (LMSC) under contract NAS 2-4252 for the National Aeronautics and Space Administration, Ames Research Center.

This summary of the technical portion of the program (Volume I), with accompanying bibliography (Supplement I), concludes the Phase I effort which was performed from 2 May 1967 through 30 September 1967.

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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 low solar absorptance (α_s), high emittance (ϵ) surface, and providing a low thermally conducting path from the low α_s, high ϵ 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 on Air Force programs. However, the materials were utilized separately to perform their intended functions.

A program 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, has been initiated. The study program was divided into two primary segments:

Phase I. Analyze existing and potential attachment techniques with respect to compatibility with spacecraft requirements and select most promising methods for development and environmental testing.

Phase II. Subject thermal-control composite system and its attachment methods to environments to be encountered during launch and orbit operations.

Phase I technical efforts are discussed in the body of this report which is sectioned by tasks:

Task	Subject
1	Literature Review
2	Summary of Attachment Methods
3	Analysis of Various Application Techniques
4	Attachment Experimentation
5	Selection of Most Feasible Attachment(s)
6	Preparation of Fabrication and Evaluation Program

Section 1
LITERATURE REVIEW

To compile a comprehensive list of attachment techniques which might prove useful in this study, LMSC conducted 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. 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 is presented as a supplement to this report.

Because the bibliography includes selected abstracts which relate to thermal design parameters as well as attachment techniques and materials of construction, the compilation will assist the thermal as well as the systems designer whenever need for reviewing data on multiple-layer insulation or second-surface mirrors occurs. Inasmuch as the bibliography is intended to serve as a reference source for Government agencies and their contractors, reports or studies which were company funded, and thus not available to other contractors, were excluded from the bibliography.

Section 2
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 2-1.

Although none of the abstracted reports surveyed during the literature search pertains directly to the particular attachment problem that is being investigated in this study, there were some multilayer-insulation attachment methods that have been investigated previously for passive thermal control of cryogenic systems. These attachment schemes are included in Table 2-1.

To our knowledge, design of a system utilizing multiple-layer insulation and second-surface mirrors as a unitized form of insulation against high-intensity, solar, radiation has not been attempted previously. Hence, most candidate attachment schemes represent concepts which were conceived by LMSC study-team members and advisary personnel.

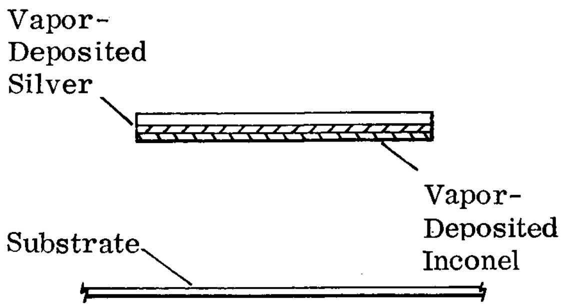
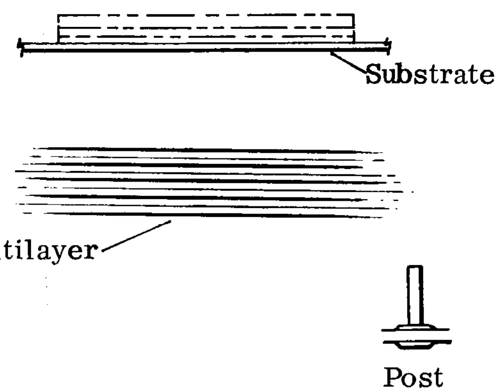
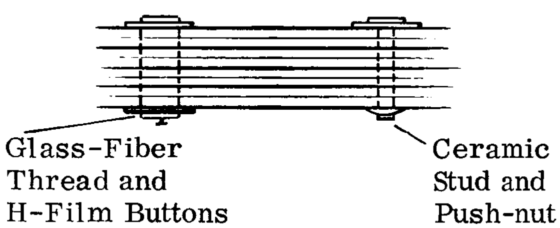
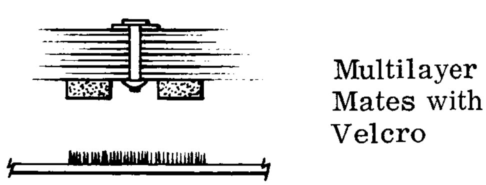
The overall problem of attaching the thermal-control composite was divided into

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.

Baseline systems selected for further evaluation and optimization during Phase II of the program are noted in Table 2-1.

Table 2-1. Matrix

Elements of Composite System	Candidate Attachment Methods
I. Second-Surface Mirrors to a Substrate 	1. Mechanical attachment: metallic track, clips, tabs 2. Weld to inconel: mirror backing a. Ultrasonics b. Brazing 3. Adhesive: mirror to substrate a. Silicones b. Double-backed polyimide tape, silicone adhesiv c. Ceramic cements
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 2. Snapon cap welded to underside of screen or foil fit over post 3. Mirrors attached to top layer of multilayer a. Adhesives b. Welded to top layer of multilayer 4. Mirror substrate attached to top layer of multilaye a. Metallic Velcro fasteners b. Thread onto multilayer buttons
III. Multilayer Insulation 	1. H-film buttons, glass-fiber thread 2. Ceramic studs moored by metallic push-nuts 3. Teflon buttons and thread 4. Sewing blankets together 5. Cylindrical or longitudinal wrap
IV. Multilayer to Vehicle Skin 	1. Nylon Velcro fasteners to multilayer and vehicle sl 2. Metallic clips or snaps to multilayer and vehicle sl 3. Bond bottom of multilayer to vehicle skin

of Attachment Techniques

	Limitations	
	Element	System
	1. Loose in holder, subject to thermal warpage	1. Compromises thermal efficiency
	2. Not sufficient film thickness to weld	2. Not replaceable if mirror is shattered during handling
	a. Temperature limited to 700-800°F.	a. Requires application technique
e	b. Temperature limited to 500-600°F.	b. Requires application technique
	c. Attack mirror surface	c. Degrades reflective properties
	1. Must have clearance between mirror substrate and multilayer to attach wires	1. Time consuming to assemble
s	2. Must apply pressure to mirror and screen	2. Alinement critical for installation
	a. Difficulty in bonding to aluminized multilayer	a. Blankets no longer removable for access to vehicle
	b. Existing welding techniques not applicable to polyimide film and mirrors	b. Weight causes multilayer to sag and tear during loading
r	a. Velcro material magnetic	a. Interference with experimentation/ communication equipment
	b. Clearance required to tie down to buttons	b. Buttons not of sufficient strength to carry loads imposed by mirrors
	1. Thread chaffing during handling	1. Threading and knotting time
	2. Weight of studs	2. Increased thermal conductivity
	3. Temperature limited to 500°F.	
	4. Compresses multilayers together	4. System not readily removable or replaceable
	5. Must be performed at launch site	5. System not readily removable or replaceable
in		1. Some alinement of Velcro fasteners necessary for installation
in	2. Clips not weldable to aluminized multilayer	2. Alinement for installation critical
	3. Difficulty in bonding to aluminized multilayer	3. System not readily removable or replaceable

PRESENT BASELINE SYSTEM

Section 3
ANALYSIS OF VARIOUS APPLICATION TECHNIQUES

During Phase I, 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. These constraints were taken from the original Request For Proposal (RFP) issued by Ames. Attachment methods were analyzed in relation to their performance capability within the application envelope:

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^{o}F.

   (Specific values to be tested are delineated in the test plan included in Section 6 of this report.)
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. Composite system must be easy to install and have capability of removal for access to vehicle substrate or replacement of damaged components.
e. Composite system must be usable on cylindrical and flat shapes.

Although not stated in the RFP, consideration has been 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 0.006 inch 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 3-1 shows individual attachment problems and lists the major performance parameters required for the thermal-control composite.

3.1 SECOND-SURFACE MIRRORS TO A SUBSTRATE

3.1.1 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 appear 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.

<u>Design Constraints</u>

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

<u>Attachment Problems</u>

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

<u>Configuration</u>

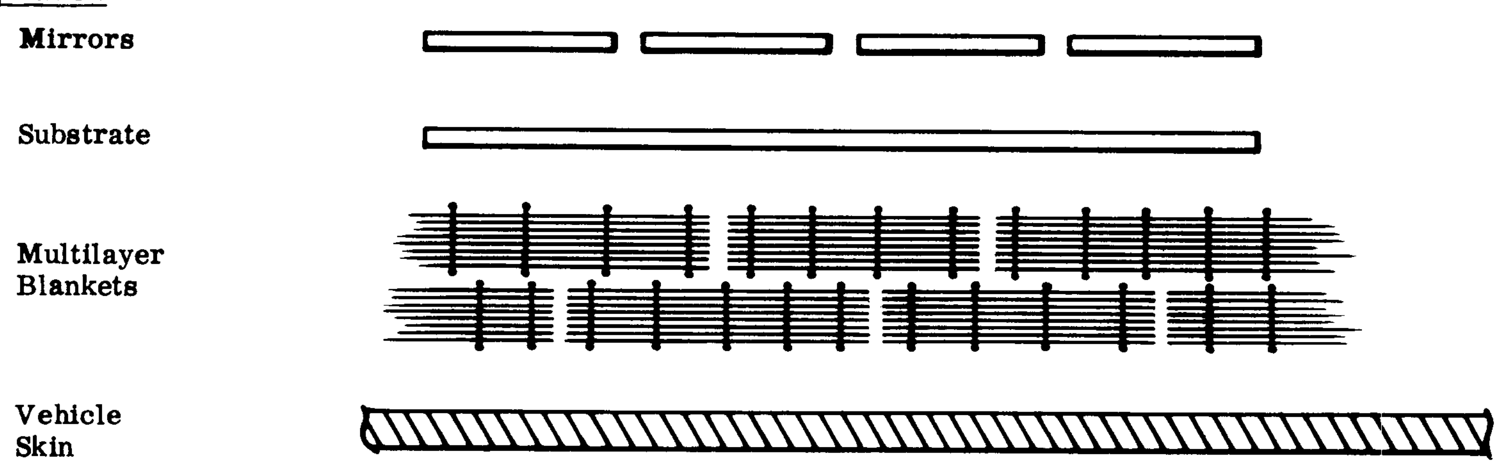


Figure 3-1. Design constraints and attachment problems for thermal-control composite system

3.1.2 Welding to Inconel Mirror Backing

This technique has been 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 activate 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, LMSC did not feel that mirrors could 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 0.006 inch 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.

3.1.3 Ultrasonic Welding

LMSC investigated the possibility of attaching gold wire to the mirror back side using ultrasonic bonding techniques. The gold wire then would be attached mechanically to a screen substrate. The principle of bonding is based upon an ultrasonic-vibration-induced scrubbing action which removes surface oxides and thus effects an amalgamation and fusion of the gold wire to the inconel backing. Attempts to join the gold wire to the inconel were unsuccessful. Cause of failure to achieve a bond is attributed to lack of sufficient inconel thickness.

3.1.4 Adhesives

The technique considered most promising for mirror attachment is the use of silicone adhesive. Silicone adhesive systems offer the advantage of ease of application and cure, and provide adequate bonding strength at the temperature range under consideration. Also, the silicone system that is proposed for use, Dow Corning Company Product

Number 92-024, has no detrimental effect on the silver reflective portion of the second-surface mirror. Section 4 of this report delineates results of extensive investigations conducted during Phase I to select an adhesive system that approaches the high temperature goal of 800°F.

Both foil substrates and open-meshed screens have been studied with respect to providing a base for the mirrors. Better bond-line strength and curing of the adhesive system is achieved when a wire-mesh screen is used as the mirror substrate. The adhesive squeezes through the screen openings and is entwined around the far side of the screen such that when cured, an excellent bond line is established. A secondary advantage is that screen openings provide an escape path for any outgassing products liberated during either the curing cycle or subsequent exposure to elevated temperature and vacuum.

Both the foil substrate and the open-meshed screen were used as mirror substrate on test specimens, and were tested for ability to withstand random vibration excitation during Phase I bench testing. The foil was used as a substrate for mirrors that were attached by means of a double-backed polyimide tape, and the open-meshed screen was used as a substrate for mirrors that were attached with the silicone adhesive system. Neither configuration showed any detrimental effects from the vibration testing. Testing parameters and test-specimen configurations are detailed in Section 4 of this report.

Polyimide tape, double-backed with a silicone adhesive, shows promise for use in the 450-600°F. range. It offers a considerable advantage in relation to ease of mirror positioning and subsequent replacement of a damaged mirror. The silicone system applied by the vendor to the polyimide tape does not appear to withstand successfully temperature in excess of 600°F. Tests will be conducted during the Phase II effort to determine maximum operating temperature for the double-backed-tape system. One problem that occurs when applying the double-backed-tape system is possible entrapment of air beneath the tape. Special procedures for applying this system will have to be developed, because subsequent escape of entrapped air could cause failures in the bond line between the mirror substrate and the tape itself.

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

During Phase I studies, LMSC concluded that a post or standoff attached to the vehicle skin was necessary to support weight of mirrors and substrate. Even for lightweight blanket assemblies, the added weight of mirrors statically and dynamically supported by the blankets would cause the multilayer system to fail. Point of failure would be either at the attachment point between the multilayer blanket and the vehicle (where Velcro fasteners are commonly used) or within the multilayer blanket itself (at the button attach points).

Posts to which the mirror substrate is attached provide an undesirable conductive heat path through the multilayer to the vehicle skin. However, the posts will be fashioned from ceramic material which has a low thermal conductivity $\left(\text{on the order of } 3 \times 10^{-5} \frac{\text{BTU-in.}}{\text{in}^2/{}^\circ\text{F./sec.}}\right)$. Plastic materials were considered for use as posts but they are unable to withstand high temperatures that will exist directly beneath the mirror substrate. LMSC currently is attempting to optimize the number of posts required to support the mirror substrate. Tradeoff considerations involve the weight penalty associated with increased mirror-substrate thickness (for mirror rigidity) in relation to overall effect on thermal conductivity for the composite system.

Posts provide some advantages in relation to the overall systems concept:

a. They serve as placement or jig pins for blanket installation.
b. They reduce number of attachments required to secure multilayer blankets to vehicle skin by providing additional strength against shear forces.
c. They provide additional venting paths for release of air entrapped within the multilayer blankets.

Small, hat-shaped, aluminum clips which are brazed to the underside of the mirror substrate serve as tabs through which aluminum wire is routed. This wire then is threaded through holes drilled into the ceramic parts and subsequently twisted. This provides a positive lock which secures the mirrors and its screen substrate to ceramic posts.

Attachment experimentation completed during Phase I indicates that, while the wire attachment technique is effective in providing a method of attaching the mirror substrate to the composite system, the installation process is difficult because of cramped working conditions. LMSC now is pursuing the possibility of using aluminum caps (brazed to underside of mirror substrate) which either may be snapped or press fitted over the free end of ceramic posts.

Metallic Velcro fasteners also were investigated as a possible means of attaching the mirror substrate to either the top layer of the multilayer or to a post. A sample of the metallic-fastener material was tested for magnetism by Ames at our request. Test results indicated that level of magnetism for the 1 inch square is 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. Fasteners fabricated from nonmagnetic materials will not be available for purchase during the period of performance for this study contract.

3.3 MULTILAYER INSULATION

3.3.1 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.

3.3.2 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.

3.3.3 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. 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.

3.3.4 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 (0.018-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 bench-testing phase of our study. A description of the fabrication technique, along with an illustration, is provided in Section 4 of this report.

3.3.5 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 are pierced through the multilayer blanket and are held in position by aluminum push-nuts installed on the underside of the blanket. Although the diameter of the ceramic stud (0.060 inch) is considerably larger than the glass-fiber thread, it is felt that the number of studs required to hold the multilayer blanket together will be considerably less than is required for the polyimide button/glass fiber arrangement. LMSC will determine the maximum spacing allowable for the ceramic stud/push-nut configuration during the Phase II effort. A trade-off analysis with respect to effects on thermal performance of the ceramic stud/push-nut technique will be the basis for final selection of the better multilayer blanket fabrication method.

3.4 MULTILAYER TO VEHICLE SKIN

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

3.4.1 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.

3.4.2 Snap or Clip Fasteners

Snaps or clips fabricated either from metallic or nonmetallic material secured to the underside of the multilayer blanket are 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 surface; and (2) clip or snap must be bonded to bottom of multilayer blanket, and most bond lines would be damaged by repeated flexes of blanket which occur during handling, installation, and removal.

3.4.3 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 3.3.4 and 3.3.5. 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.

This Velcro fastening technique has been used successfully by Lockheed on numerous NASA and company-funded developmental programs. An epoxy adhesive is used to bond the hook portion of the nylon to the vehicle surface. This adhesive provides good bonding performance in the temperature range to be encountered on the vehicle surface (70-120^{o}F.).

3.5 SYSTEMS CONSIDERATIONS

Each of the individual attachment points within the thermal-control composite have been discussed above but there are additional design considerations which govern ultimate selection of optimum attachment techniques. These considerations are enumerated and analyzed below.

3.5.1 Effect of Multilayer Decompression

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 LMSC test experience indicates that, depending on the blanket configuration and pumpdown rate, this ballooning effect can be of sufficient magnitude that the button and Velcro attachments can 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. The type of multilayer blanket system to be 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. Additionally, pumpdown tests of multilayer configurations, to be conducted during Phase II portion of study, will lend confidence to the assumption that ballooning effects for the button and thread configuration will not compromise integrity of the composite system.

3.5.2 Ease of Attachment and Removal

Necessity for access to the vehicle or to the insulation system if mirrors or multilayer are damaged during prelaunch or handling operations dictated that LMSC concentrate its efforts only on those attachment techniques which permit removal of each component comprising the composite system. This consideration, along with the previously discussed fabrication problems, eliminates most mechanical fastening techniques. The approach LMSC has taken is to make the composite system in modular fashion, such that each component is readily removable. The size of the individual module is relatable to the configuration to be covered as well as the structural integrity of the attachment points. It is anticipated that each particular use for the composite system will require optimization as far as the size of individual module is concerned.

3.5.2 Edge Effects on Thermal Performance of Systems

Near the edges of a multilayer insulation, there will be considerable distortion of the isotherms so that heat transfer is in a direction which is more nearly parallel than normal to layers. Since parallel conductivity is several orders of magnitude greater than normal conductivity, the heat-transfer rate at an edge is considerably higher than at locations remote from an edge. This effect may extend over a zone of many thicknesses. On samples having a dimension of less than 1 foot, this effect may predominate over the entire area, thus raising the effective thermal conductivity by as much as an order of magnitude over that for a large specimen.

Rather than allow the edges of the multilayer to be directly exposed to solar radiation, an overhang of the mirrors which would shield the edges of the multilayer blanket from incident solar energy is desirable. Thus, the composite system must be designed to permit some degree of shielding for the edges of the multilayer system.

Section 4
ATTACHMENT EXPERIMENTATION

This task entailed performing numerous screening tests to evaluate candidate attachment methods in relation to operational requirements for the thermal-control system. A description and results of tests performed are given below.

4.1 ULTRASONIC BONDING

LMSC attempted to bond gold wire to the silver/inconel backside of second-surface mirrors using ultrasonic bonding techniques. 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 LMSC's 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, LMSC did not feel that modified mirrors could be prepared and delivered in time for evaluation during the timespan alloted to the performance of this study contract.

4.2 ADHESIVE BONDING

The major portion of the experimentation phase 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, we restricted our testing 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 experimentation phase of the study. Table 4-1 lists candidates tested and our observations. A more 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^{o}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.

Corrosion of the mirror's silver backing was noted frequently during experimentation. Any corrosion is undesirable because of the resultant decrease in the reflectance of the mirror system. Figure 4-1 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^{o}F. for 6 hours in a vacuum of 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.

Table 4-1. Results of Adhesive Evaluations

Candidate Adhesive System	Observations
1. Sauereisen 6 (ceramic)	Good adhesion to 800°F. in air; separated when cooled to room temperature.
2. Sauereisen 7 (ceramic)	Very good adhesion to 800°F.; attacked silver mirror surface.
3. Sauereisen 8 (ceramic)	Good adhesion to 800°F. in air; separated when cooled to room temperature
4. Sauereisen 31 (ceramic)	Good adhesion to 800°F. in air; cracked mirror during heating cycle.
5. Sauereisen 66 (ceramic)	Poor adhesion at 800°F. in air.
6. Sauereisen 70 (ceramic)	Good adhesion to 800°F. in air; separated when cooled to room temperature.
7. Sauereisen 78 (ceramic)	Good adhesion to 800°F. in air; separated when cooled to room temperature.
8. MR-1 (ceramic)	Good adhesion to 800°F. in air; cracked mirror.
9. MR-2 (ceramic)	Good adhesion to 800°F. in air; separated when cooled to room temperature.
10. Alumina and potassium silicate (ceramic)	Good adhesion to 800°F. in air; attacked mirror surface.
11. Potassium silicate (ceramic)	Fair adhesion to 800°F.; separated on cooling to room temperature.
12. Potassium silicate/silica (ceramic)	Good adhesion to 800°F.; separated on cooling to room temperature.
13. Potassium silicate/Kastite refractory (ceramic)	Good adhesion to 800°F.; separated on cooling to room temperature.
14. Potassium silicate/Alumina 1139 (ceramic)	Good adhesion to 800°F.; attacked mirror surface.
15. Potassium silicate/Zirconia Yttrium oxide (ceramic)	Good adhesion to 800°F.; separated on cooling to room temperature.
16. Kellundite 371W (ceramic)	Good adhesion to 800°F.; cracked and discolored mirror.
17. Potassium silicate/stainless-steel pigment Triton X-100 (ceramic)	Adhesion good to 700°F.; cracked mirror at 700°F.

Table 4-1 (Continued)

18. Stainless-steel pigment/ Triton X-100/Alumina 1139/ Potassium silicate (ceramic)	Adhesion good to 800°F.; adhesive attacked mirror surface.
19. Silicone 92-024	Adhesion good in air to 700°F.; good in vacuum for 72 hours at 800°F.
20. Silicone 93-067	Adhesion good in air to 600°F.; separated at 800°F. in air.
21. Epoxy 1206-2	Adhesive sets up too rapidly; could not apply to substrate.
22. Silicone EP 5909 EP 5910	Adhesion fair to 700°F.; material too fluid, difficult to apply.
23. Epoxy BR-600	Adhesion good to 600°F. in air; attacked and cracked surface of mirror.
24. Lead oxide/glycerol (ceramic)	Adhesion fair to 250°F.; mirror separated from substrate at 250°F.
25. Epoxy BR-600 Nickel powder	Adhesion good to 700°F.; mirror separated from substrate at 800°F.
26. Silicone 92-010	Adhesion good to 700°F.; mirror separated from substrate at 800°F.
27. Astroceram (ceramic)	Adhesion good to 800°F.; attacked mirror surface.
28. Astroceram/stainless-steel pigment (ceramic)	Good adhesion to 700°F.; mirror surface attacked by adhesive.
29. Polyimide-polyamide 150	Adhesive did not cure at 270°F.; too fluid to apply.
30. Double-backed polyimide tape with silicone adhesive	Adhesion good to 600°F.; tape discolors and degrades above 600°F.; at 800°F., mirrors separate from substrate.
31. Scotchcast SK 651 (ceramic)	Powder form, unable to apply to mirrors and substrate.

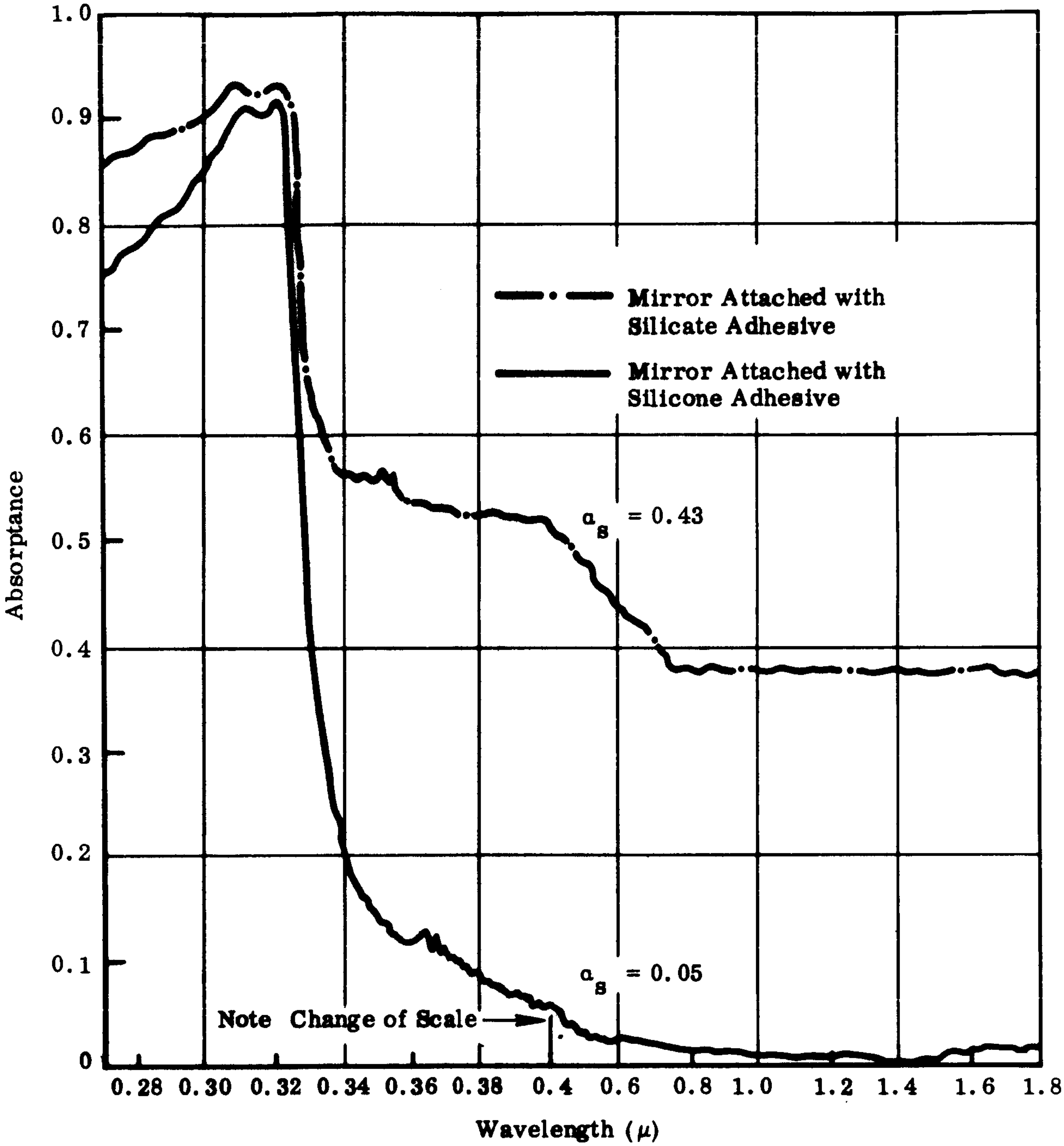


Figure 4-1. Solar absorptance of second-surface mirrors

Because the ceramic and silicate systems showed promise in retaining their bonding strength at temperatures in excess of 800°F., we 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.

The adhesive system which shows the most promising performance characteristics at elevated temperature and vacuum conditions is a Dow Corning Company silicone under the trade name of Dow Corning 92-024 Aerospace Sealant. This material is relatively easy to apply to a uniform film thickness 0.003 to 0.004 inch, 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.

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. To precondition the silicone system, LMSC cured the adhesive at 300°F. in an air oven. This reduced considerably the amount of outgassing that occurred during subsequent vacuum-temperature testing, but did not prevent completely outgassing from occurring at higher temperatures. LMSC intends to pursue this attempt to reduce outgassing by performing additional tests during the thermal-vacuum testing portion of the Phase II effort. However, pressures to be a encountered in space will be much less than 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 must be instigated.

The epoxy-adhesive system evaluated during the experimentation phase 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 are warranted.

4.3 DOUBLE-BACKED POLYIMIDE TAPE

LMSC also investigated the use of a double-backed, polyimide tape system for applying the second-surface mirrors to a metallic substrate. 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. LMSC is attempting currently to determine the upper operating limit for the double-backed tape system.

The same double-backed tape was used successfully by LMSC during repeated temperature cycling in vacuum between -108 and 500°F. during Contract NAS 2-3164. It offers a significant application advantage over conventional ones or two-part silicone adhesives because the tape system can be applied easily to curved surfaces and requires no additional curing.

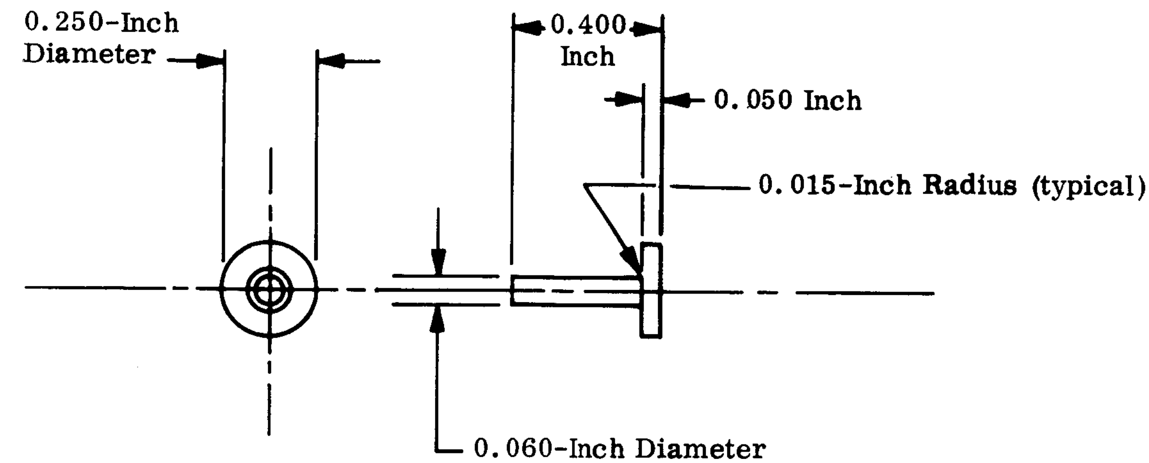
One problem was noted during an in-house development effort to qualify the tape for use on an Air Force-sponsored program. The adhesion of the silver/inconel backing on the fused silica of the second-surface mirror is not as good as the adhesion of the silver/inconel backing to the silicone adhesive used on the polyimide film. When second-surface mirrors were applied to an aluminum dome and cycled between approximately -200 and 140°F. in vacuum, the edges of the mirrors tend to lift away from the adhesive film. When this happens, some of the silver and inconel is pulled from the fused silica and remains with the adhesive on the polyimide film. The particular dome section being used for temperature-vacuum cycling has a dual curvature. Second-surface mirrors are positioned in a fixture, transferred to the double-backed tape system, and pressed into position by using a rubber roller. From preliminary results, it appears that it will be 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 are sufficient to overcome the adhesive's bond strength in a vacuum environment.

4.4 MULTILAYER INSULATION

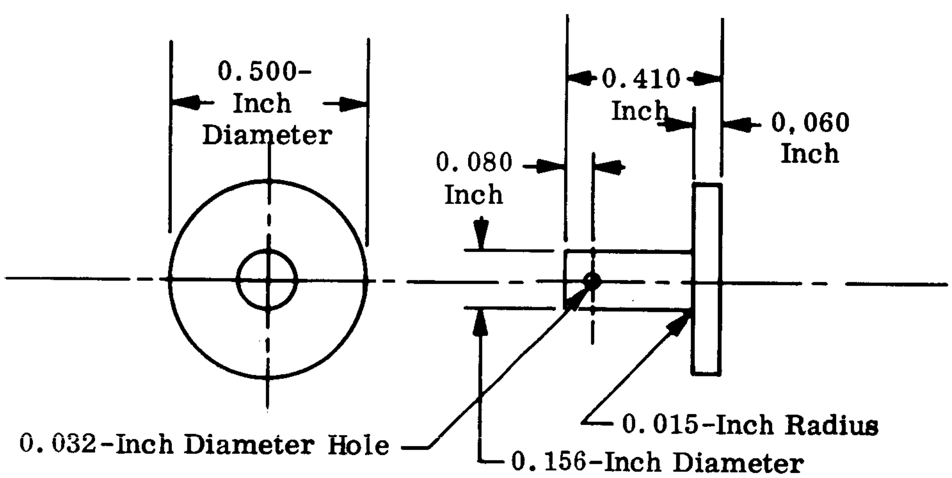
Because the upper layers of the multilayer insulation will be exposed to approximately the same temperatures as that of the second-surface mirrors, the teflon buttons and threads previously used to hold the insulating blankets together could not be used in our program. After consulting with manufacturers of glass fiber and high-temperature plastics, LMSC selected a quartz-fiber sewing thread for evaluation. The 0.018-inch-diameter thread, produced by H. I. Thompson Fibre Glass Company under the designation E-18, has a tensile strength of 18.5 p.s.i. The possibility of using polyimide thread was investigated; but it was determined that no thread is fabricated currently from polyimide material.

Techniques currently employed by LMSC production personnel for fabricating aluminized-mylar multilayer blankets were slightly modified. Aluminized polyimide film and tissueglass spacers were interleaved to form a 20-layer blanket. Buttons, 0.005 inch thick and 0.5 inch diameter, were punched from an aluminized sheet of polyimide film. Using a jig to maintain the desired spacing, the thread was looped through the multilayer blankets and buttons and knotted on the underside of the blanket. This method of blanket preparation proved quite sturdy during subsequent handling and installation operations; at no time was there evidence of button or thread failure.

In an attempt to provide a more rapid manner of blanket assembly, LMSC fabricated studs [Figure 4-2(a)] from phenolic stock which, when coupled with a metallic push-nut, could be used to attach multilayer blankets together in lieu of buttons and thread. The stud would be pierced through the blanket, and the push-nut attached to the end of the stud. This "push-on" type of attachment was considered advantageous from the



(a) Stud for multilayer blanket



(b) Post for mirror substrate

Figure 4-2. Proposed attachments

fabrication viewpoint, but does afford a large heat leak when compared to glass fiber thread. (For additional discussion of this candidate method for holding blankets together see Section 5.)

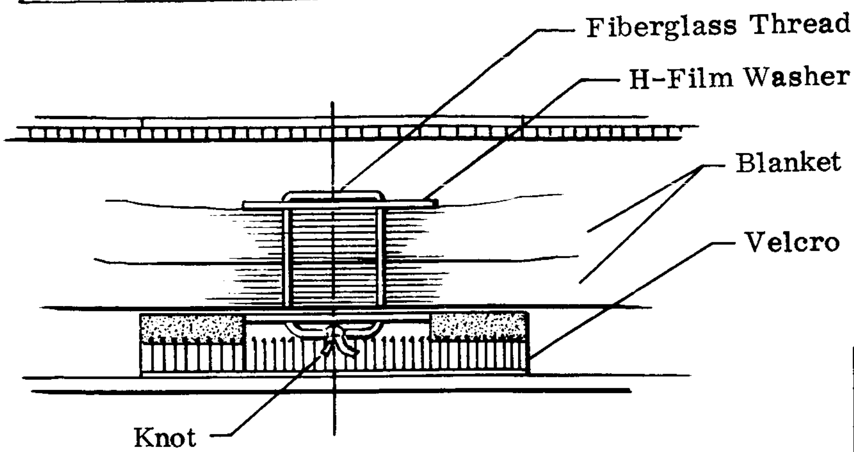
4.5 COMPOSITE-SYSTEM TESTING

To determine credibility of candidate attachment techniques in relation to the overall thermal-control composite, LMSC performed random vibration tests on two candidate systems. Random vibration was selected as the screening test because this represents the most severe loading environment that the composite system will encounter during the spacecraft mission. Random vibration, when applied normally to the plane of the composite is more severe than any loads to be imposed during the launch trajectory.

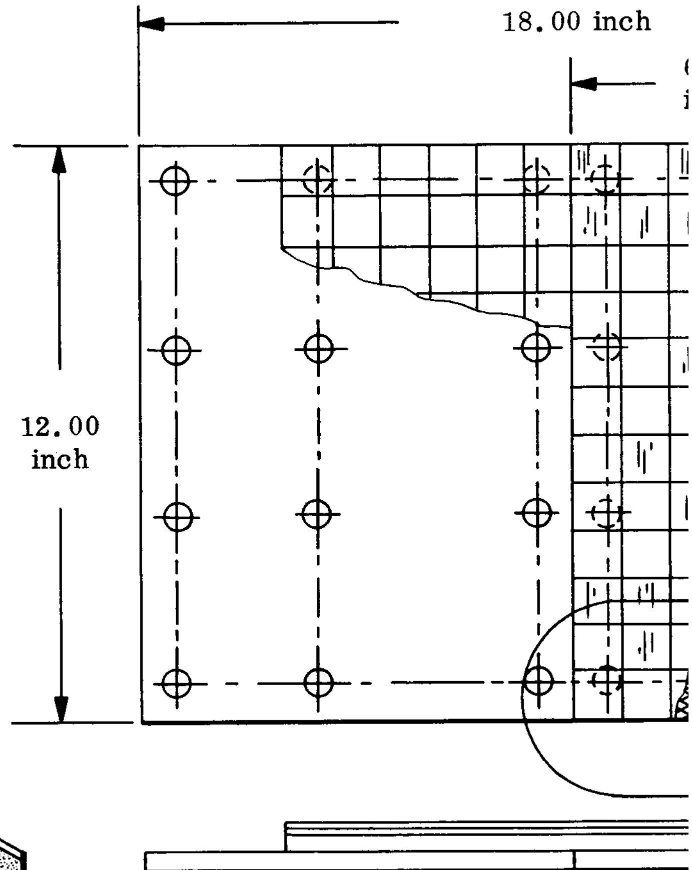
Figure 4-3 shows basic systems tested. Variations in blanket-attachment techniques (studs and push-nuts in lieu of buttons and thread) and mirror-attachment methods (double-backed polyimide tape to metal foil in lieu of silicone adhesive to metal screen) were introduced to evaluate candidate attachments.

An 18 x 12 inch panel, cut from 0.100-inch-thick 6061 aluminum-alloy stock, was used as the test plate for screening tests. Phenolic posts [Figure 4-2(b)] were bonded to the aluminum plate with an epoxy adhesive. Eight posts were placed on the test plate to support the mirror substrates. Posts were made from phenolic rather than ceramic material because of the unavailability of ceramic posts.

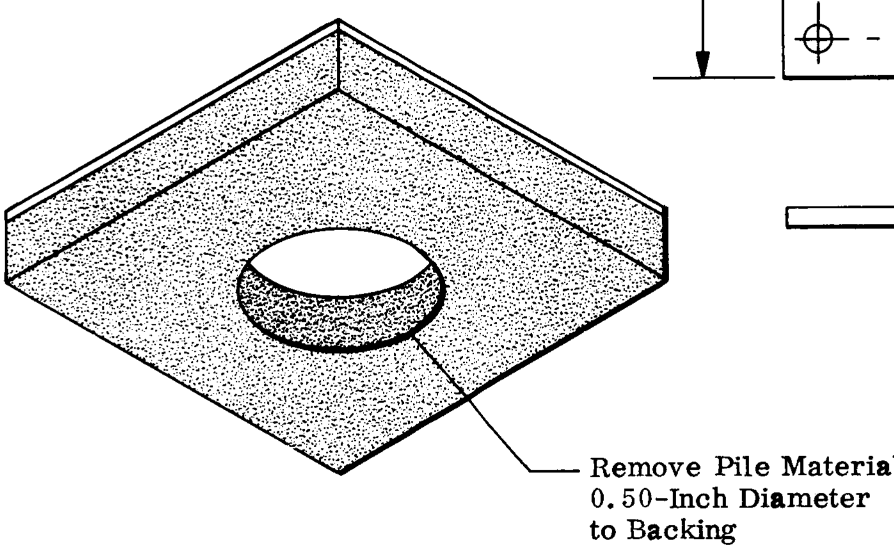
A 20-layer insulation blanket, composed of alternate layers of doubly aluminized polyimide film and tissueglass spacers, were held together with either polyimide buttons and quartz fiber thread [Figure 4-3(a)] or ceramic/phenolic studs and metallic push-nuts [Figure 4-3(c)]. Because we were unable to purchase ceramic studs of the size desired for testing, LMSC fabricated studs from phenolic stock. Ceramic suppliers advise that the most economical way of making ceramic studs would be to cast the desired shape in a mold. However, because we are only in an experimental phase and have not settled on the optimum stud size, it was not considered advisable to invest in tooling required.



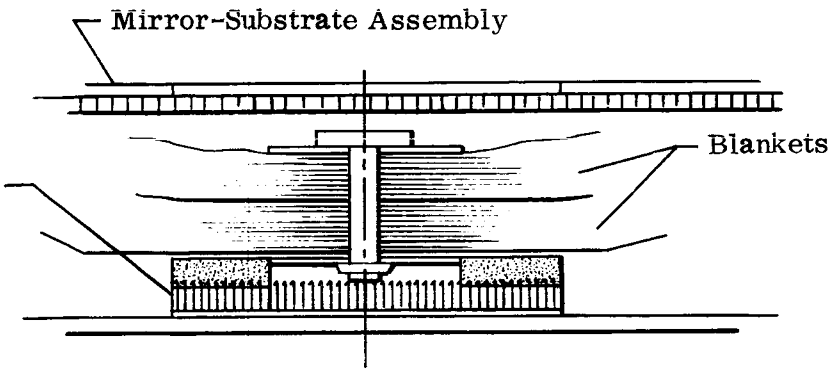
(a) Section A-A. Proposed method of tying blanket composite with buttons and fiberglas thread



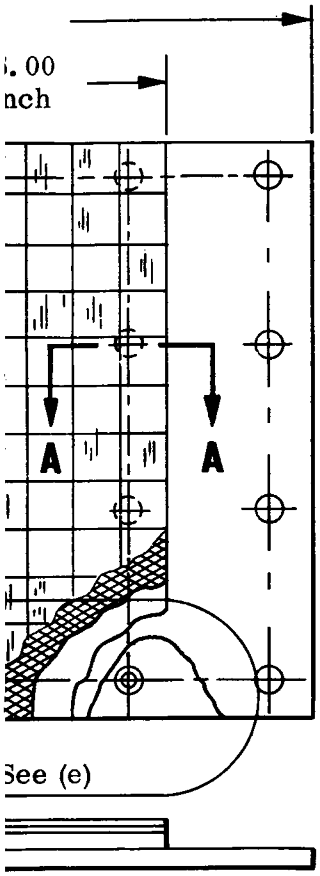
(b) Plan and side v



(d) Proposed rework of Velcro



(c) Section A-A. Proposed multilayer studs, alternate plan



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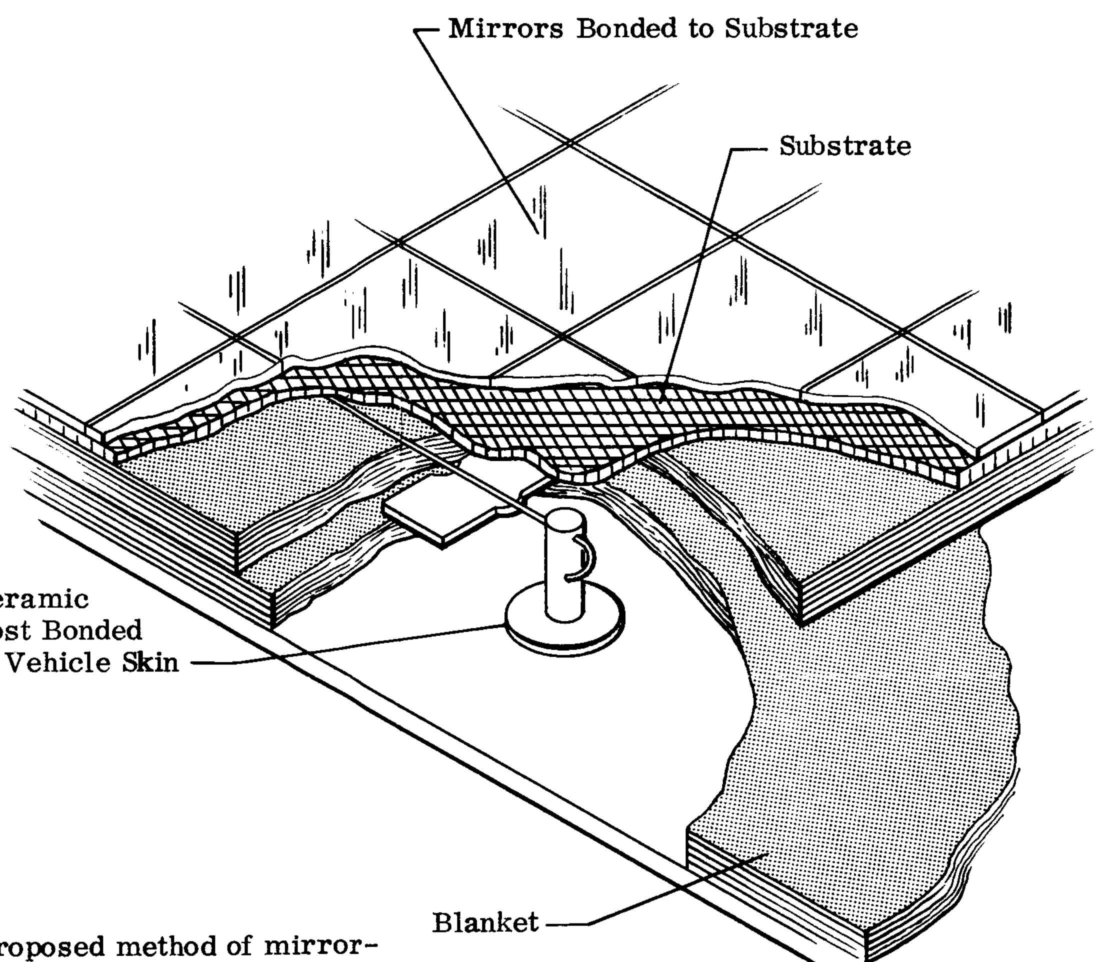


(e) Proposed method of mirror-substrate assembly to vehicle skin

Figure 4-3. Test-specimen configurations

Multilayer blankets were attached to the plate with Velcro fasteners. Pile portions of the Velcro fasteners were held to the underside of the multilayer blanket at each button location by either the quartz-fiber thread or the metallic push-nut attachment technique. A 1/2-inch-diameter area from the pile section was removed [Figure 4-3 (d)] so that the polyimide button could be countersunk to permit maximum contact between Velcro halves. The hook half of the fastener was bonded to the test plate with an epoxy adhesive. Multilayer blankets then were attached by pressing the two halves of the Velcro fastener together.

Two sets of panels covered with second-surface mirrors and glass cover slides were prepared, one consisting of mirrors and slides adhesively bonded to 0.016-inch-thick stainless-steel screens, the other consisting of mirrors and slides bonded with double-backed polyimide tape to a 0.002-inch-thick stainless-steel foil. Before applying mirrors and slides to their substrates, four metallic retainers were brazed to the underside of the screen or foil. These retainers were attached at points approximately 1/2 inch inboard from the top of the phenolic support posts which were bonded previously to the aluminum test panel.

After placing the multilayer blanket over the phenolic posts, the mirror substrates were placed on top of the phenolic posts and locked into position by threading a piece of stainless steel wire through the retainers and phenolic posts as shown in [Figure 4-3 (e)].

The test specimens which were subjected to random vibration testing are

a. Test Configuration A
   1. 1.5-foot^2, flat, aluminum test plate;
   2. Phenolic posts bonded with epoxy adhesive to test plate;
   3. Multilayer blanket held together with polyimide buttons and quartz fiber thread [Figure 4-3 (a)];
   4. Second-surface mirrors and glass cover slides adhesively bonded to stainless-steel screen;
   5. Screen and mirrors attached to phenolic posts with stainless-steel wire.

b. Test Configuration B

1. 1/5-foot^2, flat, aluminum test panel;
2. Phenolic posts bonded with epoxy adhesive to test plate;
3. Multilayer blankets held together with phenolic studs and metallic push-nuts [Figure 4-3(c)];
4. Second-surface mirrors and glass cover slides attached to stainless-steel foil with double-backed polyimide tape;
5. Foil and mirrors attached to phenolic posts with stainless-steel wire.

Configuration A was placed on a shaker and subjected to a random-vibration profile of 20 to 2,000 Hertz frequency content, with a spectral density of 0.05 to 0.18 g^2/Hertz (root-mean-square g level of 14.5 g's). Four minutes of excitation was applied along the Z axis only. No deflections greater than 1/8 inch were noted on either of the two 6 x 12-inch mirror/cover slide substrates which were positioned to form a lengthwise butt joint. No cover slides or mirrors were cracked during the test, and there was no evidence of damage to the multilayer or attachments techniques.

Configuration B was subjected to the same 4-minute random-vibration excitation used in the previously discussed test. Quartz-fiber thread was removed from six buttons of one half of the top blanket and replaced by phenolic studs and metallic push-nuts.

One of the screen panels was removed and replaced with a 6 x 12-inch foil panel which was covered with mirrors and cover slides applied with double-backed polyimide tape. Rather than the butt juncture used for the two mirror-screen configurations, the mirror-foil panel was allowed to overlap the edge of the mirror-screen panel by 1/2 inch.

No damage was incurred to any part of the composite system, nor were any mirror-panel deflections greater than 1/16 inch noted. The foil-mirror panel appeared more stable and rigid than the screen-mirror panel.

4.5.1 Conclusions

Conclusions to be drawn from the screening tests are:

a. Both techniques for applying mirrors/cover slides to substrates provide adequate bonding strength for the mirror system.

b. Manner of mirror-substrate attachment to phenolic or ceramic posts with wire provides adequate structural support.

c. Overlapping mirror-panels does not cause damage to mirrors and prevents any possibility that incident radiation would impinge directly through a butt joint to the multilayer located beneath the mirror substrate.

d. Threading wire through the retainers located on the underside of the mirror substrate and into the hole in the phenolic support posts is difficult. Eight minutes were required to thread the wires through posts supporting the panels. Clearance between the top of the multilayer insulation to the underside of the mirror substrate is approximately 1/4 inch. This makes the thread installation rather difficult.

e. No noticeable change in multilayer blanket integrity when stud/push-nut technique is substituted for the button/thread method of holding the blanket together. In both test configurations, there was no physical damage induced to the multilayer blankets from handling or vibration excitation.

f. Both configurations are over-designed from the structural standpoint. Reduction in the number of attachment posts and weight of the mirror-substrate combination is desirable.

Section 5
SELECT MOST FEASIBLE ATTACHMENT TECHNIQUES

Selection of attachment methods deemed most feasible from a design, fabrication, and installation viewpoint is based on experimentation results as well as analyses of candidate attachment schemes derived from the literature search and conceptual design sessions conducted by LMSC in support of this study contract.

The discussion given below presents the rationale used in selecting attachment techniques that LMSC recommends for environmental and development testing during Phase II.

5.1 SECOND-SURFACE MIRRORS TO A SUBSTRATE

LMSC has segregated this element of the composite into two temperature regimes: a high-temperature application (600-800^{o}F.) and a lower-temperature design (less than 600^{o}F.). Dow Corning silicone 92-024 is considered to be the best adhesive for the higher-temperature application and the double-backed polyimide tape appears to be promising for use in designs which do not exceed a maximum temperature of 600^{o}F.

During the experimental portion of the Phase I effort, test results indicate a significant difference in the performance of Dow Corning 92-024 silicone when tested in vacuum rather than atmospheric conditions. Although the upper temperature limit for extended periods of vacuum exposure will be determined during the Phase II investigation, test data already obtained show that the silicone material is capable of withstanding higher temperatures in vacuum than it can withstand in air.

Apparently, 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 adhesive 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.

Our experience with the silicone adhesive proposed for use in attaching the second-surface mirrors onto the thermal-control composite (Dow-Corning 92-024) indicates that the performance characteristics of the adhesive system degrades at a lower temperature in an air oven than they do when exposed in a vacuum environment. The material showed no detrimental effects on appearance or bond-line strength after 72 hours at 800°F. in a vacuum of approximately 10^{-4} Torr. However, the same material showed embrittlement and crazing after 8 hours exposure to 650°F. in an air oven.

Application of second-surface mirrors and glass cover slides to double-backed polyimide tape appears to be feasible as long as the temperature requirements do not exceed 600°F. Two application problems associated with the double-backed-tape system are worthy of mention:

a. Adhesion of the second-surface mirrors to the adhesive system on the polyimide film is so strong that ~~if~~ a mirror will be broken during any attempt to ~~realize~~ salvage it.

b. On curved surfaces, where complete contact of the second-surface mirror onto the tape is impossible, subsequent exposures to vacuum will cause the edges of the mirrors to lift from the tape system. When this occurs, portions of the silver/inconel backing from the mirror are pulled from the fused silica and remain adhered to the adhesive rather than the fused silica. Judicious selection of mirror size, chosen in relation to the curvatures anticipated, should prevent the aforementioned failure from occurring.

5.2 MIRROR SUBSTRATE

To obtain excellent bonding strength for the one-part silicone adhesive system, LMSC proposes to use open-meshed screen as the substrate to which the second-surface mirrors will be applied. The silicone adhesive squeezes through the screen openings and is entwined around the far side of the screen so that an excellent bond line is established after curing. The screen offers added advantages when compared with foil substrates because of reduced weight and rapid cure of the adhesive system.

For a low-temperature application, where double-backed polyimide tape is used, a thin foil (0.002-inch-thick), made from stainless steel or aluminum, must be used to provide sufficient contact area between the second-surface mirror and the substrate.

Although not available for evaluation during Phase I efforts, LMSC proposes to use expanded metal screen as the mirror substrate for the silicone-adhesive system. Expanded metal provides increased structural integrity and does not have a tendency to warp during handling.

5.3 MIRROR SUBSTRATE ATTACHMENT

Because the weight of the second-surface mirrors and their substrate is too great to attach directly to the multilayer, LMSC proposes to tie or clip the mirror substrate onto posts bonded to the vehicle skin.

Metallic hat-section retainers, brazed or welded to the underside of the mirror substrate, serve as a guide for stainless steel or aluminum wire which is threaded onto attachment posts bonded to the vehicle skin. This provides a technique for locking the mirror substrate into position. The attachment posts, made from ceramic material (although phenolic has been substituted during Phase I tests because of the unavailability of ceramic), are bonded to the spacecraft with an epoxy adhesive. Holes, drilled through the posts prior to installation, provide a space through which the wire is threaded to hold the mirror substrate into position.

Although the threading technique offers good structural integrity, the installation process is difficult. Clearance between the top of the multilayer and the bottom of the mirror substrate is only 1/4 inch, and this does not permit easy access for threading wire into the attachment posts. As part of the Phase II effort, LMSC will investigate the possible use of snaps or clips welded to the underside of the mirror substrate, which would lock into place when applied onto the ceramic attachment posts.

Ceramic posts, bonded to the spacecraft skin, present an operational restraint because of the inherent weakness associated with adhesively bonded joints and 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. LMSC recognizes that any modification to the spacecraft skin is undesirable from the structural aspect. However, it is reasonable to assume that the thermal-control composite system is a finite part of the vehicle design rather than an afterthought, and should be made a part of structural considerations during the preliminary design phase for the spacecraft. Rings, stiffners, and webs which usually serve as spacecraft structural members could also be used as attach points for the receptacle.

LMSC will originate conceptual designs for attaching posts into the spacecraft skin during the Phase II effort, but we will test and deliver only systems which have attachment posts bonded to test specimens. This approach is necessary because it cannot be assumed that drilling or riveting to the spacecraft skin can be permitted in all potential applications for the composite thermal-control system. If the second-surface mirrors and their substrates remain attached to adhesively bonded posts during environmental testing, engineering judgment indicates that the mirror substrate would remain attached also to a riveted or welded post.

5.4 MULTILAYER SYSTEMS

Two techniques for holding the multilayer blankets together have been proposed and tested. The basic system consists of alternate layers of doubly aluminized polyimide film and tissueglass spacers which are held together with polyimide buttons and quartz fiber thread. This method allows fabrication and subsequent storage of the multilayer blankets prior to final installation onto the test specimen.

Figure 5-1 shows an alternate method for holding the multilayer blanket together. Ceramic studs are pierced through the multilayer blankets, and are attached to underside of the blanket with metallic push nuts. The entire assembly is subsequently fast fastened to the vehicle substrate with Velcro fasteners. The studs must be fabricated from a material which is capable of withstanding the highest external temperature anticipated for the spacecraft mission. LMSC is attempting to develop a composite system capable of use in environments where the temperatures will exceed 600^{o}F.; therefore, ceramic was chosen over lightweight plastic or phenolic materials which decompose during exposure to high temperatures.

To prevent undesirable heat leaks at multilayer blanket joints, LMSC proposes to skarf the edges of the blanket whenever the blanket edges are to be joined (Figure 5-2). Quartz fiber thread will be laced onto buttons which have been previously installed into the blanket in order to tie the panels together.

Using the thermal analyses presented in 5.4.2.1 and 5.4.2.2 of this report, it can be seen that the glass fiber thread-polyimide button technique of holding the multilayer together does not present a significant increase in thermal conductivity for the system. Preliminaty investigation into use of ceramic studs in lieu of quartz fiber thread indicates a large increase (approximately a factor of 10) in system thermal conductivity if ceramic studs are used. As part of the Phase II effort, LMSC will determine the minimum number of studs required to permit handling and installation. If the number of studs can be reduced to the point where effective heat transfer through the ceramic studs approaches that obtainable with the quartz fiber thread, the ceramic technique will be selected for use on test specimens to be subjected to developmental testing.

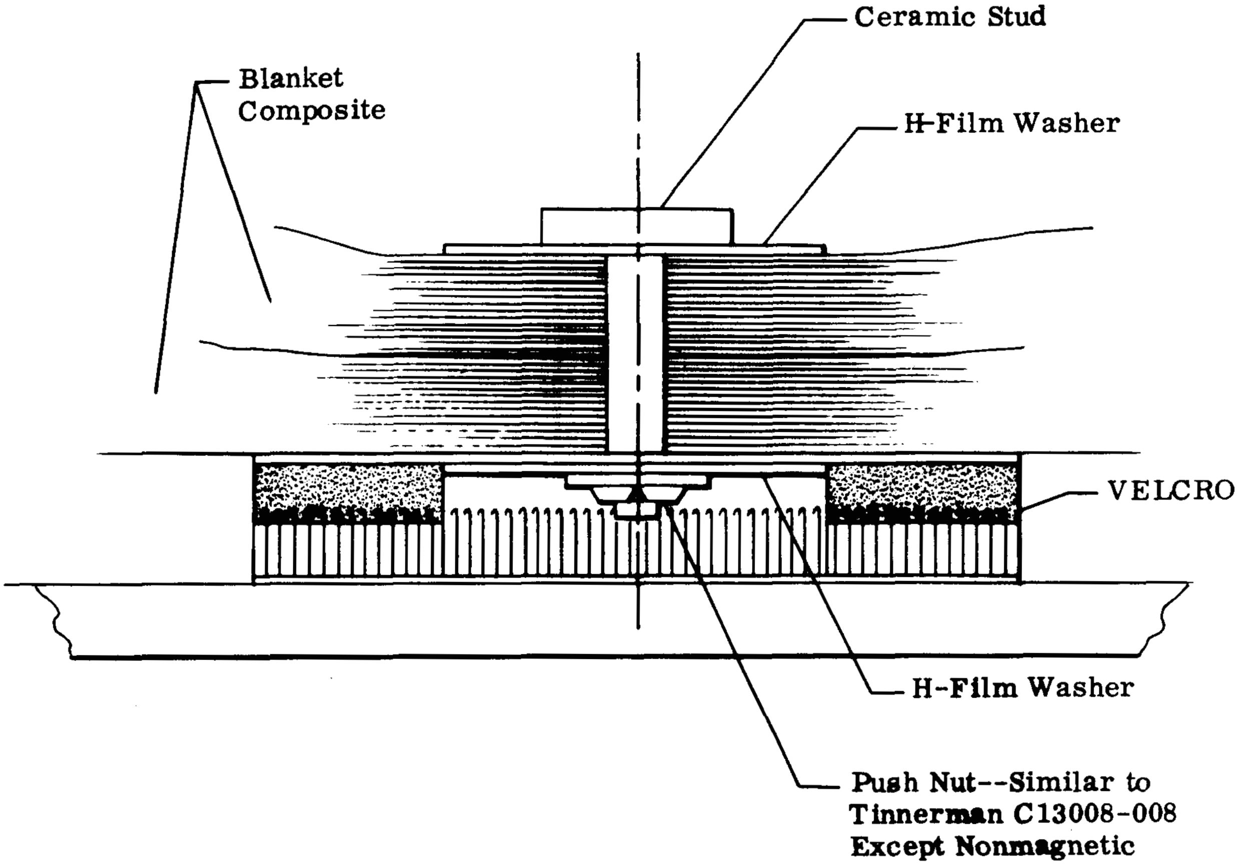


Figure 5-1. Ceramic Stud-Metallic Pushnut Attachment for Multilayer

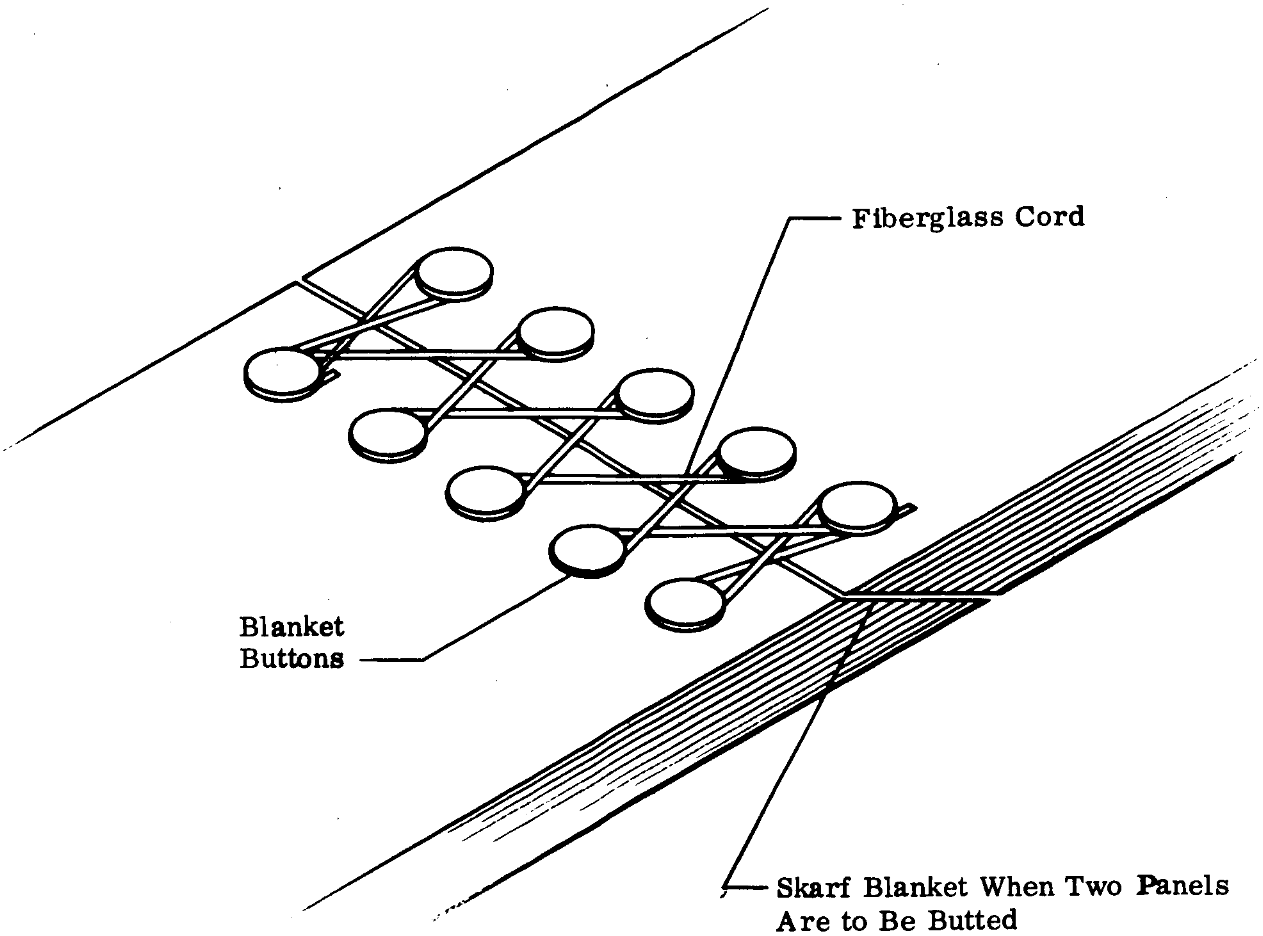


Figure 5-2. Method of tying multilayer blankets

5.4.1 Thermal Performance of High Temperature Multilayer Insulation

An analysis of data presented in technical reports submitted by LMSC in support of Contract NAS 2-2441, "Elevated Temperature Multiple Layer Insulation Study", 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 has been proposed to vary, in the thickness direction, the attachment or reinforcement materials in a manner consistant with the temperature profile and applicable material properties. It, therefore, becomes 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

Nomenclature

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 $= T/T_0$

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 $x = 0$ $\tau = 1$, 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 $x = L$ $\tau = \tau_1$ 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

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

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

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

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 Figure 5-3 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^{o}F., and a constant, 70^{o}F., inner (equipment) temperature. Curves B and C represent the distribution for outer boundary temperature of 600 and 400^{o}F. respectively, and a constant, 70^{o}F. inner temperature.

Table 5-1. Reduced Thermal Conductivity Data

Spacer Material		Layer Density	△	Calculated Values	
Type	Layers Per Spacer	$(inch^{-1})$	Reference	n*	Room Temperature $(70^{o}F.)$ Conductivity BTU/hr $ft^{o}F. \times 10^{4}$
Dexiglas	1	60	1, Figure 15	2.17	1.6
	3	20	1, Figure 13	2.76	2.0
Tissueglass		60	2, Figure 9	2.58	.63
		120	2, Figure 9	2.5	.43
		150	2, Figure 9	2.58	.40

△ References:

1. Performances of Multilayer Insulation Systems for the 300 and $800^{o}K$ Temperature Range, Contract NAS 2-2441, Phase I Report, LMSC Palo Alto Research Laboratory, July 1965.
2. Elevated Temperature Multiple Layer Insulation Study, Contract NAS 2-2441 Interim Technical Report Covering Tasks I & II, LMSC Palo Alto Research Laboratory, November 1966.

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

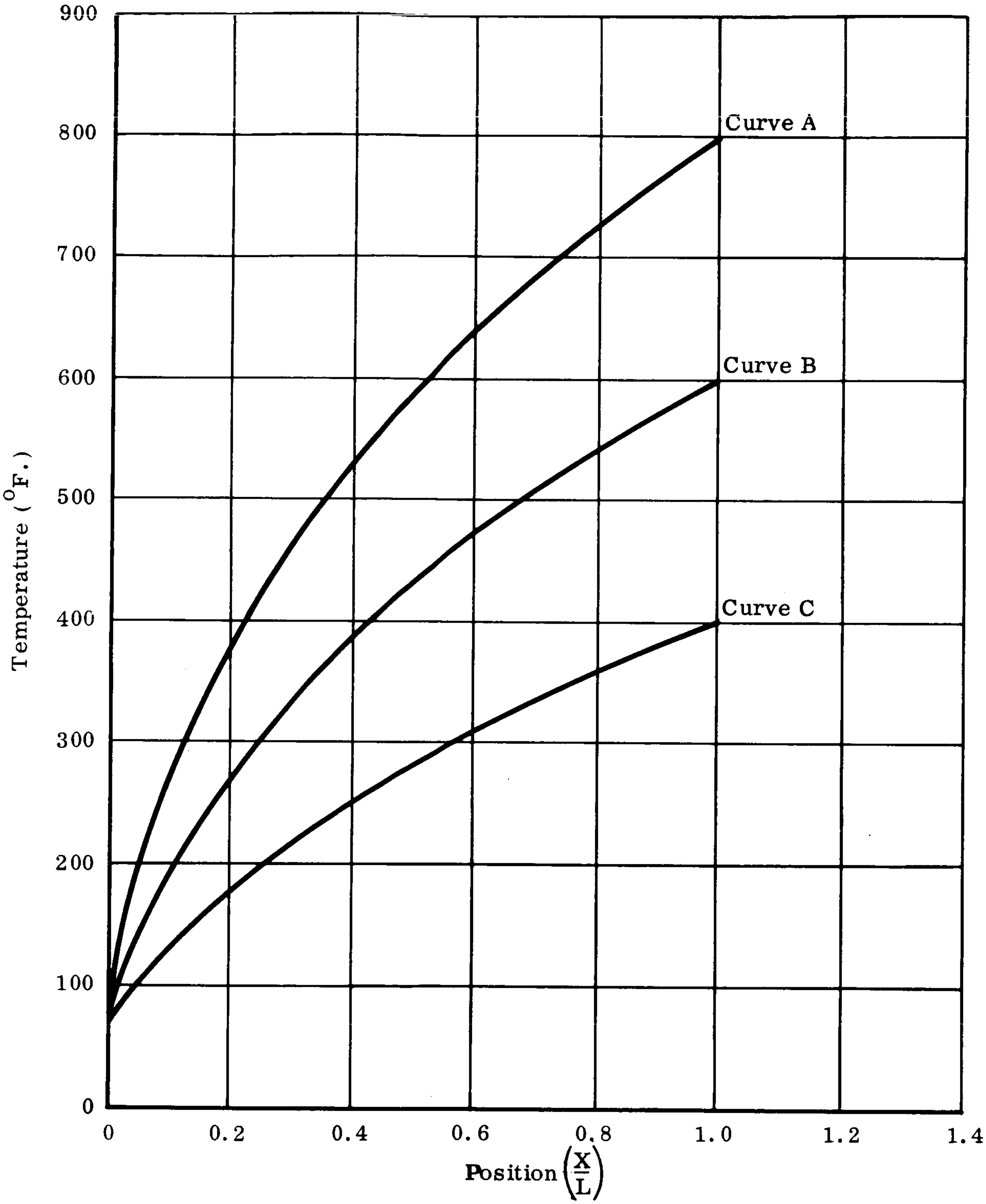


Figure 5-3. Probable temperature profiles in aluminized polyimide film-tissueglass multilayer for several boundary conditions

Inspection of the curves presented in Figure 5-3 shows that no significant drop in temperature occurs through the top half of the multilayer blanket. For an 800^{o}F. outer outer boundary temperature condition, the temperature halfway through a multilayer blanket is approximately 640^{o}F., hence materials for attaching multilayer insulation must be capable of withstanding the 640^{o}F. environment.

5.4.2 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. Figure 5-4, 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 ^{o}R)
Titanium-Chromium	8.7
Titanium-Aluminum	5.5
Stainless Steels	8.5-10
Quartz/Glass	1.0
Ceramic	3.0

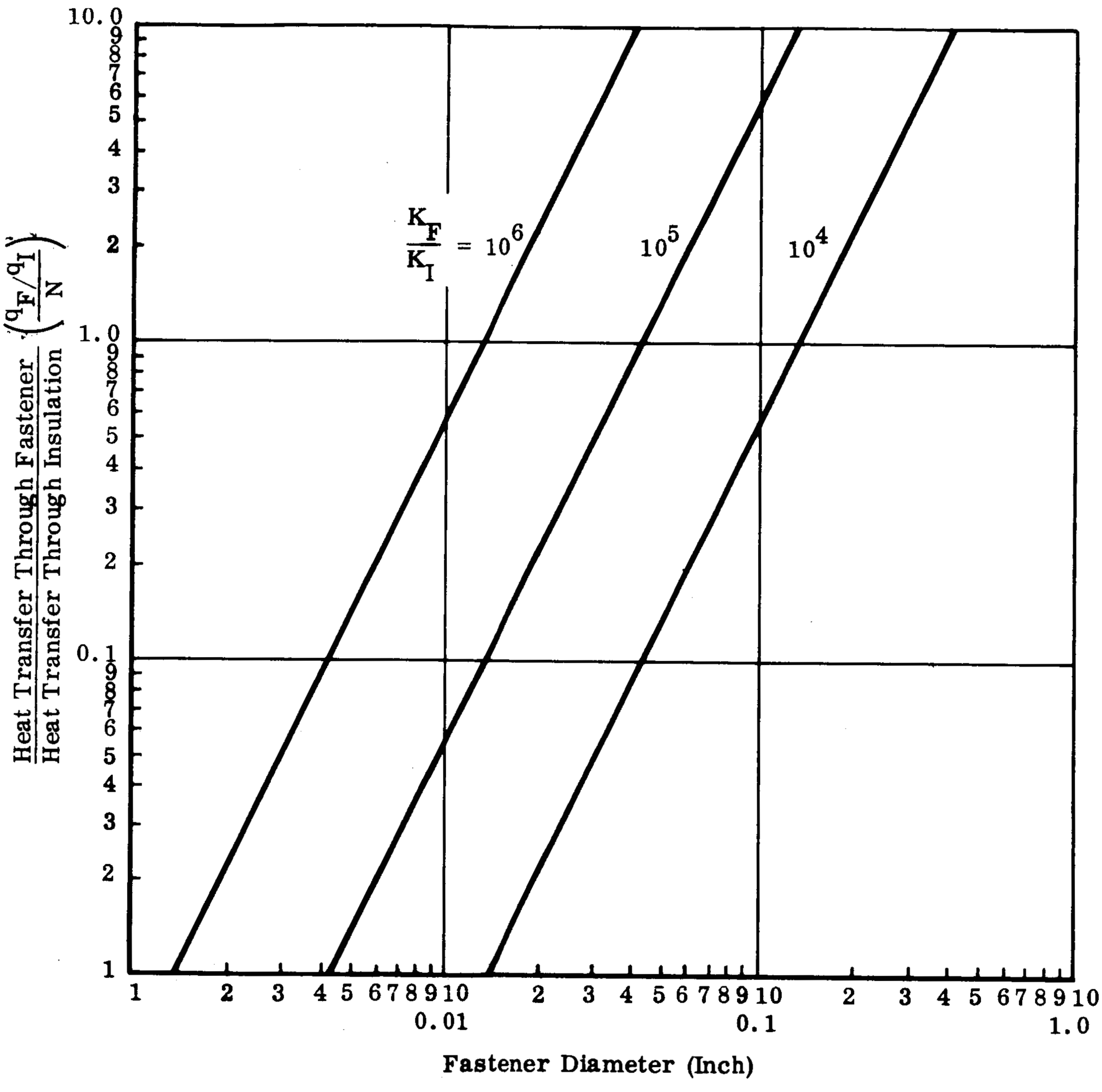


Figure 5-4. Heat transfer effects in multilayer installation resulting from fasteners

Several example calculations of the ratio of fastener heat transfer to multilayer insulation heat transfer are presented below.

5.4.2.1 Example 1. What is the ratio of heat transfer through the fasteners to that through the insulation for a system of aluminized H film and Tissueglass having a layer density of 150 layers/inch with 0.060-inch diameter ceramic fasteners. The outer surface temperature is 600°F. and the inner surface is at 70°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 5-1 the room temperature conductivity of the multilayer is 0.40×10^{-4} BTU/hr ft°R and n = 2.58. The effective thermal conductivity over the temperature range of interest is calculated with the aid of equation (10) from 5.4.1.

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

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

but

$$K_F = 3 \text{ BTU/hr}$$

so that

$$\frac{K_F}{K_I} = \frac{3}{1.2 \times 10^{-4}} = 2.5 \times 10^4$$

from Figure 5-4, at a fastener diameter of 0.06 inch and $K_F/K_I = 10^4$, $q_F/q_K/N = 0.2$

so that for $K_F/K_I = 2.5 \times 10^4$

$$q_F/q_I/N = \frac{2.5 \times 10^4}{10^4} (0.2) = 0.5$$

for 6 inch spacing, $N = \frac{144}{6 \times 6} = 4$

so that $$q_F/q_I = 4 \times 0.5 = 2.0$$

Thus, the heat transfer through the fasteners is twice that through the multilayer insulation.

5.4.2.2 Example 2. What is the ratio of heat transfers for the same insulation and boundary temperatures as given in 5.4.2.1, but with 0.018 inch diameter quartz fiber thread on four inch centers?

SOLUTION

$$K_F = 1 \text{ BTU/hr ft } ^oR$$

so that

$$K_F = \frac{1.0}{1.2 \times 10^{-4}} = 0.83 \times 10^4$$

from Figure 5-4, at d = 0.018 and $K_F/K_I = 10^4$

$$q_F/q_I/N = 0.017$$

so that for N = 144/4 x 4 = 9 and $K_F/K_I = 0.83 \times 10^{-4}$

$$q_F/q_I = 0.017 \times 0.83 \times 9 = 0.13$$

Heat transfer through the glass thread is one-tenth that through the multilayer insulation. 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.

Section 6
PREPARATION OF FABRICATION AND EVALUATION PROGRAM

During Phase I efforts of the study, LMSC has selected attachment methods which appear to be most promising for use on spacecraft systems. A developmental and testing program to modify and evaluate selected candidate systems in respect to their intended application has been prepared and represents the Phase II segment of the study. Result of the Phase II effort will be delivery of two insulated test specimens which have completed environmental testing successfully. A schedule for Phase II task items is presented in Figure 6-1.

Phase II efforts can be divided most readily into three categories: (1) system optimization, (2) test-specimen fabrication and assembly, and (3) environmental testing.

6.1 SYSTEM OPTIMIZATION

Methods selected during Phase I will be modified to produce a system which will be practicable and reproducible. Materials of construction will be optimized with respect to strength, weight, and thermal-performance considerations. Long-term temperatures and vacuum studies on attachment methods will be conducted to determine effects on materials used in the composite system. These studies will be completed during the first two months of the Phase II effort so that the deliverable test specimens will utilize optimum attachment techniques.

Specific areas of investigation include:

1. Determination of upper and lower operating temperature limits for adhesive system.
2. Development of production technique for application of second-surface mirrors to screen.

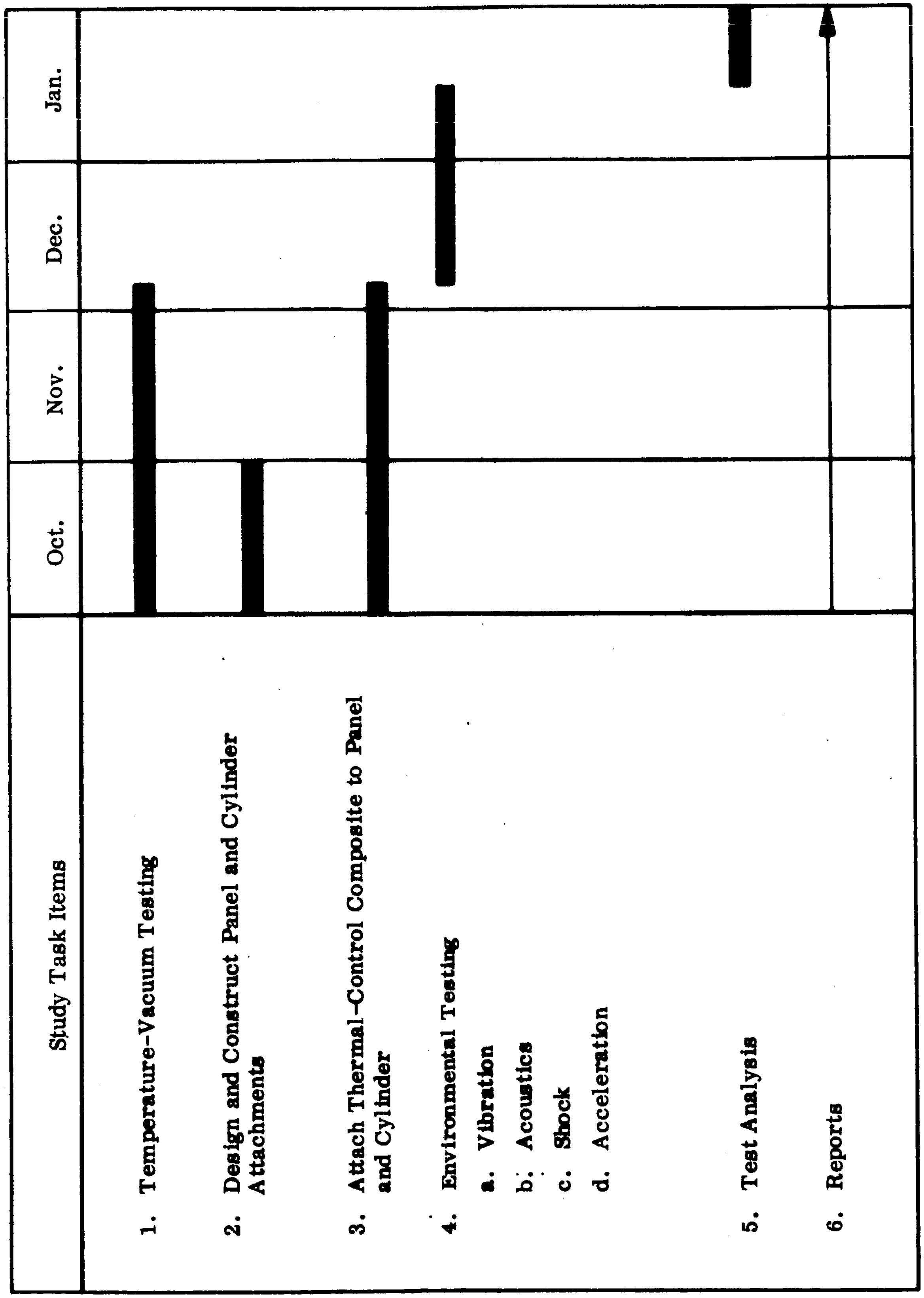


Figure 6-1. Phase II Schedule

3. Optimizing number of multilayer penetrations necessary to provide system structural integrity.
4. Reduction of overall system weight.

6.2 TEST-SPECIMEN FABRICATION AND ASSEMBLY

In accordance with requirements of the original Request for Proposal (RFP), a 1 by 1.5-foot panel and a 1-foot-long by 1-foot-diameter cylinder will be fabricated and insulated with the thermal-control composite system. The panels and cylinder, to be made from 6061 aluminum alloy, will be covered with multiple-layer insulation and second-surface mirrors. To minimize material costs, only 10 percent of the surface area of test specimens will be covered with second-surface mirrors. The remaining area will be covered with microscope cover slides which have approximately the same weight and dimensions of the mirrors. Substitution of cover slides will not invalidate test results inasmuch as their weight distribution is the same as that of the mirrors, and compatibility of mirrors with adhesive system to be utilized already has been demonstrated successfully during Phase I tests.

Procedure for attachment of the composite system to test specimens will be prepared and submitted as part of the final report.

6.3 ENVIRONMENTAL TESTING

A program test plan which defines, delineates, and integrates requirements for all development testing necessary to evaluate credibility of attachment methods for a thermal-control composite system comprised of multiple-layer insulation and second-surface mirrors (optical solar reflectors) has been submitted and approved by the study contract technical monitor, E. L. Streed of Ames. The plan supplements the original Program Evaluation and Review Technique (PERT) control chart prepared for the program, and provides basis for development of test specifications and procedures for all testing activities during Phase II efforts in support of the study effort.

Purpose of the development series of tests is to determine experimentally compatibility of attachment techniques with critical environments to be encountered during use as a passive thermal-control system for a spacecraft. Specific environments to which the thermal-control composite will be exposed are

1. Thermal vacuum;
2. Vibration (both sinusoidal and random);
3. Shock;
4. Acceleration;
5. Acoustical noise.

The schedule for environmental tests to be performed during Phase II of the study is given in Figure 6-2. A description of each test to be conducted follows.

6.3.1 Thermal/Vacuum Tests

Panels to which second-surface mirrors and multilayer insulation have been attached will be tested in a vacuum chamber to determine effects of vacuum and temperature on attachment techniques used.

Temperature range will be -100 to 800 degrees Fahrenheit (^{o}F.) at 10^{-4} TORR. If attachment techniques developed during Phase I effort cannot withstand the upper temperature constraint, the test will be revised to allow for testing at highest operating temperature deemed advisable for the particular attachment method.

Ascent temperature profile will not be simulated because protection afforded by the payload shroud during ascent prevents the thermal control composite from attaining high temperature which will be encountered later during spacecraft's mission. However, the pressure profile of an Atlas-Agena launch will be simulated in order to evaluate effects of rapid decompression and subsequent outgassing of the composite system.

The testing sequence, to be accomplished twice on each specimen, is

1. Lower pressure to 10^{-4} TORR in 6 minutes.
2. Reduce temperature to -100^{o}F. and hold for 2 hours.
3. Raise temperature to 800^{o}F. and hold for 4 hours.
4. Repeat the above cycle.

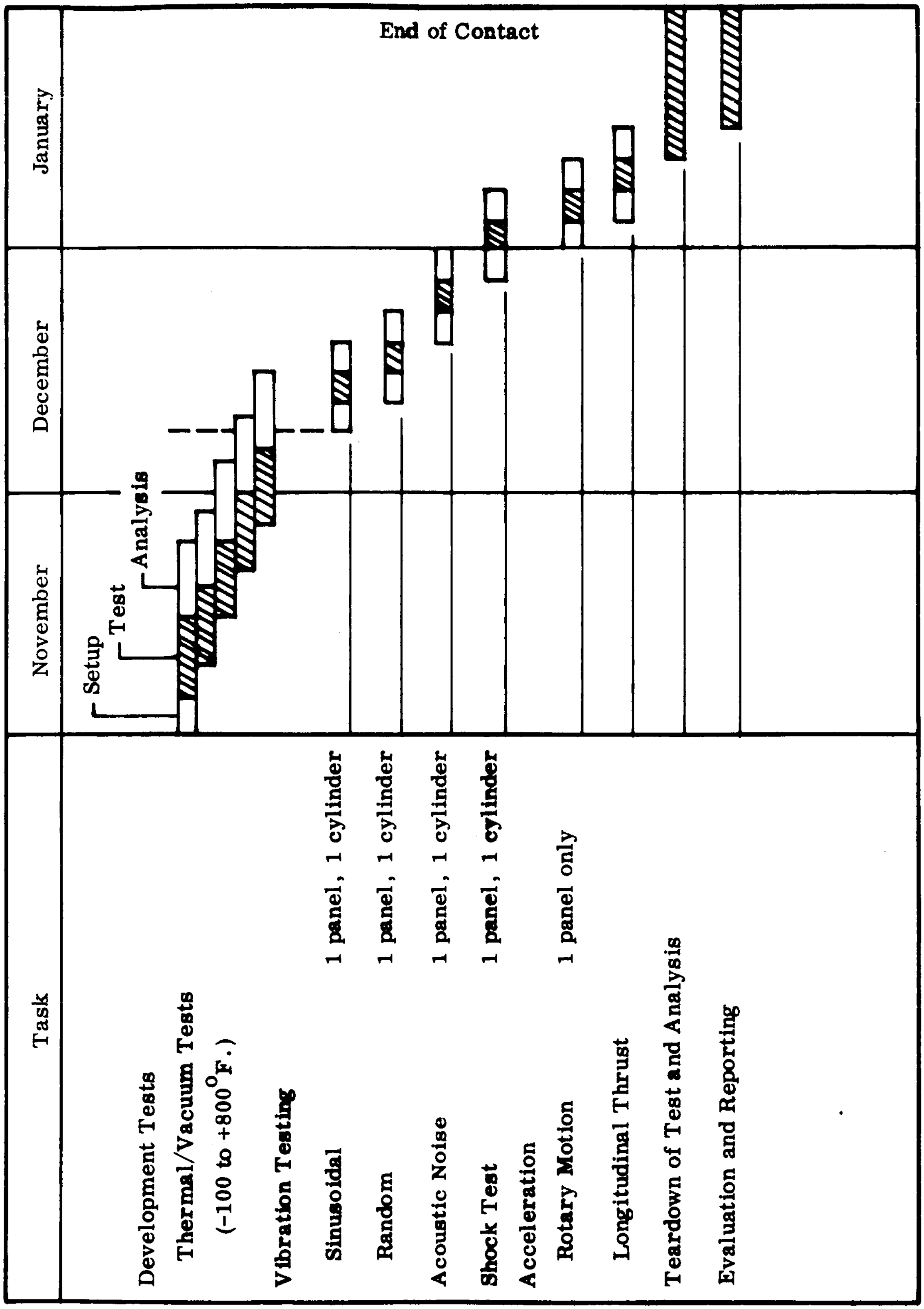


Figure 6-2. Environmental Test Schedule

6.3.2 Sinusoidal Vibration

These tests will be performed on one panel and one cylinder each. The test along the X axis only shall consist of a single, sinusoidal sweep starting at 5 cycles per second (c.p.s.) and proceed at a constant-octave sweep rate to 2,000 c.p.s. in not less than 25 minutes. A sweep rate of 3 minutes per octave will be employed. All resonant frequencies shall be noted and recorded. The vibration amplitudes shall be applied as shown in Figure 6-3. The test will be run first for boost phase and then for Agena burn phase, 2 sweeps each for cylinder and panel.

6.3.3 Random Vibration

Each test specimen will be subjected to 5 minutes of Atlas-Agena boost-phase random vibration representative of vibration level to be encountered by payload. Vibration levels to be programmed are shown in Figure 6-4 for a root-mean-square (r.m.s.) acceleration of 14.5 g's. This acceleration will be applied in one direction only, as shown in Figure 6-5. For added confidence, these tests will be repeated for each test specimen.

6.3.4 Acoustical Noise

The panel and cylinder will be subjected to random, acoustic, excitation levels shown in Figure 6-6 for a period of 5 minutes each. Excitation levels will be for launch phase only. This test is performed once for each cylinder and panel.

6.3.5 Shock

Panel and cylinder will be subjected to two 30 g shock runs for 8 milliseconds. LMSC flight data indicate that these tests will simulate shocks to be experienced during Atlas-Agena launch and the Agena ignition/burn phases. This level of testing is of sufficient magnitude to encompass transient shocks which might be encountered during ground handling operations as well.

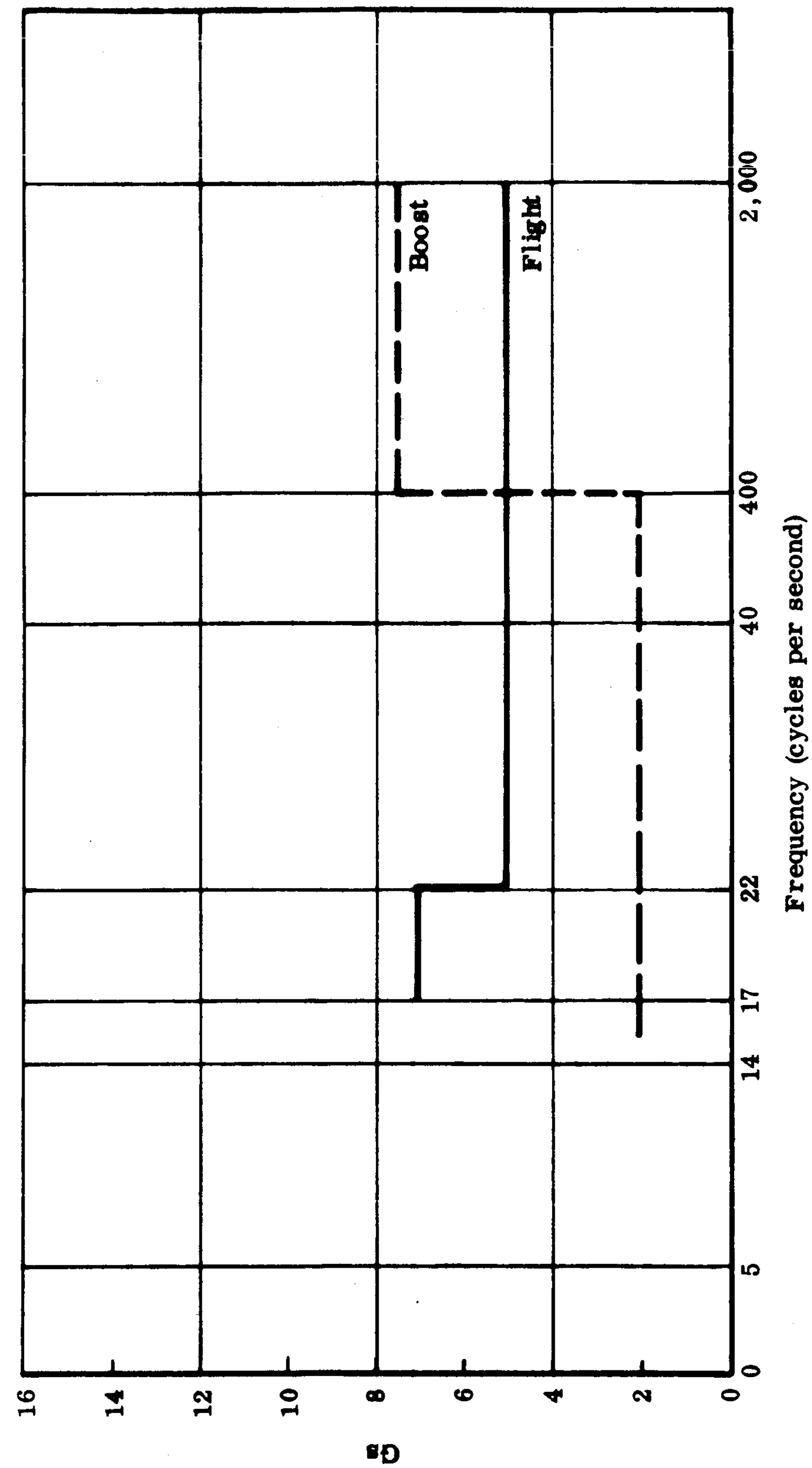


Figure 6-3. Sinusoidal Vibration During Boost and Flight Phases

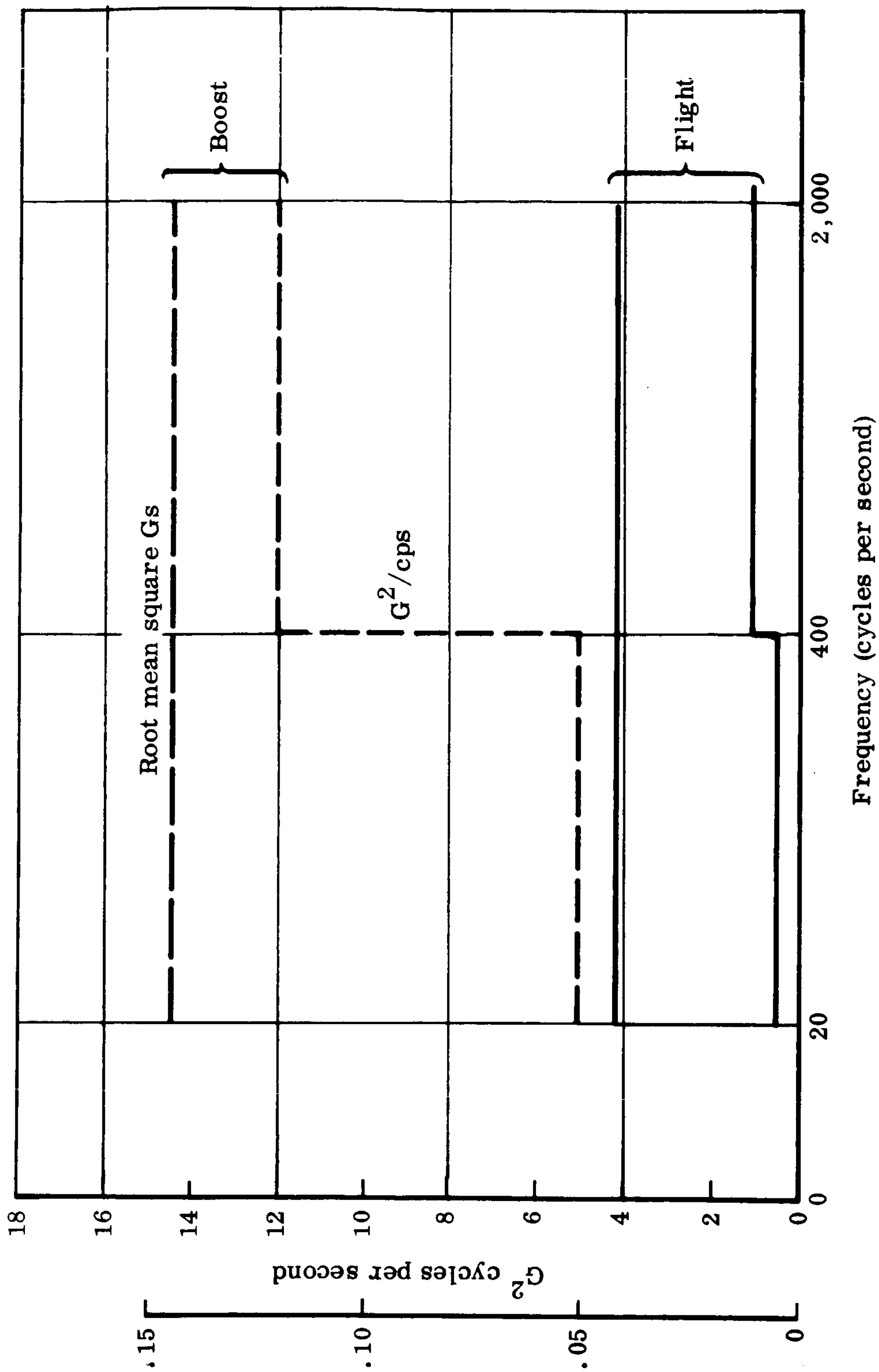
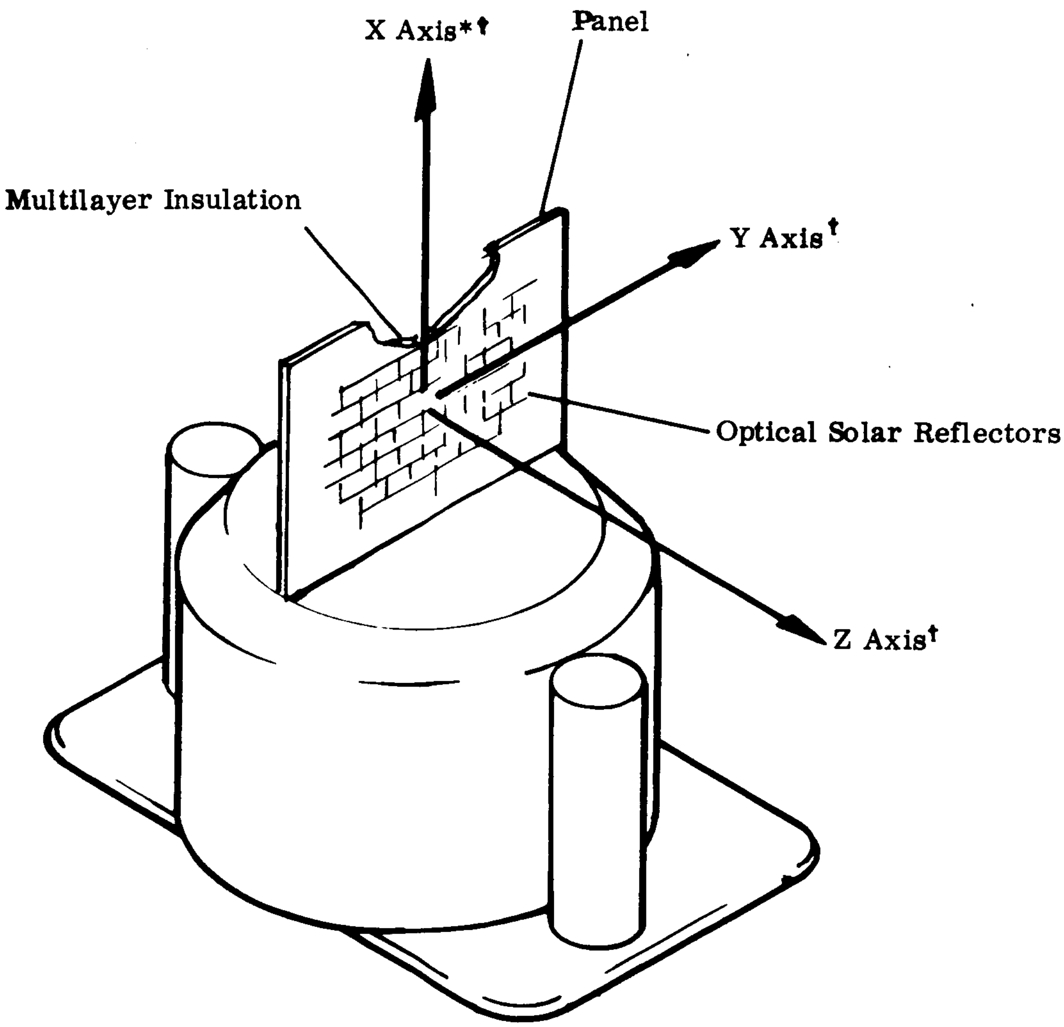


Figure 6-4. Random Vibration During Boost Phase



*May be considered axis of booster-thrust excitation
†Note axis convention for future reference

Figure 6-5. Vibration Alignment

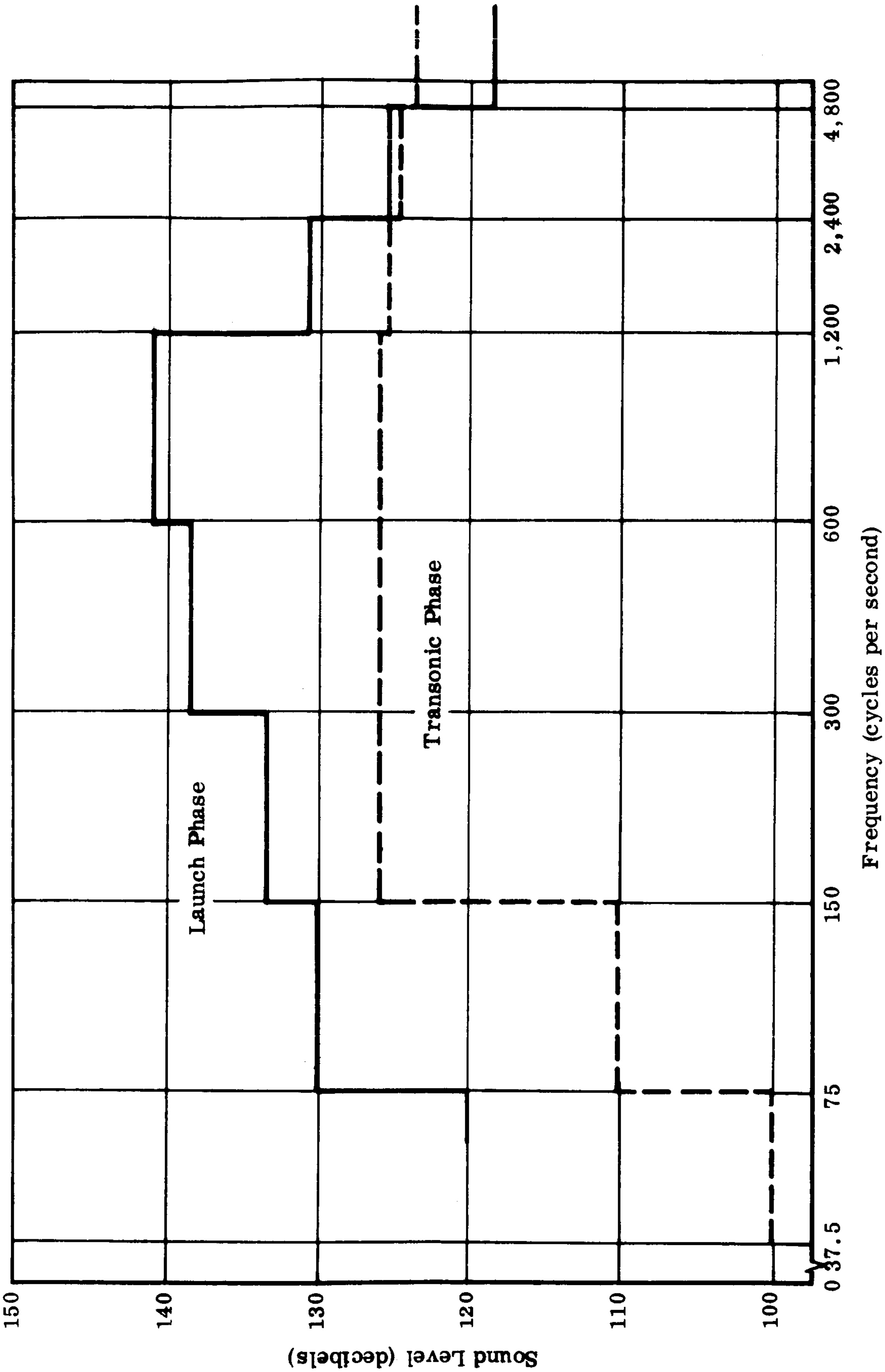


Figure 6-6. Acoustic-Noise Level

6.3.6 Acceleration (Rotary Motion)

Rotary-motion tests on the panel will be conducted in a centrifuge providing 60 revolutions per minute (r.p.m.) at a 15-foot radius (produces 1.84 g's normal to the panel Z axis). The test will be performed for a relatively long period of time, 2 hours, to demonstrate the ability of the attachment technique to withstand spin modes anticipated during spacecraft operation.

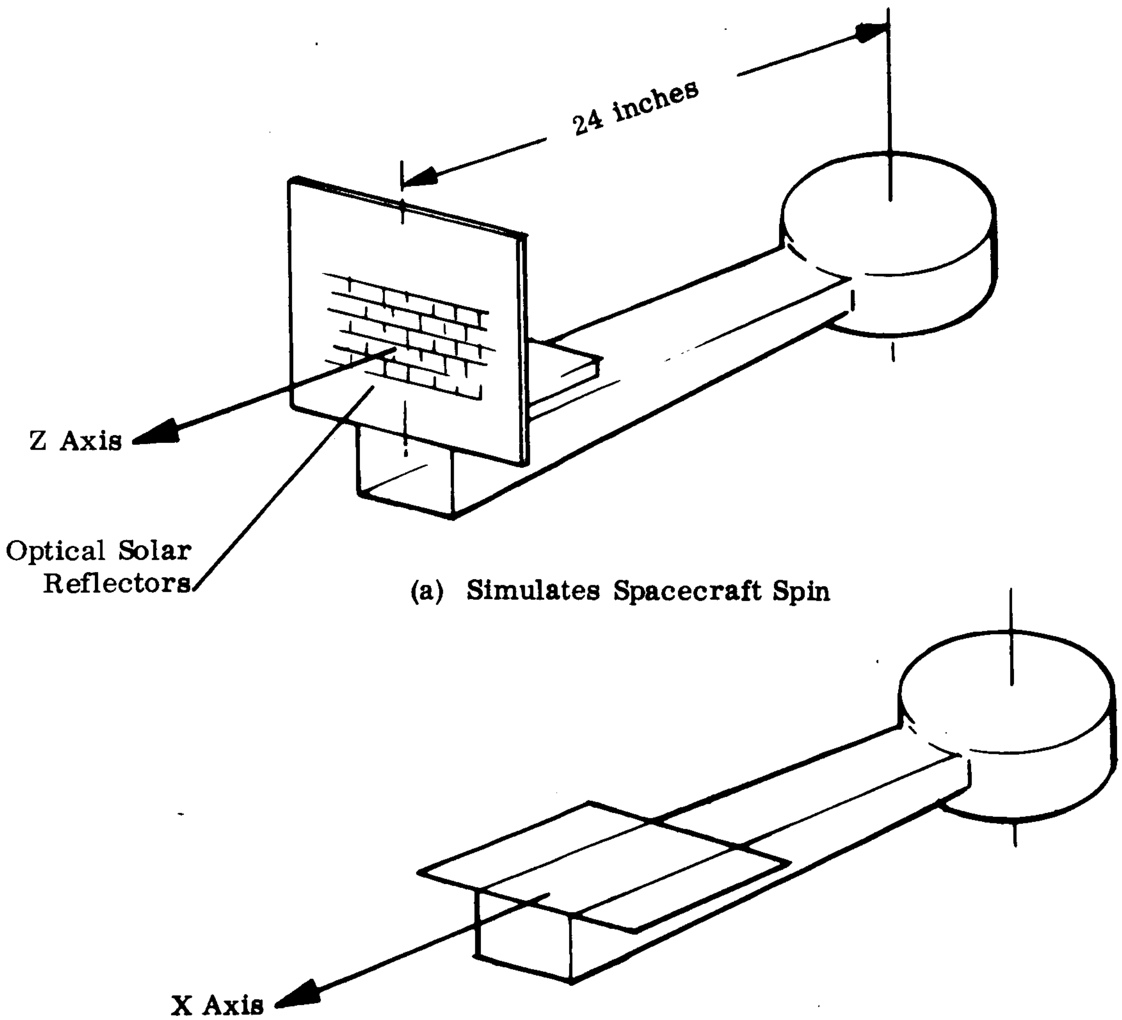
Orientation of panel will be changed 90^0 to simulate longitudinal loading experienced during boost phase. This test will last for 4 minutes and will be run only once. The centrifuge will be rotated to produce a 15 g level along the X axis. Figure 6-7 shows the positioning of the panel on the test apparatus.

6.3.7 Test Documentation Requirements

To correlate laboratory test results with future flight data, care will be given to recording of all significant environmental-condition data as well as failure-mode recording and analysis if a failure occurs during tests.

Test data will be summarized according to a plan wherein one-to-one comparisons may be made at any time during developmental test periods. Laboratory test result reports will be prepared and all data will be summarized and evaluated with regard to potential engineering applications. Flash reports, to be issued within 48 hours after completion of a specific test, will be forwarded to the project leader for his review. These reports will include all observations made during installation of the thermal-control composite into the test fixture, and will rate all problem areas noted during performance of the environmental test.

Sketches, or photographs, of test setup and fixtures will record actual configurations used during test. These will be included in reports submitted to the contracting agency, NASA Ames Research Center.



(a) Simulates Spacecraft Spin

(b) Simulates Boost Thrust

Figure 6-7. Acceleration-Test Configuration

6.4 PHASE II TEST POLICY

Generally, requirements for developmental testing are derived from the RFP. Testing will be accomplished on insulated panels and cylinders representative of the type which will be used on advanced spacecraft designs. The intent is to obtain initial performance data under environmental conditions other than ambient. It should be pointed out that these developmental tests conducted under selected environmental conditions, are the "first cut" at qualifying attachment techniques. Actual qualification of hardware would entail use of flight hardware positioned in the exact configuration to be used during flight. LMSC recognizes that development tests to be accomplished during Phase II of the contract will not qualify attachment techniques for any application other than those being tested. However, successful completion of the developmental series of tests will provide assurance that the basic attachment techniques are sound. Slight modification to basic concepts may be desirable for each intended application.

Development testing obviously is kept to a minimum wherever possible because of cost and schedule impact. However, where new equipment design is involved, it is absolutely essential to screen out those questionable items not satisfied by even the most thorough analysis. These tests, then, will satisfy the requirement of the contract to investigate and evaluate experimentally the attachment's ability to withstand shock, vibration, and torques encountered during launch and flight. Thermal/vacuum tests will simulate a temperature and pressure profile which is typical for the payload area of an Atlas-Agena vehicle during flight. Additionally, the composite system will be exposed to temperature excursions which are representative of temperatures predicted for external thermal-control surfaces for a solar-probe spacecraft.

6.5 TEST MANAGEMENT

The testing program outlined herein will be under overall direction of the project leader, L. A. McKellar, while direct program supervision of all test activities will be handled by O. B. Renalds, staff engineer of LMSC's Test Engineering Department. N. H. Kordsmeier, of the Materials Engineering Group, will assist Mr. Renalds in the analysis and evaluation of test data relating to performance of composite thermal-control systems.

Preparation of test specimens will be under the direction of F. J. Schoeneweis of LMSC's Manufacturing Research organization.

Environmental tests will be performed under the guidance of R. A. Cowan in LMSC's Development Test Laboratory at the Sunnyvale facility.

Study team members will obtain advice of LMSC specialists from thermophysics, structures, and thermodynamics groups during design of specific tests to assure environmental tests are representative simulations of launch and orbit conditions.

Appendix A

ADHESIVE CANDIDATE AND EVALUATION

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°F. for 1 hr. 4. Slowly heated to 800°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°F. for 1 hour. 4. Heated slowly to 800°F. 5. Cooled slowly to room temperature. 6. Adhesion good at 800°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°F. 4. Heated slowly to 800°F. in air; adhesion good. 5. Adhesive attacked mirror surface.

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.

Appendix A (Continued)

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. Studies in progress to determine upper and lower temperature limits for continuous service.
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.

Material and Manufacturer	Test and Evaluation
20. (Continued)	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.
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.

Material and Manufacturer	Test and Evaluation
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. 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.

Appendix A (Continued)

Material and Manufacturer	Test and Evaluation
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. 6. Tests in progress to determine system effectiveness in vacuum for extended period of time.
31. Scotchcast SK351 3 M Company St. Paul, Minn.	1. 10 g Scotchcast resin 2. Unable to apply to mirror and substrate; material requires high temperature and pressure for cure.

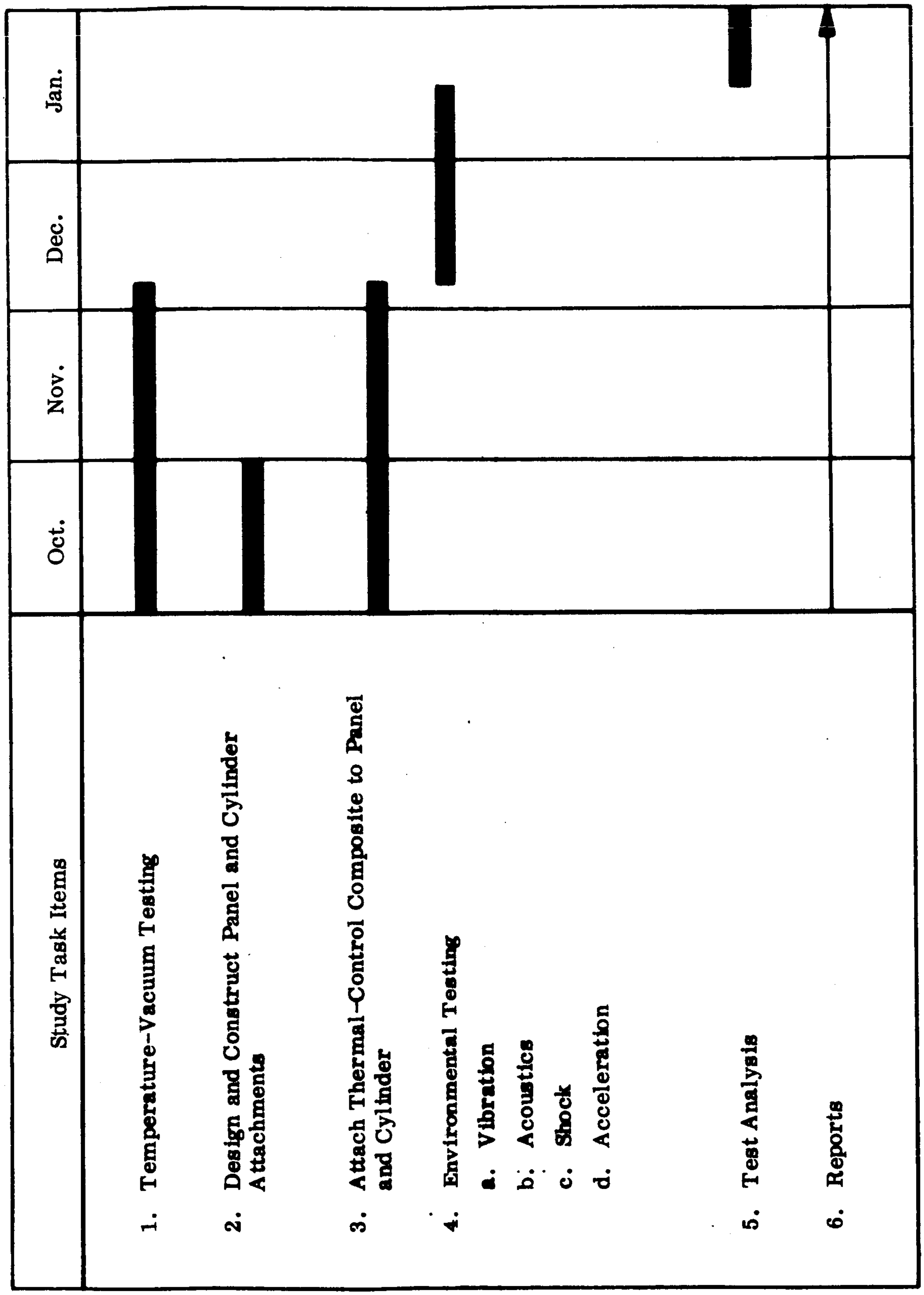


Figure 6-1. Phase II Schedule

the analysis and evaluation of test data relating to performance of composite thermal-control systems.

Preparation of test specimens will be under the direction of F. J. Schoeneweis of LMSC's Manufacturing Research organization.

Environmental tests will be performed under the guidance of R. A. Cowan in LMSC's Development Test Laboratory at the Sunnyvale facility.

Study team members will obtain advice of LMSC specialists from thermophysics, structures, and thermodynamics groups during design of specific tests to assure environmental tests are representative simulations of launch and orbit conditions.