RELSAT DAMPED EQUIPMENT PANELS - FABRICATION*

K. SCHMIDT, F. CURTIS, E. MUZIANI, L. AMORE

GENERAL ELECTRIC SPACE SYSTEMS DIVISION
VALLEY FORGE SPACE CENTER
P.O. BOX 8555, PHILADELPHIA, PA 19101

ABSTRACT

This paper discusses the material considerations and fabrication methods used in the GE RELSAT program and describes the technology needed to produce viscoelastically damped spacecraft equipment panels. Tests of the panels presented elsewhere in these proceedings indicate the damping is predictable and highly effective in reducing the vibroacoustic environment of electronic packages. The materials technology described herein builds on more than 15 years of GE experience in damping spacecraft electronic packages and other devices using a SMRD 100 viscoelastic epoxy. Material requirements are driven by prelaunch thermal vacuum testing, launch temperature of 60 to 72 degrees F, launch vibration frequency of 50 to 500 Hertz, and the need to survive 10 years in orbit without contaminating the spacecraft. GE SMRD 100 materials were selected that satisfied these requirements and were known to maintain their excellent damping properties after 4 years in orbit. Modulus and loss factor of candidate materials are compared at the temperature of interest for frequencies from 10 to 10,000 Hertz. Standard panel fabrication methods are used except for viscoelastic material (VEM) machining which uses diamond tooling. Quality control methods needed to assure panel structural integrity and damping performance rely on X-ray and and ultrasonic techniques to evaluate bonding and resonant beam measurements to determine material properties. Alternate fabrication methods that eliminate some bonding operations are presented. Because current measurements of VEM properties have a large variation, it is recommended that improved methods be investigated. Improved property measurement should address experimental errors, relations used to derive properties from test measurement, derivation of the reference temperature used in the shift relation, and VEM formulation controls that assure uniform properties.

*This work was performed for the Air Force Flight Dynamics Laboratory under the RELSAT (Reliability for Satellite Equipment in Environmental Vibration) Contract.

INTRODUCTION

This paper presents the material considerations, basic fabrication techniques and quality control measures critical to the fabrication of damped spacecraft equipment panels. In conjunction with this paper, two others have been written, which address the design and testing of Dynamic Test Article (DTA) Panels.[1,2] The purpose of this effort, is to demonstrate the use of viscoelastic damping to reduce vibroacoustic environments for satellite equipment mounting structures in a launch environment. Research, testing and subsequent evaluation have shown that the technology and material resources are available to fabricate and implement constrained layer damping on spacecraft structures.

BACKGROUND

The formulation and application of viscoelastic materials in spacecraft has been under development at GE-SSD for over 15 years. SMRD (Spacecraft Materials Research and Development), a highly efficient damping compound developed by GE, was first flown on Landsat I Earth Observation Satellite where avionics reliability was enhanced by limiting relay panel vibrations.[3] Subsequent applications include Viking Lander, Acoustic Cannisters, Gimbals, and Camera Mounts.[4] In addition, it is used extensively on printed circuit boards, providing efficient damping and additional stiffening of the boards and/or components. Figure 1 shows a typical constrained layer damping strip installation. The board has a center strip extending from the edge to the connector and an additional strip bonded to the connector. A minimum amount of space is occupied by the strips which use unidirectional graphite epoxy constraining layers.

The constrained layer fabrication is shown in Figure 2. The constraining layers are bonded to the viscoelastic material (VEM). They are then machined to the final dimensions. Typical damping strips using SMRD 100F90 with unidirectional graphite epoxy constraining layers are shown in Figure 3 and can be made in a wide variety of shapes and sizes. Sizes range from a few inches to a few feet in length. The DSCS III spacecraft uses approximately 2000 damper strips. Most use unidirectional graphite epoxy constraining layers. The keel member shown in Figure 4 employs the use of a large damper strip to limit vibration levels so that vibration of adjacent packages stays within specified limits. This keel damper was added after acoustic tests indicated package qualification random vibration levels were being exceeded.

Currently, the concept of viscoelastic damping is being evaluated in relation to reducing vibroacoustic environments for satellite equipment mounting structures during launch. To date, testing has been conducted which has shown the damping to be highly effective in attenuating vibroacoustic response. In addition, the structural integrity of damped panels under static load, sinusoidal load and creep effects under steady state load were measured. The results of acoustic and shock tests, and the design, analysis and modal tests are presented in two other papers included in the proceedings.[1,2] This paper discusses the viscoelastic material requirements and properties, material selection, fabrication methods and quality control procedures.

RELSAT PANEL DESIGN APPROACH

The approach used in the design of the damped panel configuration is shown in Figure 5. The original panel design provided integrally machined stiffeners with riveted flange sections to support the panel components. The damped panel design uses a similar concept with a constrained layer damper added to the flange section. Although the figure indicates the same size stiffener, the damped panel designs actually used smaller stiffeners using the VEM and constraining layers to provide added stiffness. With this concept, the thermal design of the panel is unaffected. Heat is conducted through the panel structures and the VEM effect is negligable.

MATERIAL CONSIDERATIONS

Requirements

Key requirements to be considered when selecting damping materials for spacecraft applications include space compatibility, weight, strength, stiffness and high damping in the frequency and temperature range of interest. These requirements are summarized in Table 1 for the various flight phases. Prior to launch, the material is subjected to thermal cycling for an extended period of time during subassembly and spacecraft tests. In addition, a storage capability of 2 years is also required. The launch conditions are critical for the damping performance of the material which requires high damping from 60 to 72 degrees F in the 50 to 500 Hertz frequency range. High shear strength is required so that structural integrity is assured. A wide range of stiffness values are acceptable although they influence the thickness of the damping layer. During orbital flight, the VEM must not contaminate the spacecraft during its 10 year life. This is reflected in the outgassing requirements of ASTM E-595 which requires less than 1 percent mass loss and less than 0.1 percent collectable Volatile Condensible Materials under elevated temperature and vacuum conditions. By selecting the dampened panel stiffener approach, thermal conduction requirements are precluded.

Candidate Materials

The properties of candidate materials are compared in Table 2. The material density varies from .028 to .066 pounds per cubic inch which affects the weight but is not critical because of the small amount of material used. The outgassing results, however, do eliminate the AF32 (SMRD 100F90A is an acceptable material although it slightly exceeds the outgassing values).

Aging Effects

It is imperative that materials used on the spacecraft withstand the thermal vacuum conditions imposed without changing stiffness and damping properties, i.e. stability of the viscoelastic material properties is essential. In addressing this requirement, SMRD panels are post cured under vacuum for 96 hours as a stabilization process. To verify the stability of GE developed SMRD, recent events have enabled an evaluation of SMRD following four years in space. The Solar Max Attitude Control Module launched in February of 1980 and retrieved from space in April of 1984, used SMRD in its interior structure. A sample recovered from the Attitude Control Electronics (ACE) package was tested and found to have retained high damping properties after four years in space. Figure 6 compares SMRD 100F90 retrieved from space to standard SMRD 100F90 data. The individual data points shown for the SMM material were obtained from modified Oberst beam tests. The curves correspond to the original material before extended space exposure. The comparison indicates that the properties have not changed significantly. A maximum loss factor of approximately 1.0 was measured for the SMM material. This value is in close agreement with the maximum value for the corresponding curve. The data verify the stability of the SMRD material. Similar data are not available for the other materials in Table 2.

Damping and Stiffness Properties

This section addresses material characterization of VEM damping and stiffness. This information can be readily displayed on Reduced Temperature Nomograms (RTNs). Past research has shown that there is a definite correlation between many rheological materials in regard to behavioral similarities at different temperatures and frequencies. Measurements of the stiffness, E or G, and loss factor, η, as a function of frequency for various temperatures can be obtained. Using a shift parameter, α_T, and the data derived above, stiffness and loss factor information at various temperatures can be collapsed into a single curve. As a result, modulus and loss factor can then be plotted as two curves on a Reduced Temperature Nomogram.[5] This is illustrated in Figure 7. Ultimately, this nomogram can be used to determine material properties for the temperature and frequency of interest in a particular application. Figure 7 illustrates modulus and loss factor data at an average temperature of 65 degrees F, the temperature of interest, for various frequencies. Because the RTN includes the shift parameter which is material dependent, material comparisons and selections must be made using the material property curve shown on the right of Figure 7 which is independent of the temperature shift relation.

The accuracy of the material property measurements are also indicated by the individual data points in Figure 7. The temperature shift relations can be used to translate the properties from the RTN to the material properties at a specific temperature, including the curves and the original data points. The scatter in the data points provide an indication of the accuracy of the property measurements. Although the scatter appears small on the three cycle log scale, the scatter is relatively large with factors of two or more for many points. The scatter is particularly large for the loss factor.

In essence, the goal in searching for a good damping material is to find one whose high damping properties coincide with the temperature and frequency ranges of interest. In the specific case of DSCS III launch environment, the temperature and frequency ranges of prime importance for the North Panel Structure are 60 to 72 degrees F and 50 to 500 Hertz, respectively. In an attempt to attain the required stiffness and damping under these conditions, material formula variations were researched and tested. One way to evaluate the difference in damping properties between the material candidates is to compare them in relation to glass transition temperature. Modifications were made to the standard material in an attempt to shift the transition temperature, so that peak damping would occur in the desired temperature and frequency range. Figure 8 shows that SMRD material properties can be altered to meet specific requirements. Of the three materials shown in this graph, SMRD 100F90C performed ideally for the RELSAT application. Peak damping occurred for about 50 to 500 Hertz at 65 degrees F.

In addition to the GE-SSD material formulations, commercial damping materials were investigated. Two materials selected for initial evaluation were DYAD 601 and 3M ISD112. Both materials satisfy the outgassing requirements, however, at 65 degrees F the peak damping for DYAD 601 was at a frequency above the range of interest for the DSCS III panel. Measured material properties from beam tests are shown in Figure 9. In addition, ISD112 properties were also measured, Figure 10. It appeared to be too soft, and required very thin layers to be effective. It did not have the required bond strength for the stiffener aplication. UDRI 3 was also considered, but was rejected because its tacky consistency posed fabrication problems and could cause contamination of the spacecraft. The final selection of candidate materials for panel fabrication and tests were four SMRD100 materials. The material properties are compared in Figure 11. The four prime material candidates are described below:

> SMRD 100F90B is a modified 100F90 formulation which has significantly better outgassing characteristics and a temperature of peak damping closer to the ranges of interest than the original formulation. It is relatively stiff with a low density, and has been used by GE-SSD for electronic packages.
>
> SMRD 100F90C is a further modification of 100F90, formulated in an attempt to reduce the transitiion temperature so that peak damping would occur in the temperature and frequency ranges of interest.
>
> SMRD 100B50A has the damping properties which appear ideally suited for DSCS III transponder panel application. The material loss factor is high over a relatively broad frequency range and is nearly unity over the frequency range of interest. It has the same base resin system as 100F90, however it is modified by the addition of a conductive filler. The temperature of maximum damping at 100 Hertz is 63 degrees F and lies within the desired temperature range.
>
> SMRD 100B50B - This is a modification of the previous material which is stiffer. At 65 degrees F, the frequency for peak damping is shifted to about 200 Hz, and has high damping over the frequency range of interest.

The decision to use the SMRD 100 materials was based on the fact that these materials satisfy the outgassing, strength, stiffness and damping requirements established. Refer to Table 3 for material selector parameters. In addition past experience in viscoelastic damping facilitates the application of various techniques used in damped printed wire boards to those for the damped spacecraft equipment panels.

DAMPED EQUIPMENT PANEL FABRICATION

VEM Fabrication Process

Both SMRD 100F90 and 100B50 are cast and cured in teflon coated aluminum molds in thicknesses ranging from 0.1" to 0.25". The sheets are stabilized and outgassed under vacuum at 135 degrees C for 96 hours; see Figures 12 and 13. The SMRD can be used as fabricated or milled to the desired dimensions. In the past, an aluminum oxide cup wheel was used to mill the SMRD. Due to obvious surface imperfections, diamond tooling replaced the former tool. Figure 14 is a photograph of a diamond compax end mill used primarily for milling smaller sections of VEM. The diamond flycutter shown in Figure 15 mills approximately a two inch wide strip per pass as compared to 1/2 inch strip produced with the end mill. This tool is used in larger applications.

Surface Preparation

Once the materials are machined to size, the SMRD can be bonded to constraining layers such as aluminum and graphite/epoxy laminates. To obtain optimum bond strength, an effective method of surface preparation is employed. The SMRD and constraining layers are abraded using 100 grit Aluminum Oxide paper. All surfaces are thoroughly cleaned with isopropyl alcohol and allowed to air dry.

Adhesive Selection/Bonding

Proper adhesive selection is essential in terms of space application. Once again, outgassing requirements, in addition to strength under rigorous environmental conditions are critical factors which must be considered. SMRD 100F90 and 100B50 can be bonded to both graphite/epoxy laminates and aluminum using epoxy adhesives such as amine or polyamine cured epoxy resin. The adhesive selected for this application was Hysol EA9309.3 commercial grade aerospace adhesive. This material offered adequate strength and rigidity in addition to being compatible with the materials under consideration.

Finally, the actual bonding of the SMRD to the constraining layers is a simple procedure. A thin film of adhesive is applied using a fingerprint roller. The materials are mated in such a manner as to preclude excessive air entrapment. The bonded sections are then cured under pressure.

Two damped panel configurations were designed and tested, one incorporated aluminum honeycomb stiffeners and the other aluminum hat section stiffeners. Figure 16 is representative of the honeycomb stiffener panel prior to completion. Aluminum honeycomb stiffeners are bonded to SMRD which will subsequently be bonded to a graphite/epoxy honeycomb constraining layer. Traveling wave tube amplifier (TWTA) mass simulators are bolted to the aluminum panel. Figure 17 shows a completed honeycomb panel prior to test. The aluminum hat section stiffener panel shown in Figures 18 and 19 consists of aluminum hat sections riveted to the aluminum base plate. A viscoelastic damping layer is bonded directly to the hat, followed by a graphite epoxy constraining layer. TWTA mass simulators are then added for dynamic testing.

The method of damping used on these panels simulates the predicted effect of constrained layer damping on the transponder panel of the DSCS III spacecraft.

FUTURE DAMPED PANEL FABRICATION

Looking into the future of constrained layer viscoelastic damping, a technique has recently been developed to eliminate the bond between the voscoelastic material, in this case SMRD, and the graphite epoxy laminate. Figure 20 compares the interfacial bonds between the VEM and laminate for adhesive and direct bond methods.

The new procedure incorporates the bonding process into the layup of the graphite epoxy laminate. As in the current process, the SMRD must be abraded and thoroughly cleaned. The graphite/epoxy prepreg is then layed up directly onto the surface of the SMRD sheet and cured under vacuum. The damper strip assemblies can then be machined to required dimensions. The benefits of this new procedure include improved bond strength, elimination of the bonding step and surface preparation of the graphite/epoxy laminate and most importantly, it virtually eliminates the possibility of interfacial voids because of high resin flow from the graphite/epoxy prepreg and the high pressure under which the composite is cured.

QUALITY CONTROL PROCEDURES

VEM Properties Confirmation

To validate the material properties of the SMRD, several tests were conducted. Hardness, using a Shore A durometer measured the materials resistance to indentation. It is a simple and effective means of monitoring changes in material stiffness. Density was determined through weight and dimensional measurement. Finally, to determine the damping properties of the viscoelastic material, the modified Oberst beam method of test was employed.[6] Specifically, the beams consisted of an aluminum layer sandwiched between two pieces of viscoelastic material. A series of beams were then mounted to a shaker and excited using base excitation. Damping properties of the materials under consideration, were determined over a wide range of frequencies and temperatures.

Structural Assessment

In addition to material property confirmation, non-destructive testing to determine structural integrity is critical. Delamination between the constraining layers or panel and the damping medium could cause a significant reduction in damping efficiency. As a result, it is important that non-destructive inspection techniques be employed to insure structural integrity. Three methods of test suggested are Ultrasonic Pulsed Echo techniques, Ultrasonic Impedance Plane Analysis and Real Time Radiographic Examination.

Ultrasonic and Contact Pulse Echo operates on the principle of pulsed ultrasonic waves. The waves are monitored as they interact with the material being inspected. A pulse ultrasonic beam is introduced into the part and the returning echos are monitored. This test method gives information regarding the type, size, location and depth of the defect. Figure 21 illustrates the difference between a bonded area and one with a known void. The large peak present on the photograph on the left is the back reflection of the aluminum hat section. This peak diminishes when a voided area is contacted. Since this signal will not transmit through air, the last material the signal detects is the adhesive coated SMRD, signifying a void or debond as indicated in the photograph on the right.

Ultrasonic Impedance Plane Analysis using a Bonda Scope, is an alternate method of Non-Destructive Evaluation. The acoustical impedance plane method uses a small probe to generate a standing wave across the material thickness. The test frequency is selected to vibrate the laminate in such a fashion that the response to bondline and anomaly size is enhanced. The standing wave, which contains acoustical material information, affects the impedance value at the material surface. This value is then transformed through the probe's acoustic impedance into its electrical impedence. It is this electrical impedence which is subsequently processed for display on the acoustic impedance plane. Figure 22 illustrates a typical setup, where a bonded area appears as a dot located at the center of the grid and a non-bonded area shows up as a dot in one of the four quadrants depending upon depth and location of the anomaly.

Radiographic Examination or X-Ray, is another technique used to evaluate structural integrity. X-Rays are directed through the part being inspected and monitored with a screen or film sensitive to X-rays. Figure 23 shows an X-ray evaluation of a debonded area. Since a void will absorb fewer X-rays than a non-voided area, a dark spot will appear. Radiography can be performed through the thickness to detect anomalies or tangentially to detect delaminations.

CONCLUSIONS

As a result of this research and development effort, the following conclusions are made:

- The necessary technology is available to fabricate damped panel structures.
- Performance can be enhanced by altering material formulation to conform to application requirements.
- Key outgassing requirements can be satisfied.
- SMM damping material retains high damping properties after four years in space, verifying material stability.
- Standard fabrication methods can be used for all operations except VEM machining.
- Quality Control Methods are available to assure properties of the panel.
- The variation in measured VEM properties should be reduced.
- The VEM test method should be revised to reduce experimental errors.

- The VEM temperature shift relations should be improved.
- Material uniformity should be maintained within close tolerances.

REFERENCES

1. J. C. Strain, J. A. Staley, and C. V. Stahle, "Design and Experimental Verification of Damped Spacecraft Equipment Panels," Vibration Damping Workshop II, March 1986.

2. C. V. Stahle, J. A. Staley, and J. C. Strain, "Vibroacoustic and Shock Performance of Damped Spacecraft Equipment Panels," Vibration Damping Workshop II, March 1986.

3. C. V. Stahle and W. H. McCandliss, "Controlling Vibration of Viking Lander Electronic Packages," 44th Shock and Vibration Symposium, December 1973.

4. C. V. Stahle and J. M. Medaglia, "SMRD Damping Applications," SAMPE Series Volume 25, 1980, pp. 90-102.

5. D. I. G. Jones, "A Reduced-Temperature Nomogram for Characterization of Damping Material Behavior," 48th Shock and Vibration Symposium, Oct. 1977.

6. Ahid D. Nashif, "A New Method for Determining Damping Properties of Viscoelastic Materials," Shock and Vibration Bulletin No. 36, Pt. 4, 1967.

ACKNOWLEDGEMENTS

The authors of this paper gratefully appreciate the assistance of Art Rachild for his expert machining, John Haggerty for his assistance in fabrication and Paul Juneau for consultation.

Table 1. VEM Requirements for DSCS III North Panel

PRE-LAUNCH

- COMPONENT/SUBASSEMBLY THERMAL CYCLING

  TEMPERATURE: -34 TO 71°C
  VACUUM: 10^{-6} TORR
  TIME: 10 DAYS

- SPACECRAFT THERMAL CYCLING

  TEMPERATURE: -17 TO 60°C
  VACUUM: 10^{-7} TORR
  TIME: 25 DAYS

- STORAGE-COMPONENTS AS PART OF THE SATELLITE FOR 2 YEARS

LAUNCH

- TEMPERATURE (SHUTTLE BAY): 60 TO 72°F
- FREQUENCY OF HIGH DAMPING: 50 TO 500 Hz
- SHEAR STIFFNESS: 100 TO 1000 PSI
- SHEAR STRENGTH: 100 TO 10000 PSI AT 100 Hz

ORBIT

- SURVIVE ORBITAL ENVIRONMENT FOR 10 YEARS WITHOUT LOSS OF STRUCTURAL INTEGRITY OR CONTAMINATING THE SPACECRAFT
- OUTGASSING PER ASTM E-595
  - TOTAL MATERIAL LOSS: <1%
  - COLLECTIBLE VOLATILE CONDENSIBLE MATERIALS: <0.1%
- HEAT CONDUCTION: NOT A CONCERN BECAUSE OF DESIGN APPROACH

Table 2. Candidate Materials

		OUTGASSING		PROPERTIES AT PEAK DAMPING		
MATERIAL	DENSITY (LB/IN^3)	VCM %	TML %	G (PSI)	LOSS FACTOR	TEMP (°F) @ 250 Hz
ISD 112	.034	.02	.68	140	1.2	89
DYAD 601	.04	.01	.37	2.3K	1.0	35
AF 32	.0382	.46	1.97	76K	.9	84
UDRI 3	.034	.03	0.58	8K	1.0	62
SMRD 100F90A	.0285	.11	1.10	4.6K	1.0	98
SMRD 100F90B	.0296	.08	.81	2.7K	1.0	86
SMRD 100F90C	.0295	.05	.83	3.7K	1.0	71
SMRD 100B50A	.0613	.08	.57	4.1K	1.1	63
SMRD 100B50B	.0635	.10	1.17	4.2K	1.2	70
SMRD 100B50C	.0662	.05	.47	3.8K	1.0	74

Table 3. Material Selection

ISD 112
- LOW BOND STRENGTH
- FABRICATION DIFFICULTY

DYAD 601
- TEMPERATURE/FREQUENCY RANGE NOT MATCHED

AF 32
- EXCESSIVE OUTGASSING

UDRI 3
- FABRICATION DIFFICULTY (TACKY)
- CONTAMINATION

SMRD 100
- PROPERTIES CAN BE ALTERED TO MATCH APPLICATION
- FAMILIAR WITH FABRICATION METHODS
- HIGH BOND STRENGTH
- GOOD OUTGASSING REQUIREMENTS
- STABLE AFTER INITIAL VACUUM "BAKE OUT"

SMRD MATERIALS USE GE-SSD TECHNOLOGY BASE

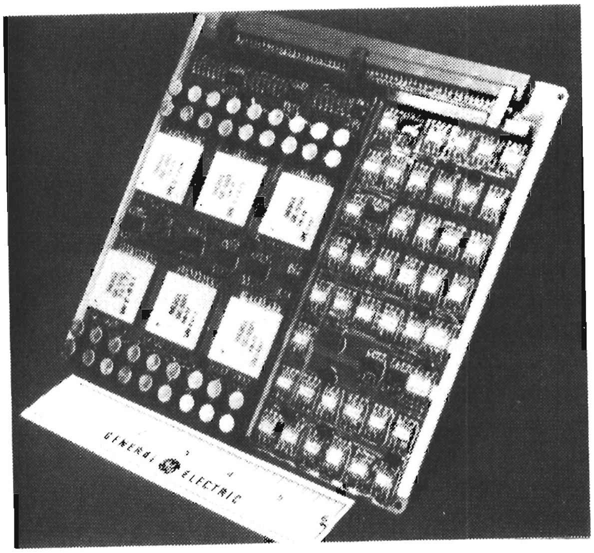


Figure 1. Typical Damped Printed Wiring Board

Figure 2. Constrained Layer Damper Fabrication

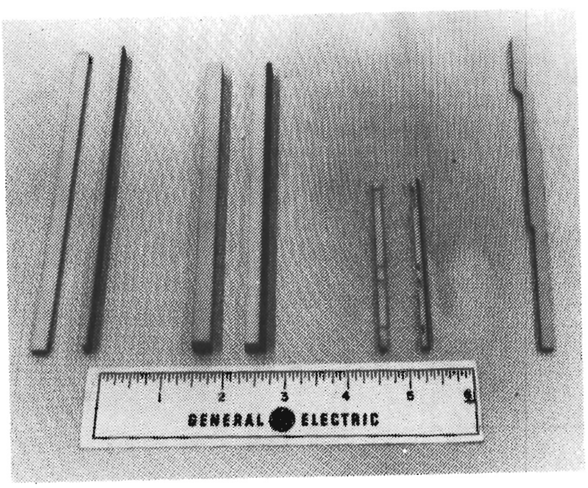


Figure 3. Typical PWB Damper Strips

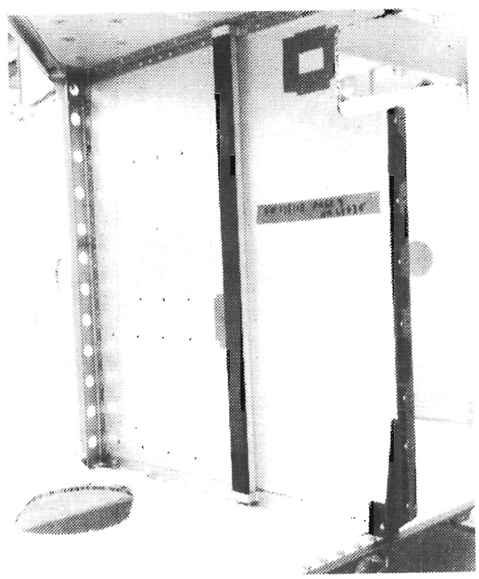


Figure 4. DSCS III Application to JLE Panel

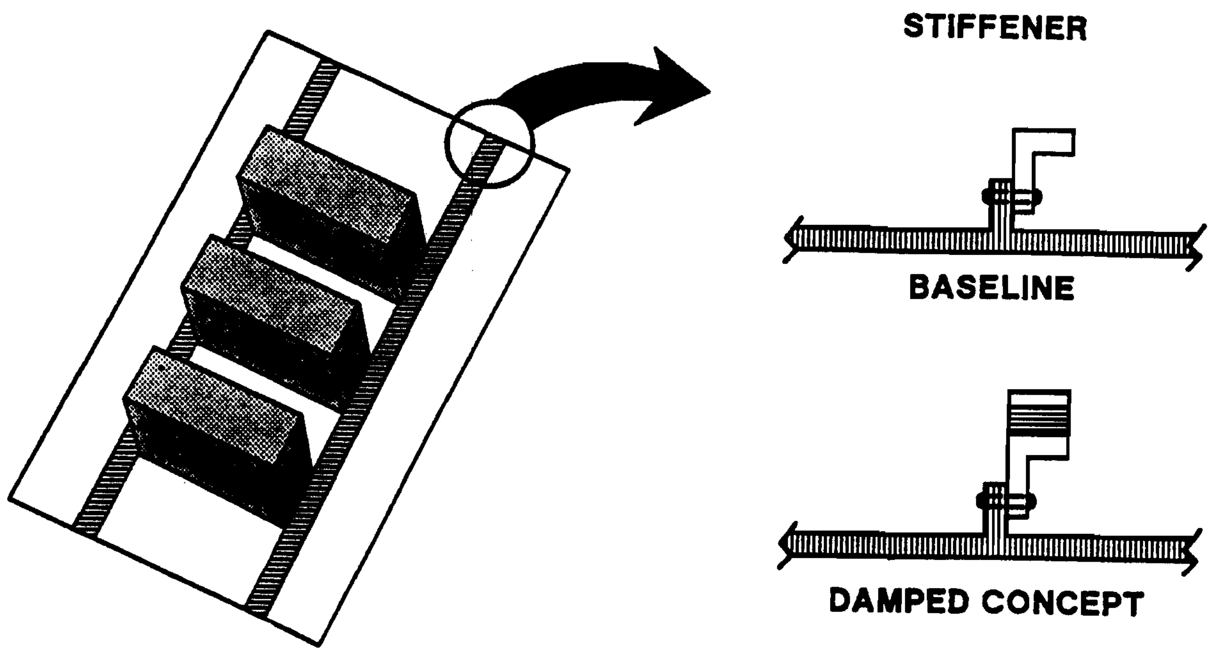


Figure 5. RELSAT Damped Panel Design Approach

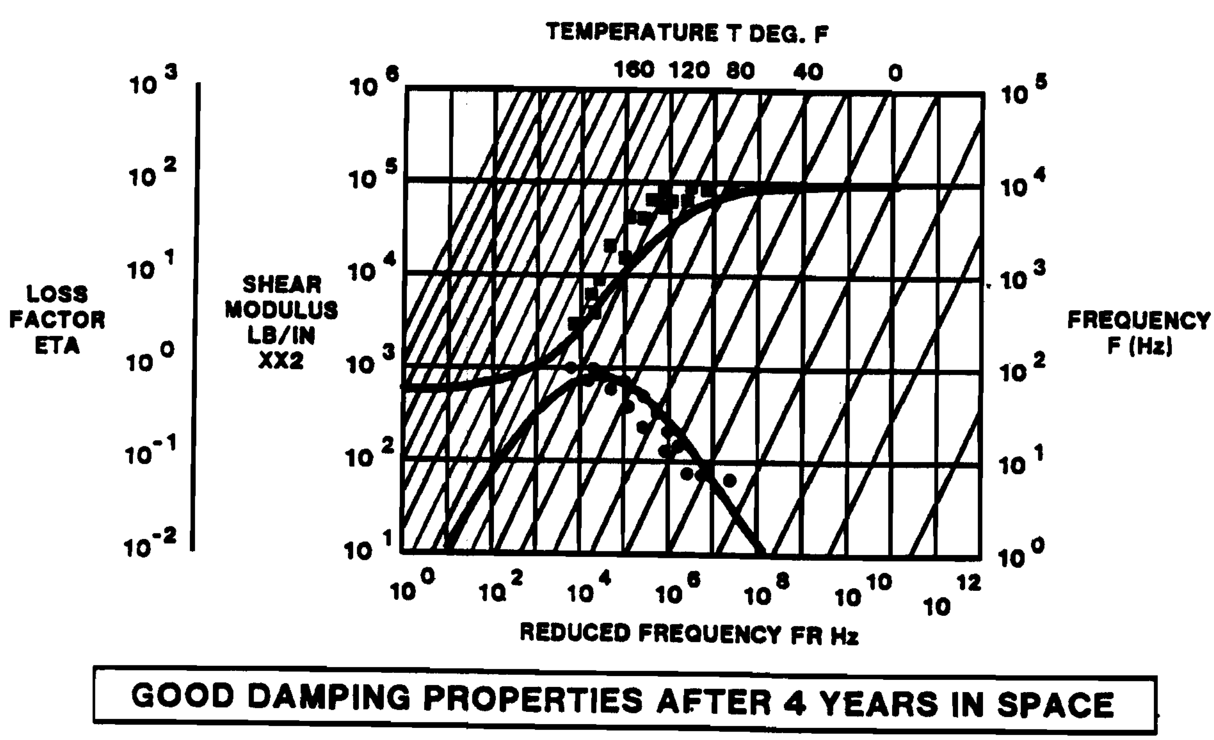
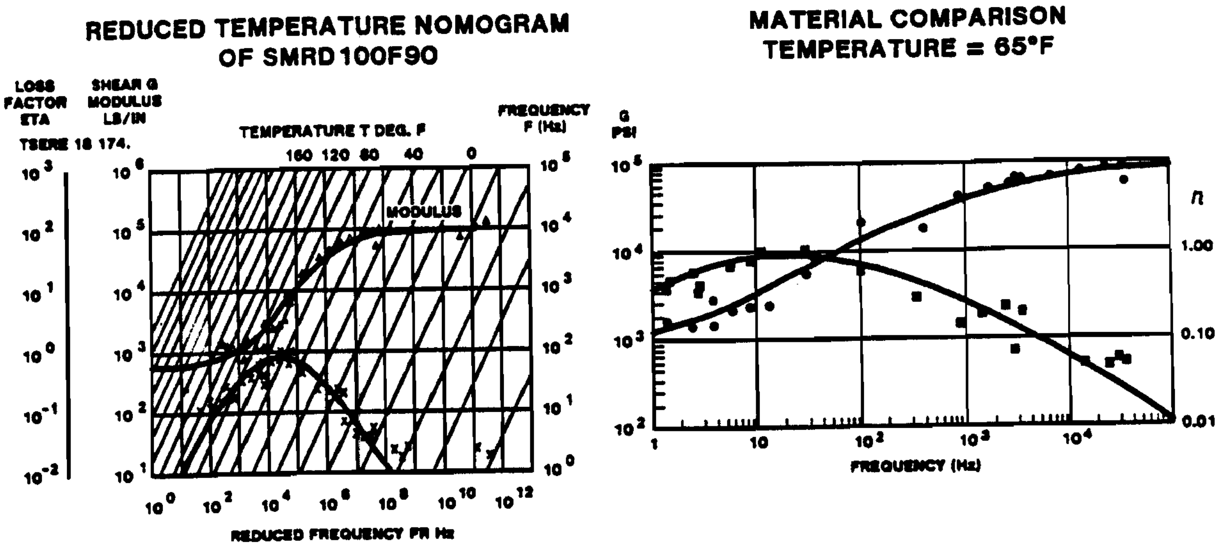
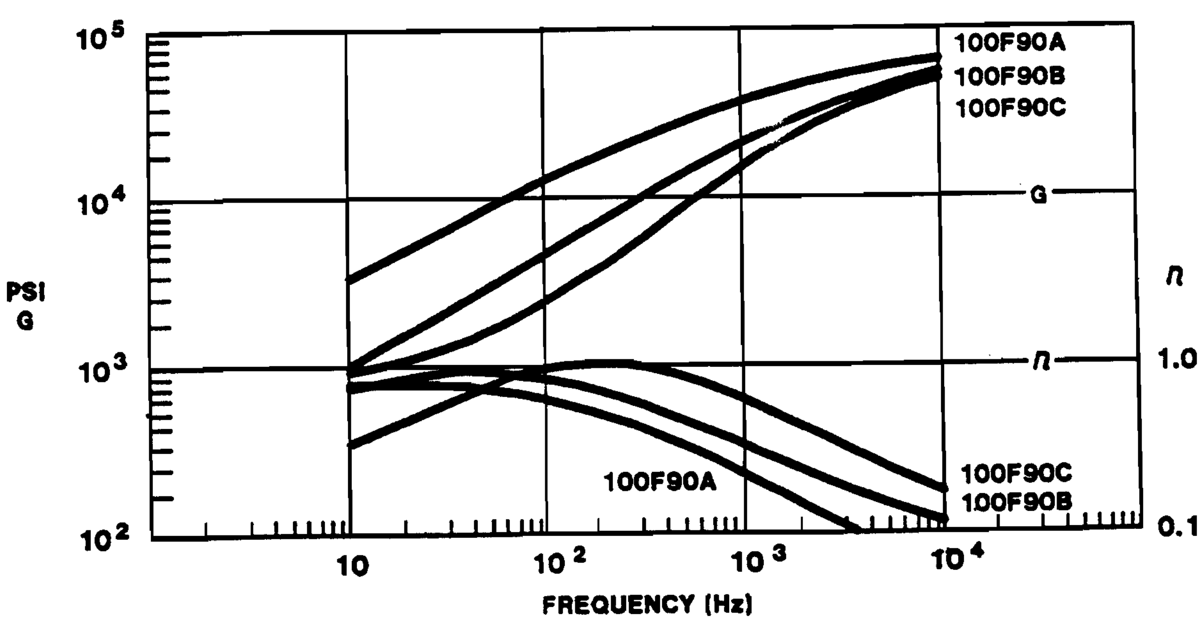


Figure 6. Comparison of SMM and Current SMRD 100F90 Properties



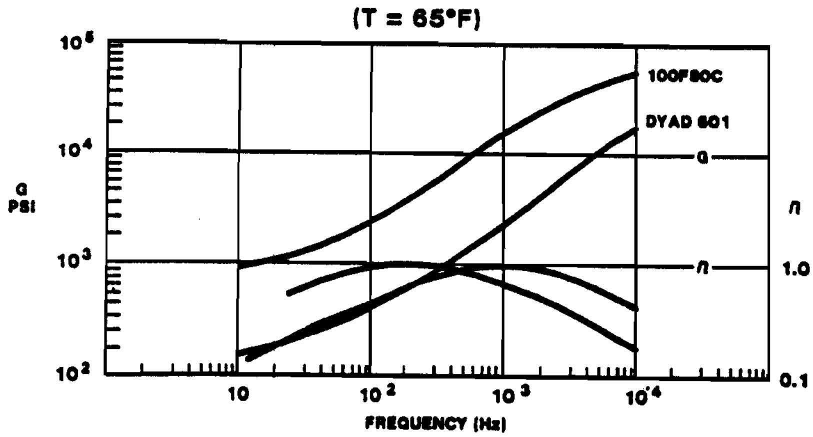
MATERIAL SELECTION MUST BE MADE USING PROPERTIES AT TEMPERATURE OF INTEREST

Figure 7. Material Characterization



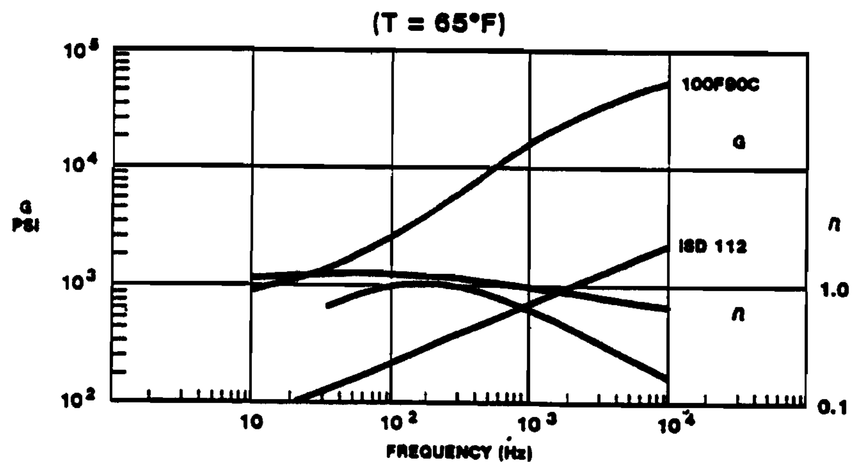
GE MATERIAL PROPERTIES CAN BE ALTERED TO MEET SPECIFIC REQUIREMENTS. SMRD 100F90C IS IDEAL FOR RELSAT.

Figure 8. Effect of SMRD 100F90 Formulation Changes



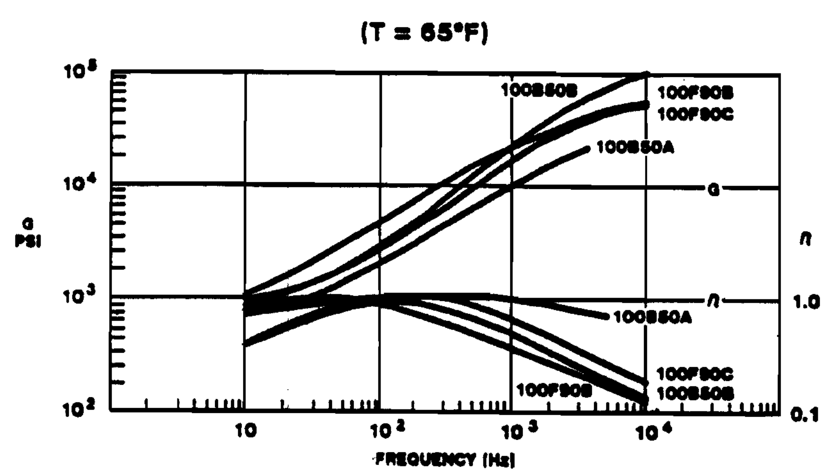
THE PEAK DAMPING FOR DYAD 601 IS ABOVE THE FREQUENCY RANGE OF INTEREST. SMRD 100F90C COMES CLOSER TO DESIRED RANGE.

Figure 9. Comparison of SMRD 100F90 and DYAD 601



ISD 112 HAS A LOW MODULUS AND, CONFORMS TO RELSAT TEMPERATURE/FREQUENCY RANGE

Figure 10. Comparison of SMRD 100F90 and ISD 112



4 SMRD MATERIALS WERE SELECTED FOR PANEL FABRICATION & TEST

Figure 11. Properties of Selected Materials at 65 Deg F

- CAST AND CURED IN FLAT SHEETS
- STABILIZED AND OUTGASSED UNDER VACUUM AT 135°C FOR 96 HOURS
- BONDED TO CONSTRAINING LAYER
- MACHINED TO FINAL DIMENSIONS
- BONDED TO STRUCTURE

Figure 12. VEM Damper Strip Fabrication Process

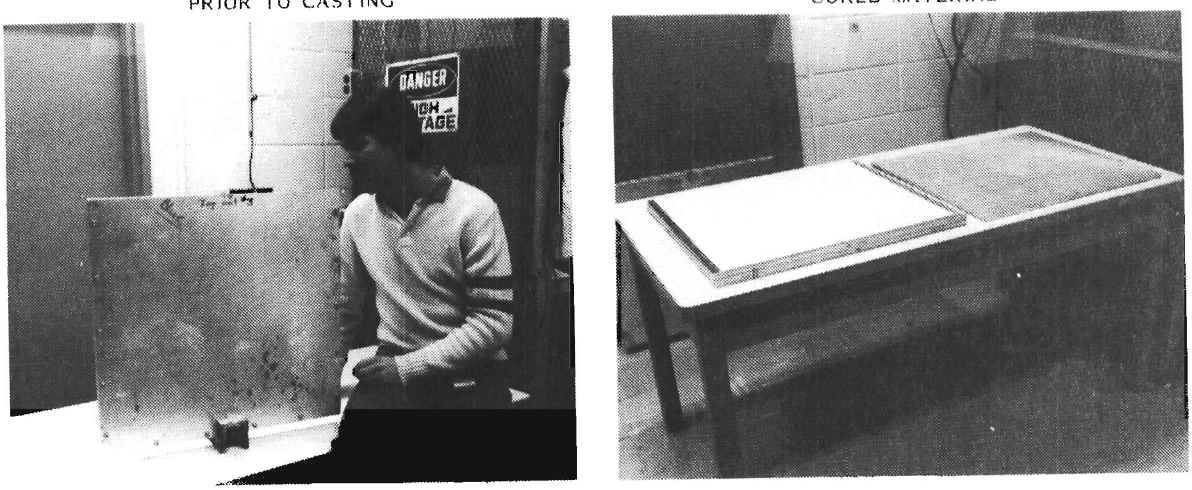


Figure 13. SMRD Fabrication

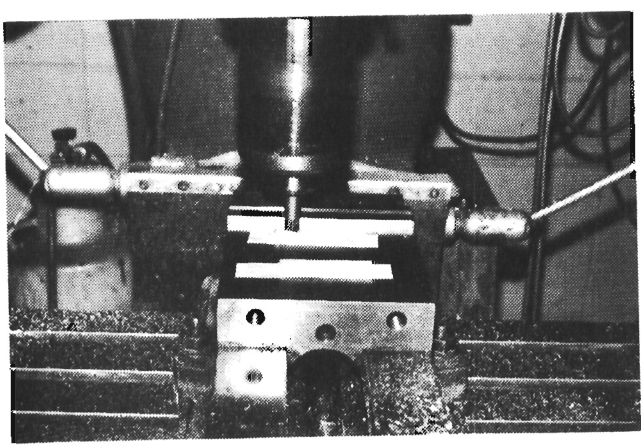


Figure 14. SMRD 100F90 Milled with a Diamond Compax End Mill

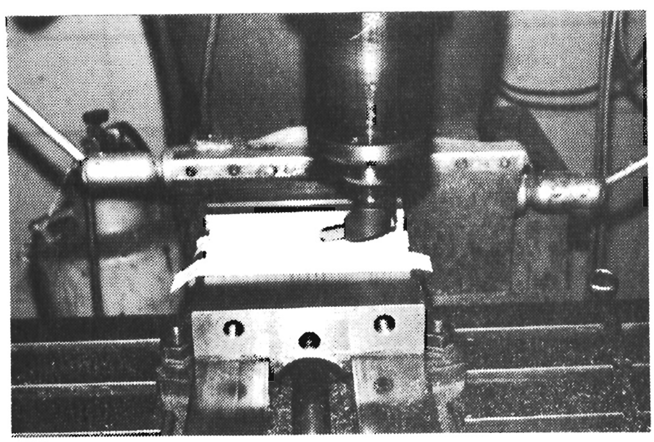


Figure 15. SMRD 100F90 Milled With a Diamond Fly Cutter

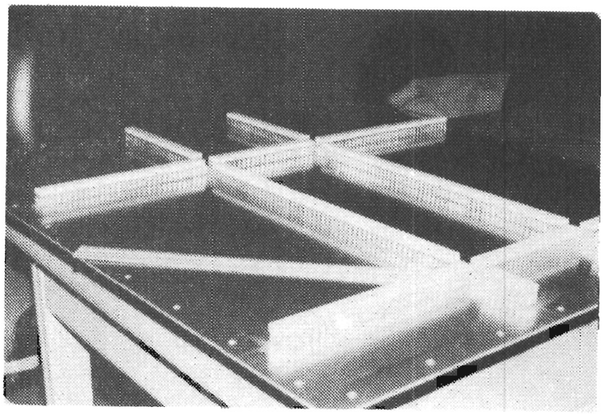


Figure 16. Honeycomb Stiffener Panel Prior to Completion

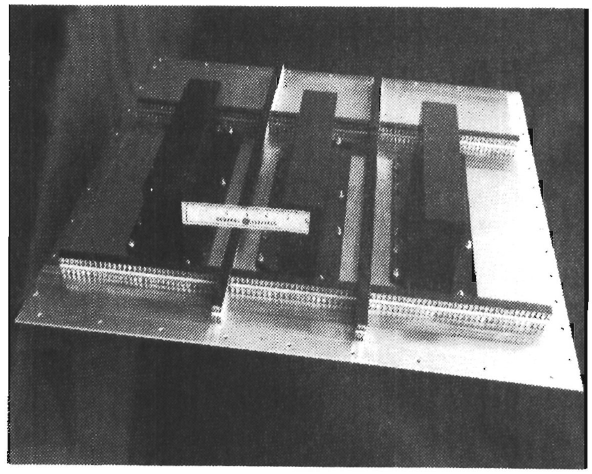


Figure 17. SMRD 100F90C Damped Honeycomb Stiffener Panel

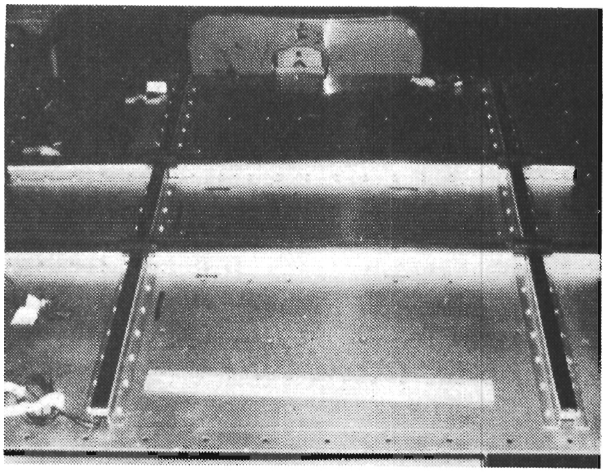


Figure 18. SMRD 100B50C Damped Hat Section Stiffener Panel

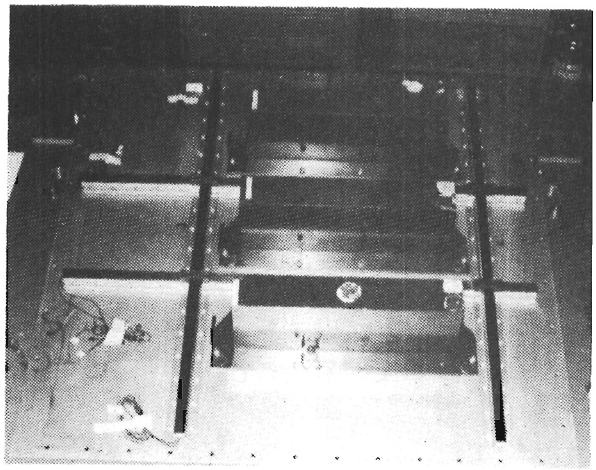


Figure 19. Completed Hat Section Stiffener Panel

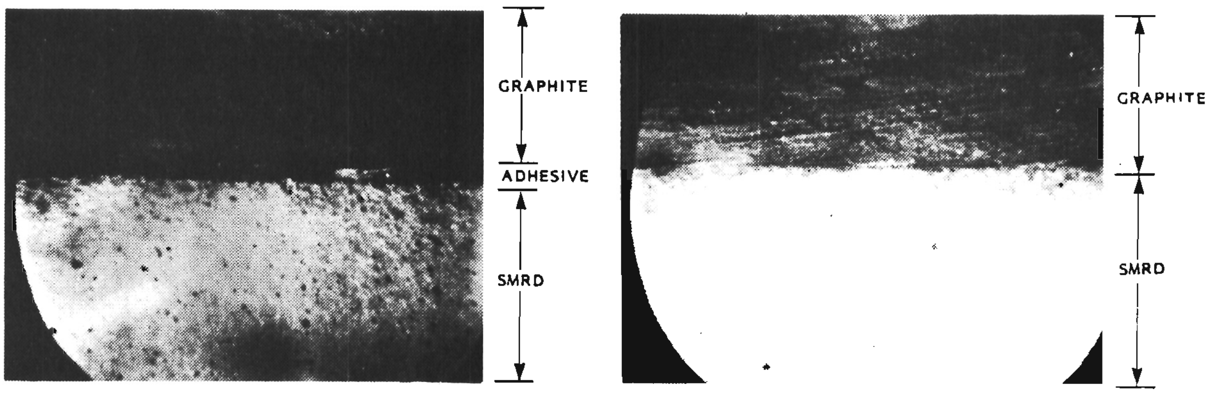


Figure 20. Direct vs Adhesive Bonding of Graphite/Epoxy Constraining Layer

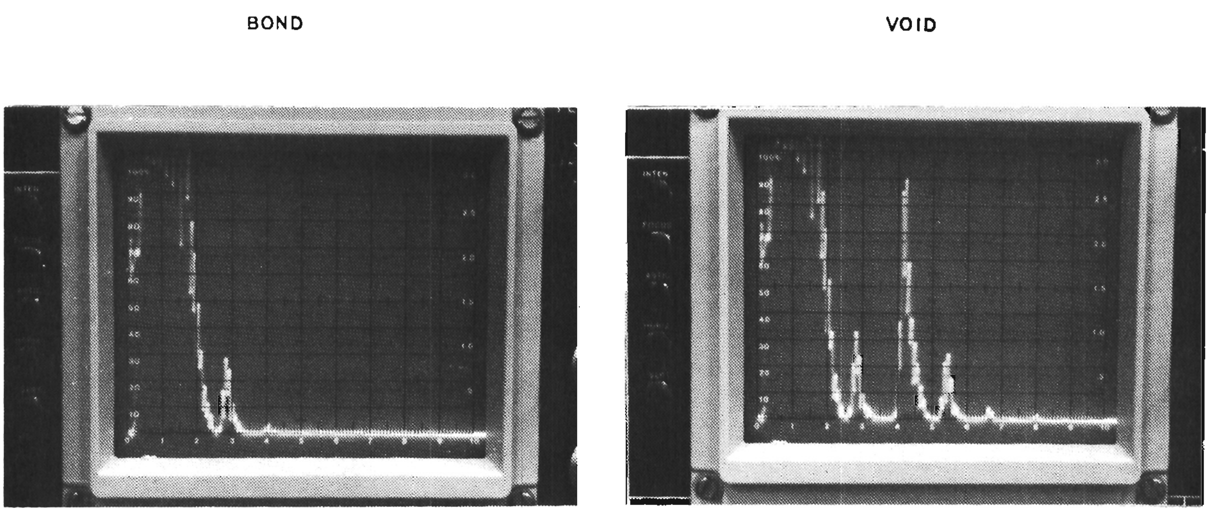


Figure 21. Pulsed Echo Ultrasonic Method for Assessing Bond

Figure 22. Ultrasonic Impedance Plane Analysis

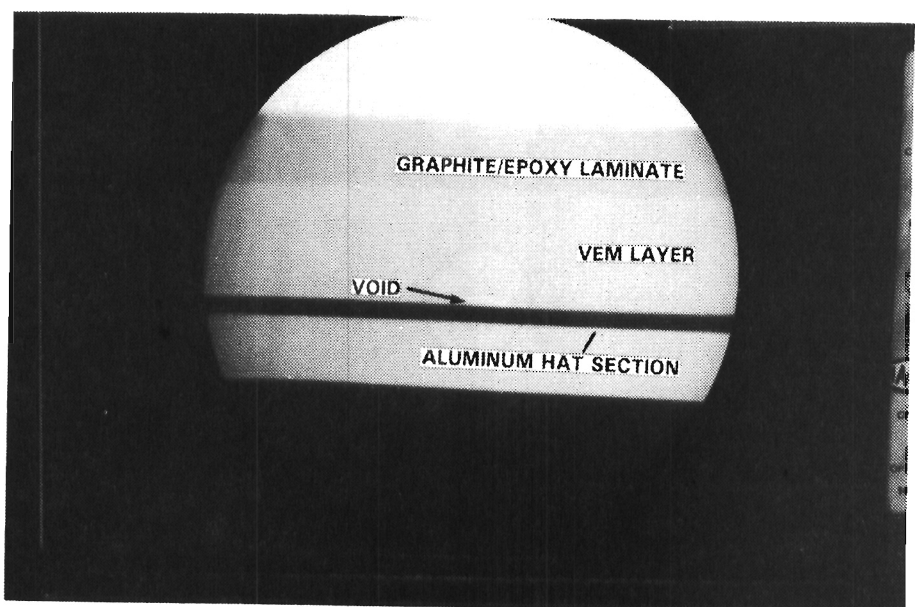


Figure 23. Bond Evaluation by Real Time X-Ray