RELSAT DAMPED SATELLITE EQUIPMENT PANELS - DYNAMIC PERFORMANCE*

by

C. V. Stahle, J. A. Staley, and J. C. Strain

General Electric Space Systems Division

ABSTRACT

This paper presents performance results for viscoelastically damped satellite equipment panel designs. Results show that launch vibroacoustic response acceleration power spectral densities at component mounting locations are reduced by up to 20 dB by damped panel designs. Corresponding derived component random vibration test specification PSDs are reduced by about 13 dB by damped panel designs. Component RMS response levels for the specifications for damped panels are predicted to be reduced by over 50 percent compared to baseline undamped panel designs based on a random response spectrum prediction method. Damped panel designs showed low hysteresis under application and removal of static loads. Test data show that viscoelastic material which had been in space for about four years maintained good damping and stiffness properties compared to materials which had not been in space. Viscoelastic damping treatments appear applicable to alignment critical structures because of low hysteresis under load application and removal and good property stability under long term space vacuum exposure. Results shown demonstrate the validity of methods used to design and fabricate viscoelastically damped satellite equipment panels.

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

1.0 INTRODUCTION

Figure 1 shows a summary of the General Electric RELSAT program objective, approach and expected payoffs. The RELSAT program is aimed at improving satellite reliability by reducing satellite equipment failures due to effects of the launch vibroacoustic environment. The specific objective is to demonstrate the use of passive damping to control vibration of panel mounted equipment during launch. The approach is to design, fabricate, and test damped panels corresponding to Bay 3 of the DSCS (Defense Satellite Communication System) III Transponder Panel. This effort involved three major tasks: 1) evaluation of candidate damping material characteristics; 2) development and implementation of design concepts based on selected viscoelastic materials (VEMS); and 3) performing vibration, acoustic, static, and shock tests to evaluate the performance of damped equipment panel design concepts. This paper presents some of the performance results from the third task. Results from the first two tasks are reported in two other papers.[1,2] The payoffs which are expected to result from development of damped panel designs for satellite equipment panels include: 1) improved stability and pointing accuracy for alignment critical items which might be sensitive to effects of onboard disturbances and maneuvers; 2) a 20 percent increase in the satellite reliability on orbit as a result of a 50 percent reduction in the component vibroacoustic environment during launch; 3) a reduction in the potentially large number of ground test failures by 50 percent; and 4) a reduction of the spacecraft system development and operating cost by an estimated $40 million for a system consisting of a total of 14 DSCS III type satellites with a constellation of four satellites on orbit at any given time.

Figure 2 shows several key points relative to the RELSAT program. The DSCS III spacecraft shown is the system selected as the basis for the demonstration program. It is an Air Force communication satellite. Four are in geosynchronous orbit at any given time to give global communication coverage. The specific test article selected for study was Bay 3 of the DSCS III Transponder (North) panel. This bay has three 10 watt Traveling Wave Tube Amplifiers (TWTAs) and several smaller components mounted on it. Bay 3 is about 2 ft by 2 ft square and weighs about 50 lb including components and structure. The baseline panel structure consists of a magnesium base plate with two stiffeners. The design requirements for the panel include interdisciplinary constraints such as the need to radiate waste heat from the TWTAs through the base panel to space. Optical Solar Reflectors (OSRs) are mounted on the space side of the panel for solar radiation reflection and survivability. The panel must also have the structural integrity to withstand the steady state and low frequency accelerations during the launch phase. The center of Figure 2 shows a typical reduced temperature nomogram[3] for a VEM which might be considered for design of a damped equipment panel for the baseline DSCS III. The nomogram shows VEM shear modulus and damping properties as a function of frequency and temperature. An important requirement for VEMS for satellite applications is that they be space compatible, i.e., have low outgassing characteristics.[4] Figure 2 also indicates that the ultimate objective of the demonstration program is to develop damped stable platforms for satellite equipment and to develop damped stable platforms for satellite equipment and to demonstrate the technology for design and manufacture (fabrication) of such platforms.

2.0 DAMPING PAYOFFS

The interest in providing damping in satellite equipment panels has resulted from a history of failures after launch of a satellite and during ground development and production testing of a satellite, its subsystems, and its components. A significant number of spacecraft anomalies have been related to the launch vibration environment.[5] Figure 3 shows flight failures or malfunctions vs days after launch. Figure 3 also shows that about 40 percent of these are related to vibration. A reduction of these failures from 40 to about 20 percent and a corresponding reduction in ground test failures is expected to result in a total savings of about $40 million for a complement of 14 DSCS III type satellites. Vibration is also a major cause of failures occurring during ground environmental tests of spacecraft, its subsystems, and its components. Figure 4 shows that during design qualification, 64 percent of failures were related to vibration.[6] Following qualification of the satellite design, 30 percent of failures in production acceptance tests were vibration related. With damped equipment panel designs similar to those developed under the GE RELSAT program, a 50 percent reduction in vibration/acoustic related ground test failures is expected.

A cost/reliability model which can be used to determine payoffs from equipment panel damping is available in a computer program known as OCTAVE (Optimized Cost of Testing for Acoustic and Vibration Environments.[7,8] This computer program showed that a significant increase in reliability and decrease in satellite system cost could be obtained if the vibroacoustic responses during launch could be reduced by 50 percent. The cost and reliability improvements were based on a statistical decision theory model which in turn used a data base of cost/failure rate information for satellite components. A model of the spacecraft system was first developed which consisted of three major elements: 1) satellite housekeeping components; 2) the satellite structure; and 3) the payload (i.e., the communication system components). Various types of cost elements were incorporated in the model including direct and probablistic cost types. Ground test options were considered which would assure that the satellite had a high reliability on orbit at optimum cost. The value of 50 percent reduction in the launch vibroacoustic environment for components was assumed due to equipment panel damping. The results showed a 20 percent improvement in reliability on orbit and a $40 million savings for a 14 spacecraft production (DSCS III type system).

The history of increasing severity of vibration environments over the past decade for spacecraft components shows a smaller portion of spacecraft components passing vibration tests. This trend of increasing vibration environment is related to the increased acoustic sound pressure levels at launch and the need for increased vibroacoustic reliability. In particular, the Space Transportation System (STS) (or Space Shuttle) exhibits an increase in sound pressure levels in the low frequency range (below 300 Hz) compared to earlier expendable launch vehicles. Vibration requirements for new spacecraft currently being developed are higher than for previous spacecraft. Figure 5 shows: 1) a component random vibration test specification for a large diameter spacecraft being developed for launch on the Shuttle; 2) a corresponding specification for a small diameter (9 ft or less) spacecraft which was developed for launch on an expendable launch vehicle; and 3) the specification for the large diameter payload reduced by a factor of two on an RMS basis (by a factor of four or 6 dB on a PSD basis). Figure 5 shows that damping could reduce component random vibration levels for large diameter Shuttle payloads to levels for smaller payloads developed for flight on expendable launch vehicles. Figure 5 also shows that the most significant random vibration environment is currently in the low frequency range (below 300 Hz) for shuttle launched payloads.

3. TEST PANELS

Damping materials were evaluated, damping materials were selected, damped panel design concepts were developed and evaluated, and baseline and damped panels corresponding to Bay 3 of the DSCS III transponder panel were designed and fabricated. Figure 6 shows a baseline panel consisting of a base plate with two stiffeners. Three mass simulated TWTAs are mounted directly to the base panel. Figure 7 shows a corresponding damped panel. This damped panel has damped honeycomb sandwich stiffeners. An aluminum core/aluminum face sandwich is bonded to the base plate to provide inherent stiffness of the panel independent of the damping treatment. The VEM is bonded to this honeycomb sandwich stiffener. An aluminum core/graphite-epoxy face sandwich is then bonded to the VEM to provide a constraining sandwich for the VEM. Damped panels were also made with hat stiffeners riveted to the base plate and with a VEM layer with a graphite-epoxy constraining layer bonded to the hat stiffener. Various tests were conducted on the baseline and damped panels. These included acoustic, sine vibration, static, creep, and pyro shock tests. Pyro shock test results are described briefly below. Results of acoustic tests are then discussed in some detail. Component random vibration test requirements are derived from the vibroacoustic tests for the baseline and damped panels. The implication for component random vibration test requirements are considered to be the primary result of the RELSAT satellite equipment panel damping demonstration effort.

4. PYRO SHOCK TESTS

Pyro shock tests were performed on the baseline and a damped panel. In separate tests, these panels were mounted in one bay of a dual bay simulator which is normally used to perform spacecraft separation shock tests for components mounted on the DSCS III transponder panel. The shock was produced by firing an explosive separation nut. In these tests, the separation nut was activated by a high pressure gas supply connected to the nut. This separation nut is used to separate the DSCS III from the IUS and from a second DSCS III spacecraft. Separation nuts are on bolts at either ends of the two longerons which form two ends of the DSCS III transponder panel. Three separation nut firings were made each for the baseline and a damped panel. Triaxial accelerometers were mounted at the shock source and two accelerometers were attached near the mounting locations of each of the TWTA masses on each of the panels tested. One of these two accelerometers was oriented normal to the test panel and the other was oriented in the in-plane direction of the panel in the direction of separation nut firing (in the direction of the longeron).

Figure 8 shows comparisons of damped and baseline shock spectra for the two accelerometers mounted near TWTA number 2 which was mounted in the middle of each panel. Results shown are envelopes for three firings, although results from the three firings for each panel showed little variation in the shock spectra. Figure 8 shows results for the out-of-plane and in-plane accelerometers. The figure shows that the shock spectra peak near 2200 Hz with maximum levels on the order of 1000 g. This is above the frequency where significant damping occurs. Damping treatments were designed primarily to reduce vibroacoustic response in the out-of-plane direction in the 50 to 500 Hz range. Damping reduced the peak shock in the out-of-plane shock spectra by about 30 percent. The out-of-plane direction is the direction in which damping was intended to be provided by the damped panel design. Figure 8 shows that the peak in the shock spectra for the in-plane direction was increased by about 30 percent for the damped panel relative to the baseline. This may be due to the addition of stiffeners for the damped panel configuration which connect the longerons to the TWTA's.

5. VIBROACOUSTIC TESTS

Acoustic tests were conducted on the baseline and seven damped panel configurations. Panels with both hat and sandwich damped stiffeners were tested. The configurations included four different viscoelastic materials. Tests were conducted at temperatures ranging from 60 to 78 degrees F. Two tests were conducted with four panels suspended in the GE acoustic test facility for each test. Tests were conducted at 139.3 and 143.8 dB overall. Instrumentation on each panel consisted of 12 out-of-plane accelerometers and two in-plane accelerometers attached at component mounting locations. Thermocouples were used to monitor temperatures of viscoelastic materials. Four microphones were used to measure and control the acoustic test environment. Figure 9 shows one-third octave band qualification sound pressure levels for small diameter and large diameter shuttle payloads.[9,10] The acoustic environment used for acoustic tests corresponded to the shape of the 9 ft payload sound pressure level curve. Test vibroacoustic levels were scaled to correspond to acoustic levels shown in Figure 9. The 9 ft diameter levels correspond to a DSCS III qualification test level.

Figure 10 shows four of the damped panels suspended in the GE acoustic test facility. Each panel was mounted to a heavy aluminum frame which was supported by a low frequency suspension system. Figure 10 shows the location of four out-of-plane accelerometers at the mounting locations for each TWTA mass. Each panel had two in-plane accelerometers. In-plane vibroacoustic responses were small compared to out-of-plane responses. For each of the panels tested, the 12 out-of-plane accelerometers were analyzed statistically to obtain a 95 percentile level. The spectral content of the data were then scaled to acoustic levels shown in Figure 9 for the 9 and 15 ft diameter shuttle payload qualification acoustic test levels. Figure 11 shows results for the 9 ft diameter payload for test data for 72 degrees F. Results are shown for the baseline and a damped panel. Results for all damped panels were very similar. Results shown in Figure 11 are for the damped panel which gave the best results for all panels tested. Other damped panel designs had similar vibroacoustic responses but were slightly higher above 500 Hz. Figure 11 shows that damping reduces response by up to 20 dB. The largest peaks for the baseline panel were reduced the most and these peaks were in the low frequency range. Damping reduced responses significantly for frequencies up to about 400 Hz. Figure 12 shows results scaled for the 15 ft diameter shuttle payload acoustic environment at launch. These results indicate that damping can provide very significant benefits for large diameter shuttle payloads.

6. RANDOM VIBRATION SPECIFICATIONS

The Random Response Spectrum (RRS) method[11] was used to determine component random vibration test requirements corresponding to the 95th percentile out-of-plane random vibration levels determined from the acoustic tests for the baseline and best damped panels. The RRS method is similar to the shock spectrum concept. The RRS is the RMS response of a single-degree-of-freedom oscillator to a random vibration input spectrum vs the oscillator resonant frequency. A Q of ten was assumed for the component. The objective was to generate a random vibration test spectrum which had an RRS similar to the RRS for the actual component random vibration environment, i.e., for the 95th percentile out-of-plane random vibration spectrum. Random vibration specificatons were generated in this manner for the baseline and damped panel component random vibration environments. Figure 13 shows the out-of-plane random vibration spectrum and corresponding test spectrum for the 9 ft diameter payload (DSCS) baseline panel qualification level. The RRS for this specification level and the the 95 percentile out-of-plane data are also shown in Figure 13. The RRS for the specification is seen to envelope that for the actual baseline panel test data. The peak value of about 30 GRMS occurs for a component natural frequency just above 100 Hz. Note that the largest magnitudes of the test data, the specification, and the RRS are in the low frequency region (below 300 Hz). Corresponding results for the damped panel are shown in Figure 14. Damping significantly reduces the low frequency test and specification random vibration spectrum levels. The largest RRS level now occurs at about 2000 Hz for both the damped panel test data and specification. The peak GRMS at this frequency, however is now only about 13 g. Figure 15 compares the specifications for the damped and baseline panels shown previously in Figures 13 and 14. The maximum specification PSD has been reduced 13 dB using damping. The maximum GRMS has been reduced by 64 percent for the damped panel. Corresponding results for the 15 ft diameter shuttle payload are shown in Figure 16. Here the damped panel PSD is seen to be reduced by 14 dB relative to the baseline panel and the peak GRMS is reduced by 53 percent due to damping. This figure shows that major benefits from damping can be expected for large diameter payloads on the shuttle. Component random vibration test responses might be reduced from about 40 to about 20 GRMS by the addition of damping to equipment panels.

7. DAMPED PANEL HYSTERESIS AND LONG TERM VEM STABILITY

A static load test was conducted on a panel with damped hat stiffeners. A load was applied to each TWTA normal to the plane of the panel. The panel was loaded statically to an 11 g (550 lb) load in increments of approximately 1 g. The load was then removed in approximately 1 g increments. Deflections of the panel and strains in hat stiffeners were measured. Figure 17 shows a plot of strain in a hat stiffener vs total panel load for both the loading and unloading cycle. Figure 17 shows that very low hysteresis occurred. This result indicates that for the damped panel designs developed under RELSAT, viscoelastic treatments may be feasible for application to platforms requiring high alignment and pointing stability without introducing hysteresis during loading and unloading events such as launch, orbit transfer, deployments, and separations.

In April 1984, The Modular Attitude Control System (MACS) module was retrieved form the Solar Max Mission (SMM) spacecraft on a Shuttle repair mission. The SMM spacecraft was launced in January of 1980. The Attitude Control Electronics (ACE) component on the MACS module used viscoelastic materials extensively for damping treatments. A piece of this material which had been in orbit for over four years was tested to determine its material properties after four years exposure to space environment. Figure 18 shows the measured loss factor and shear modulus (discrete data points) compared to properties of similar non-flight material (curves). The material retrieved from space is seen to have excellent damping properties (circles) which are nearly identical to the non-flight material. The shear modulus (squares) for the material which was in orbit is slightly stiffer than the similar material which was not flown. These results indicate that damping materials of the type used in the GE RELSAT damped panel designs will retain their viscoelastic characteristics for long periods of time when in orbit and could be quite useful for orbital damping applications.

8. SUMMARY AND CONCLUSIONS

The primary objective of the GE RELSAT program was to develop and demonstrate damped panel designs which would reduce the vibroacoustic response. An initial goal was to reduce the RMS response by 50 percent (6 dB). A reduction of this magnitude was estimated to result in a cost savings of $14 million for 14 spacecraft system (DSCS type). The most significant Shuttle vibroacoustic environments are in the low frequency range. The largest deflections and stresses of components are expected here. Pyro shock tests showed attenuation of out-of-plane shock spectra due to damping but an increase was seen in the in-plane shock spectra for damped panels. Vibroacoustic responses were reduced up to 20 dB for power spectral densities in the 50 to 300 Hz range. Corresponding component random vibration specificaiton levels were reduced about 13 dB. The expected component RMS acceleration responses to derived component random vibration specifications were reduced by 50 to 60 percent by damped panel designs. Low hysteresis in static load deflection tests indicates that damping may be applicable to alignment critical structures. Data recently obtained on viscoelastic material which had been in space for four years showed that long term space exposure had little or no effect on the material damping and stiffness properties. Materials of this type appear applicable to orbital damped panel designs for alignment critical structures.

9. ACKNOWLDEGEMENTS

The work for design, development, and testing of damped RELSAT satellite equipment panels was performed under AFWAL contract F33615-82-C-3223. Technical monitors are James Eichenlaub and Lynn Rogers who provided valuable guidance and assistance. Testing and test data reduction were performed by the General Electric Space Systems Division vibration and acoustic laboratory personnel. Harold Gongloff performed statistical analyses of vibroacoustic and shock spectra data and derived component random vibration test specifications using the Random Response Spectrum method.

10. 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. K. A. Schmidt, F. P. Curtis, E. F. Muziani, and L. Amore, "Fabrication of Damped Spacecraft Equipment Panels," Vibration Damping Workshop II, March 1986.

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

4. R. Moss, "Using the Outgassing Test to Screen Materials for Contamination Potential," SAMPE Journal, March/April 1984.

5. A. R. Timmins and R. E. Heuser, "A Study of First Day Space Malfunctions," NASA TND-6474, September 1971.

6. R. B. Laube, "Methods to Assess the Success of Test Programs," October 1982 Aerospace Testing Seminar.

7. C. V. Stahle, H. R. Gongloff, J. P. Young, and W. B. Keegan, "Shuttle Payload Minimum Cost Vibroacoustic Tests," Proc. 1977 Annual Rel. and Maint. Symp.

8. C. V. Stahle, "Cost Effectiveness of Spacecraft Vibration Qualification Testing," Proc. of Inst. of Environmental Sci., 20th Annual Meeting, May 1974.

9. "Acoustic Requirements for DoD Shuttle Payloads Launched from KSC," Doc. No. DS-YV-0093, Rev. 1.

10. C. S. Tanner, "Acoustic Environments for DoD Payloads on the Shuttle," Proc. of the Shuttle Payload Dynamic Environments and Loads Predictions Workshop, JPL D-1347, 1984.

11. C. V. Stahle and H. R. Gongloff, "Development of Component Random Vibration Requirements Considering Response Spectra," The Shock and Vibration Bulletin, August 1976.

(RELIABILITY FOR SATELLITE EQUIPMENT IN ENVIRONMENTAL VIBRATION)

OBJECTIVE

- GENERICALLY DEMONSTRATE PASSIVE DAMPING CONTROL OF PANEL MOUNTED COMPONENT VIBRATION

APPROACH

- DESIGN, FABRICATE AND TEST DAMPED DSCS-III TRANSPONDER PANEL
  - EVALUATE MATERIAL PROPERTIES
  - DEVELOP AND IMPLEMENT DESIGN CONCEPTS
  - PERFORM VIBRATION, ACOUSTIC, SHOCK AND STATIC TESTS

PAYOFFS

- STABLE PLATFORM WITH HIGH POINTING ACCURACY FOR MANEUVERS AND ON-BOARD DISTURBANCES
- 20 PERCENT INCREASE IN RELIABILITY THROUGH 50 PERCENT REDUCTION IN VIBRATION ENVIRONMENT
- REDUCE LARGE NUMBER OF TEST FAILURES BY 50 PERCENT
- REDUCE SPACE SYSTEM DEVELOPMENT/OPERATING COST BY $40M

Figure 1. RELSAT Program

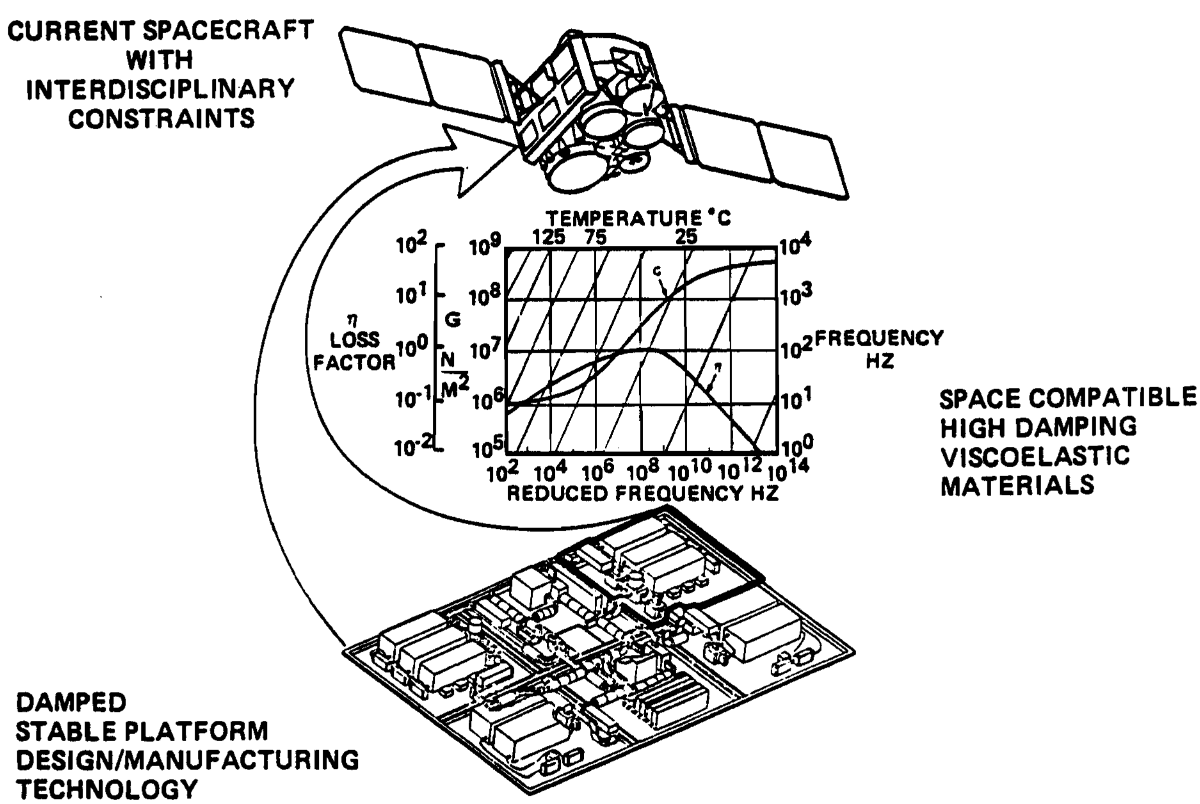

FIGURE 2. RELSAT DSCS III Baseline System

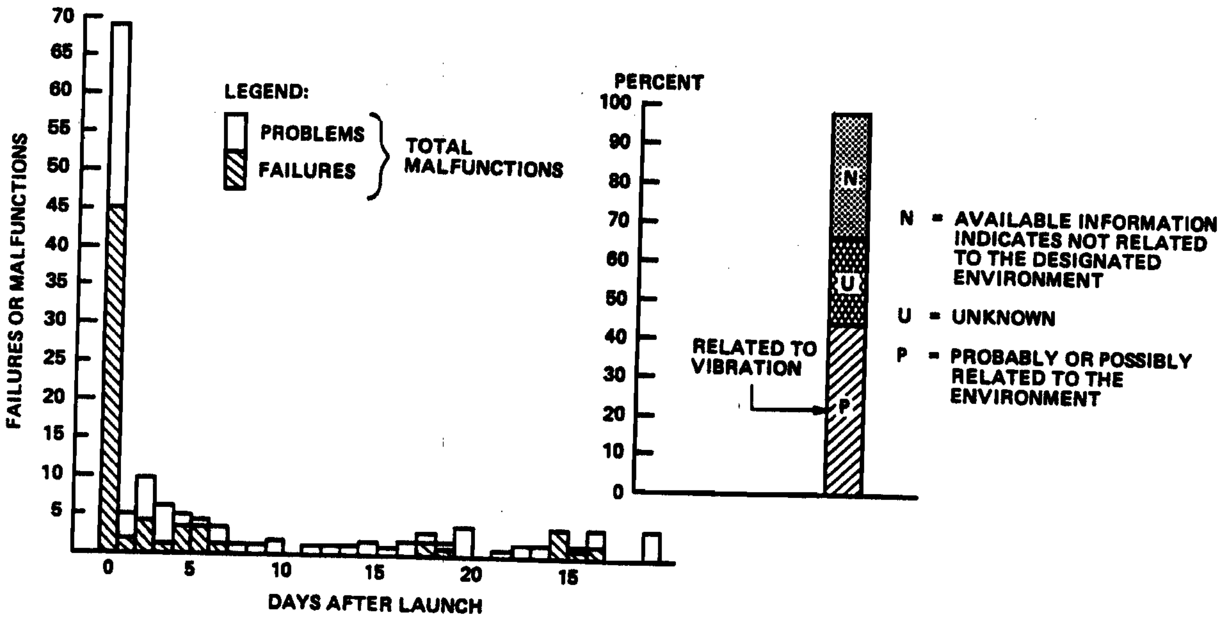

Figure 3. Spacecraft Flight Failures

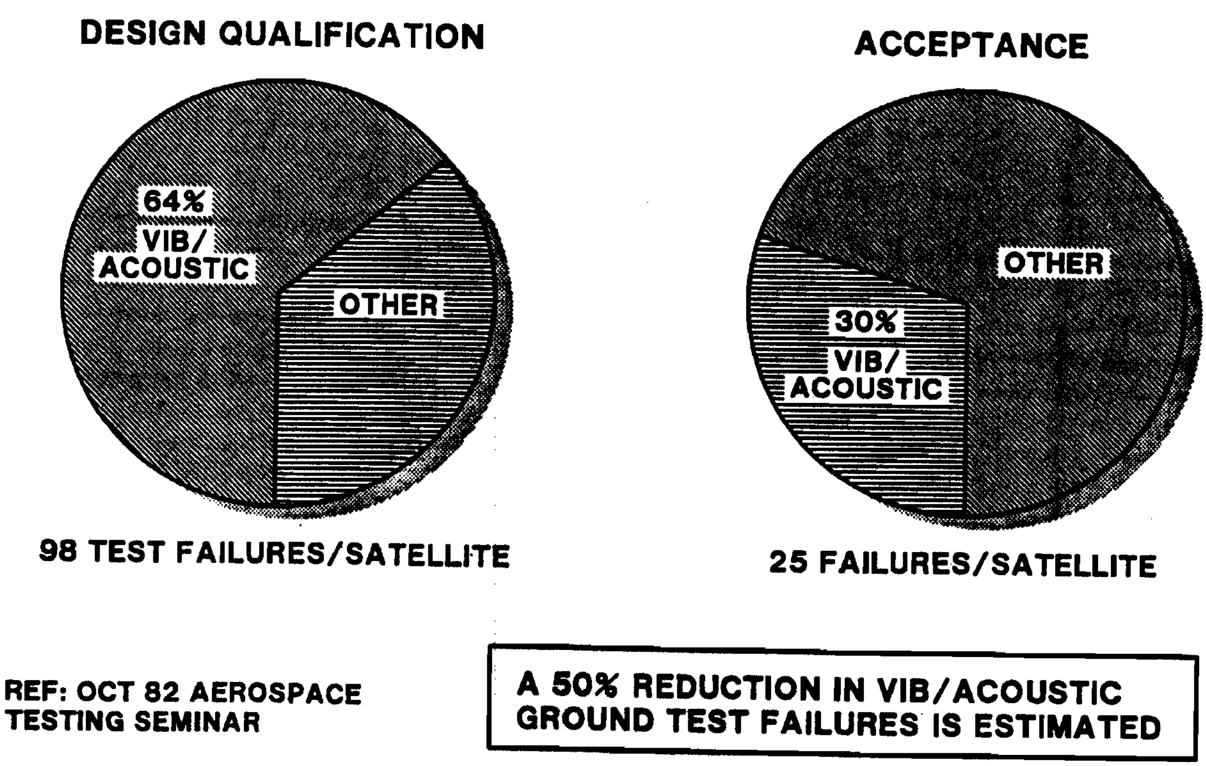

Figure 4. Environmental Test Failures

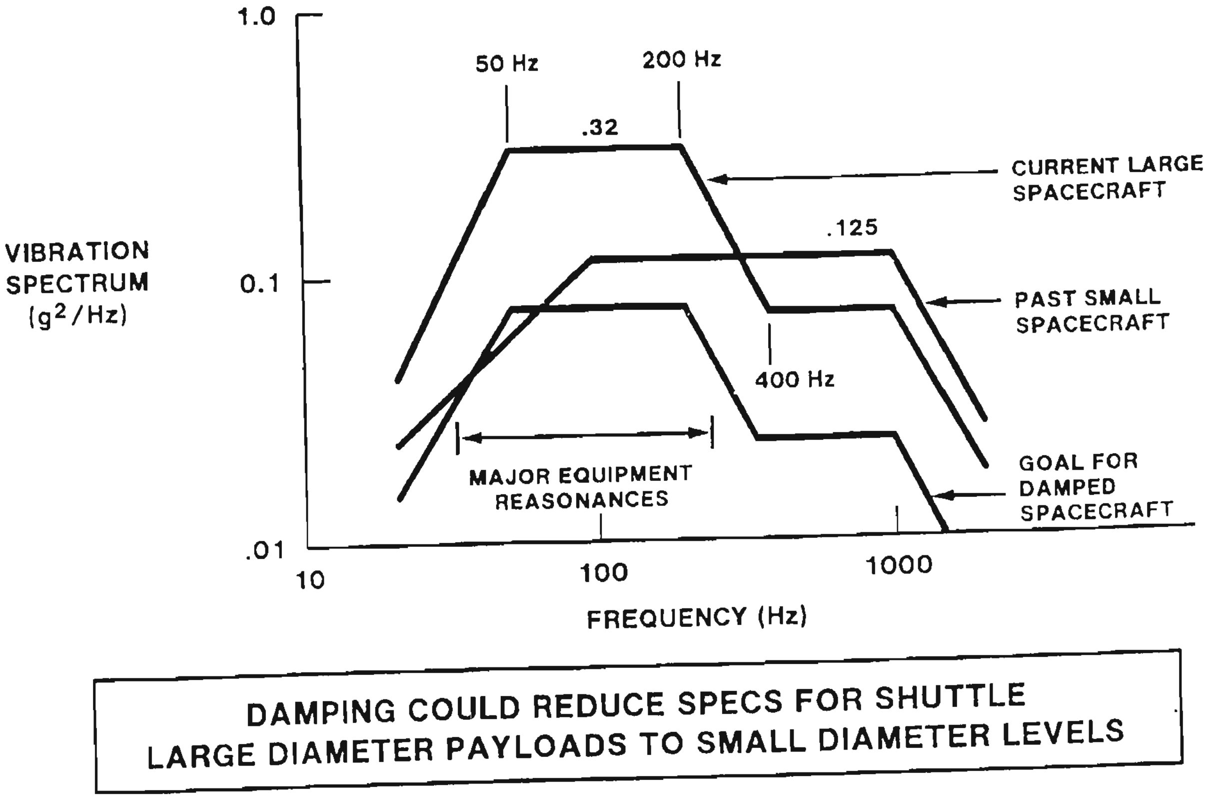

Figure 5. Equipment Random Vibration Requirements

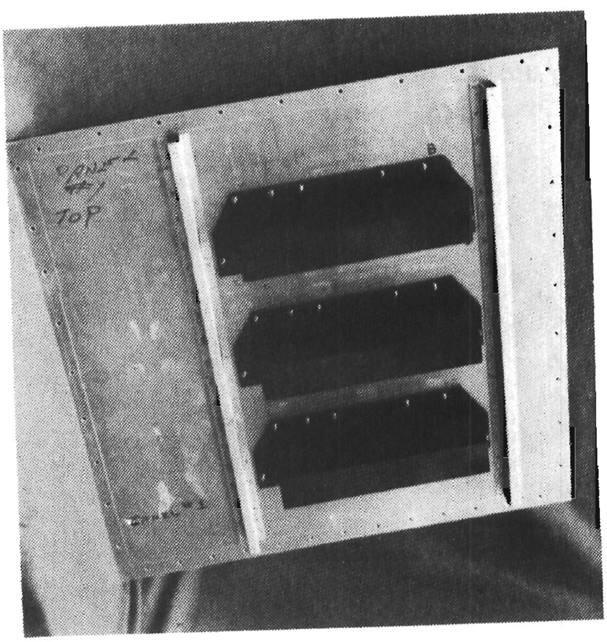

Figure 6. RELSAT Baseline Panel

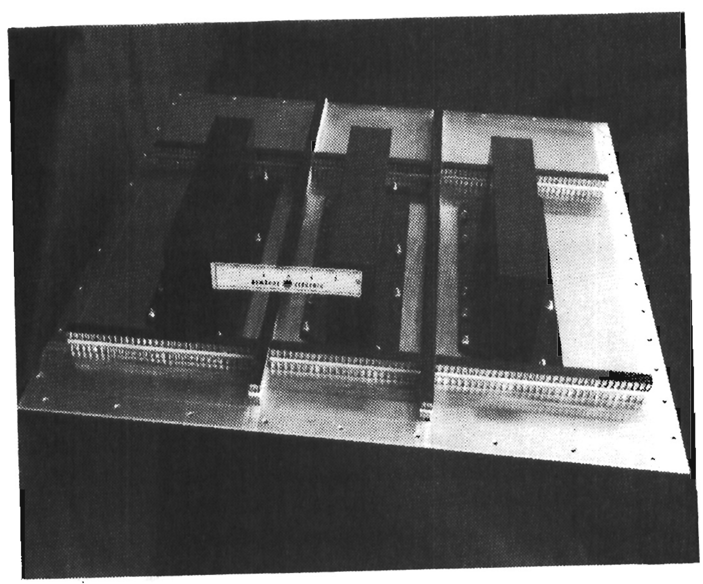

Figure 7. RELSAT Test Panel With Damped Stiffeners

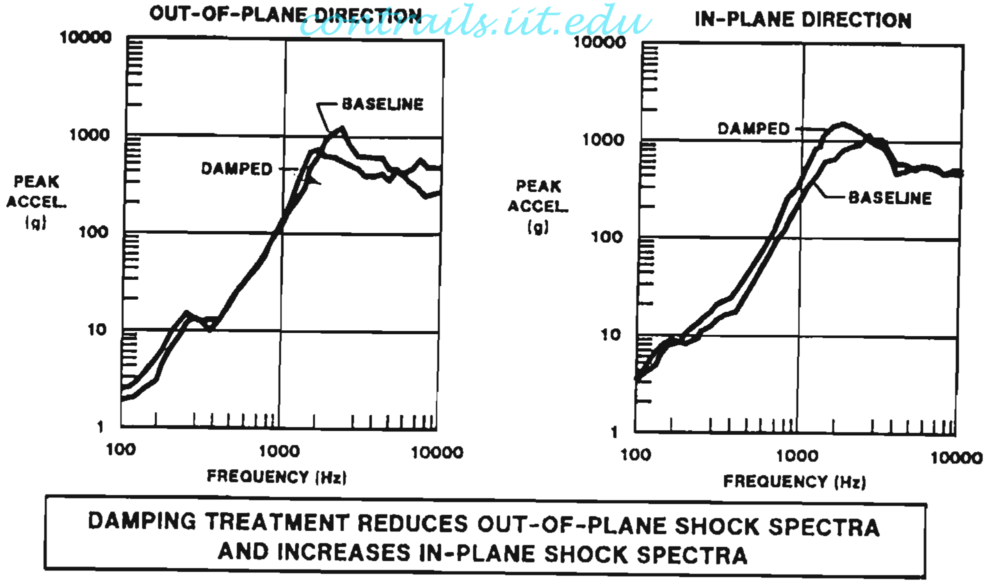

Figure 8. Pyro Shock Test Results

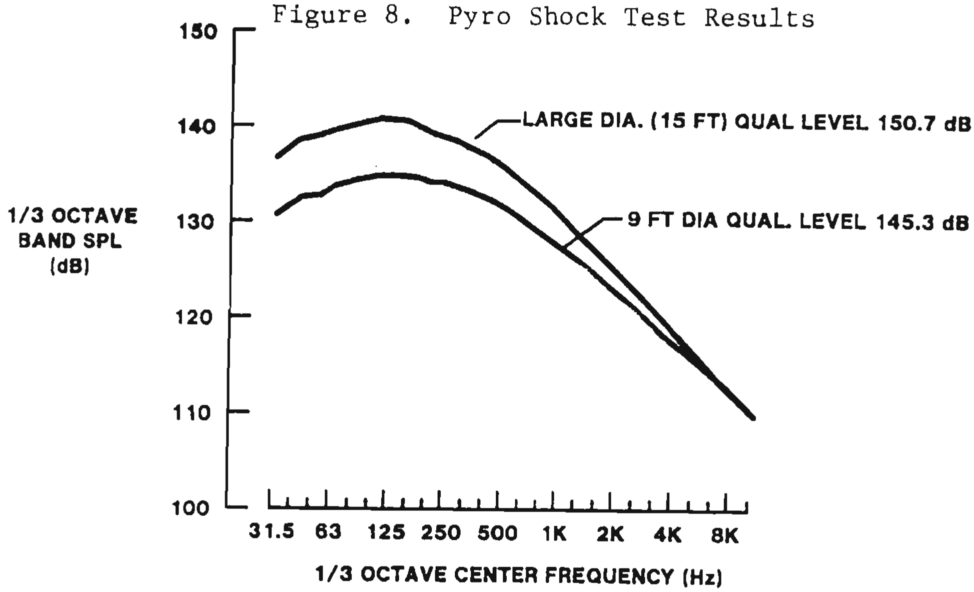

Figure 9. Qualification Sound Pressure Levels

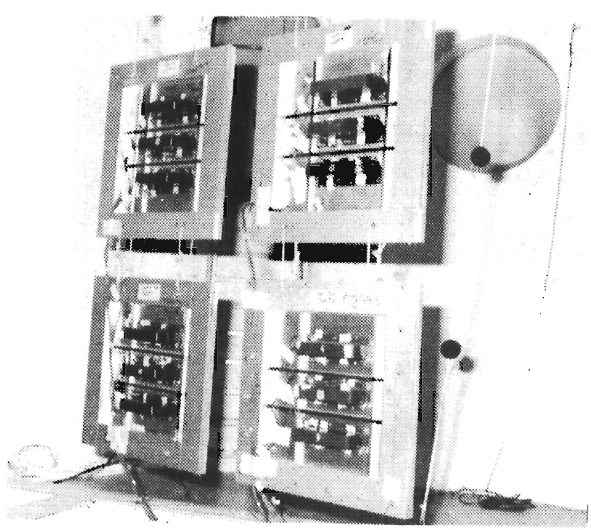

Figure 10. RELSAT Panels in Acoustic Test Facility

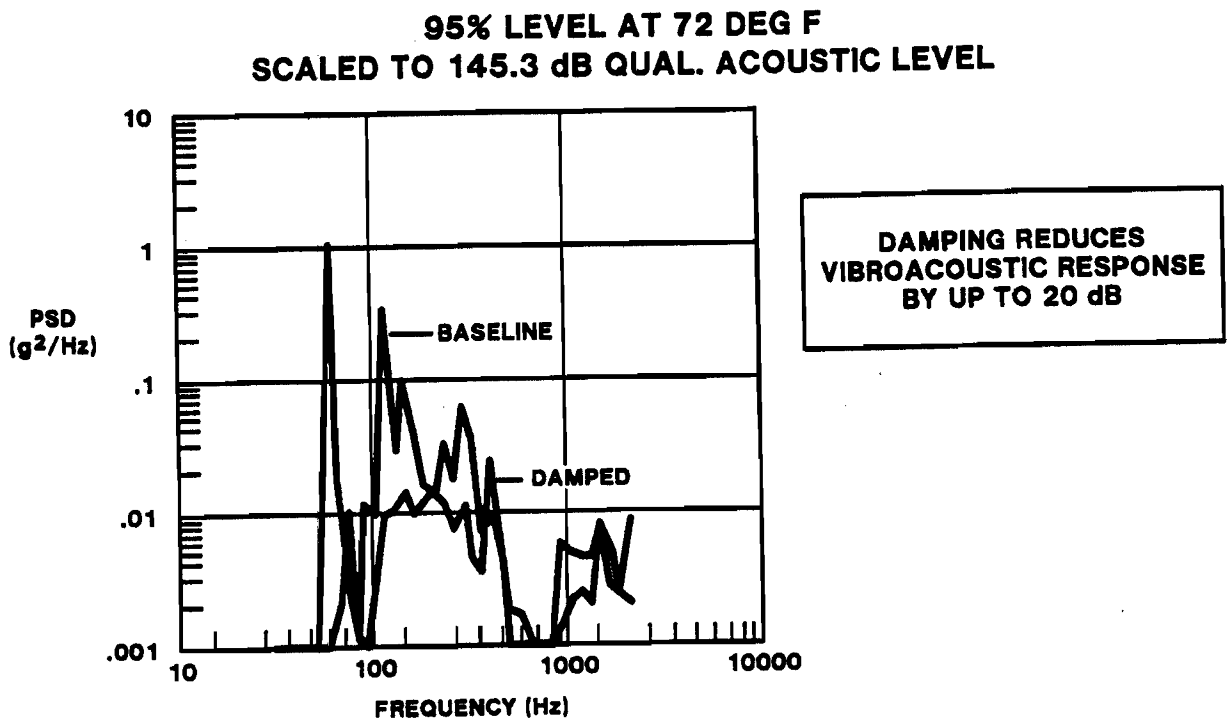

Figure 11. Out-of-Plane Vibroacoustic Response

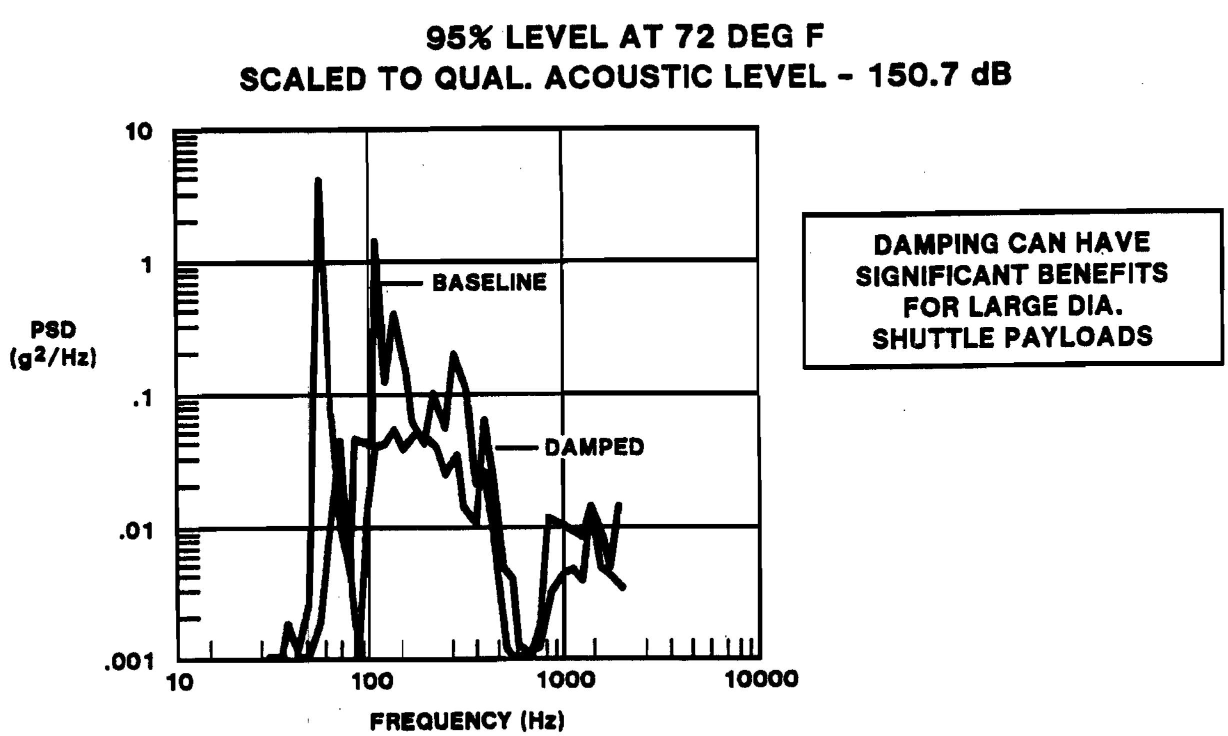

Figure 12. Vibroacoustic Response - Scaled for 15 Ft. Dia. Payload

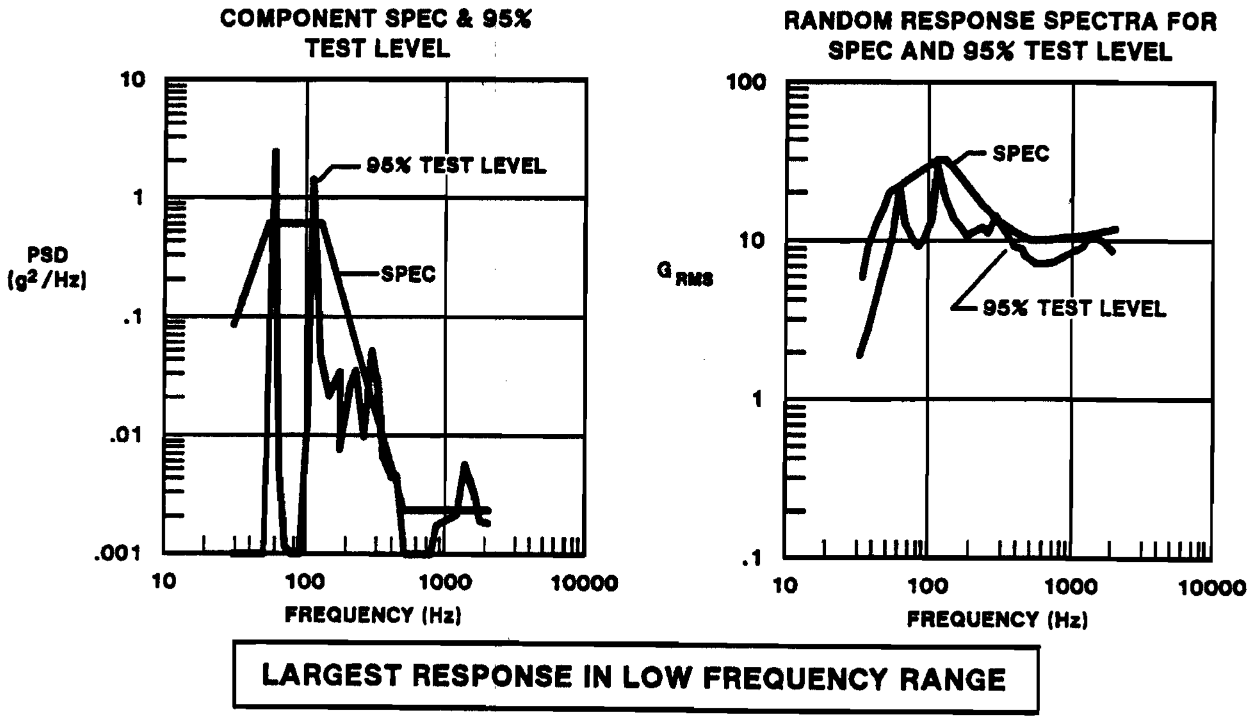

Figure 13. DSCS III Baseline Panel Random Vibration Specification

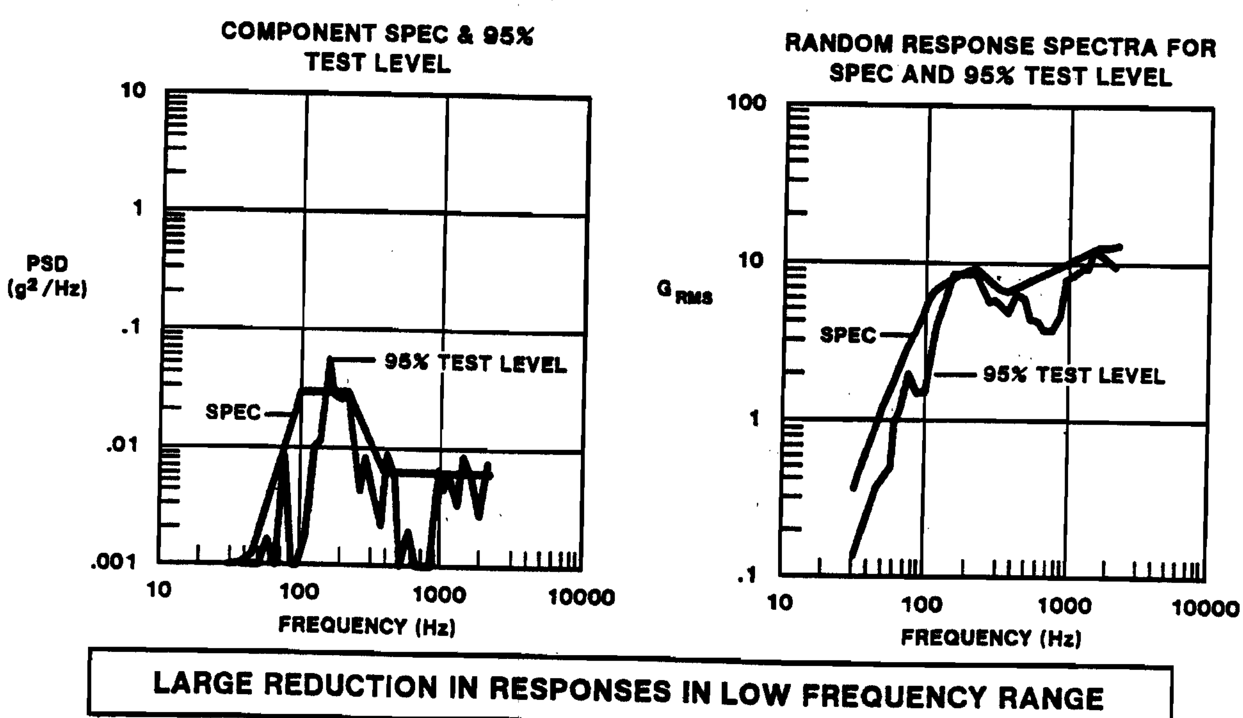

Figure 14. DSCS III Damped Panel Random Vibration Specification

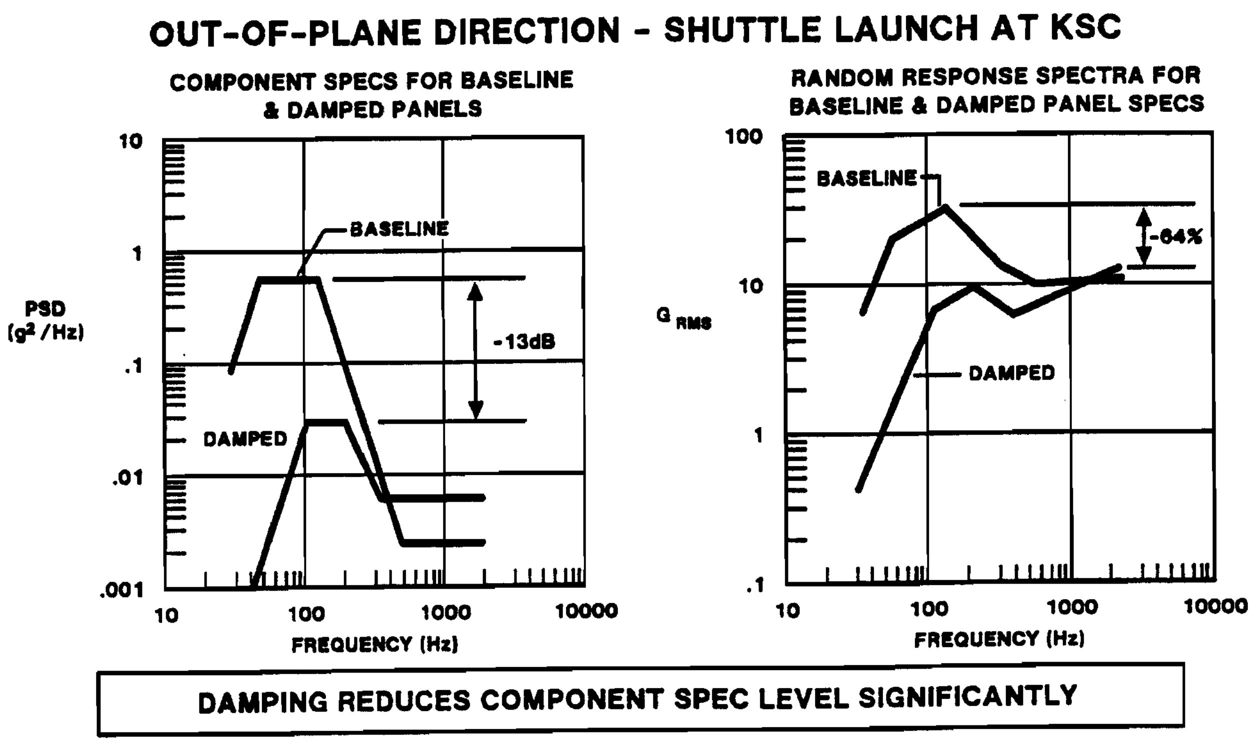

Figure 15. DSCS III Baseline and Damped Panel Qualification Level Random Vibration Specifications

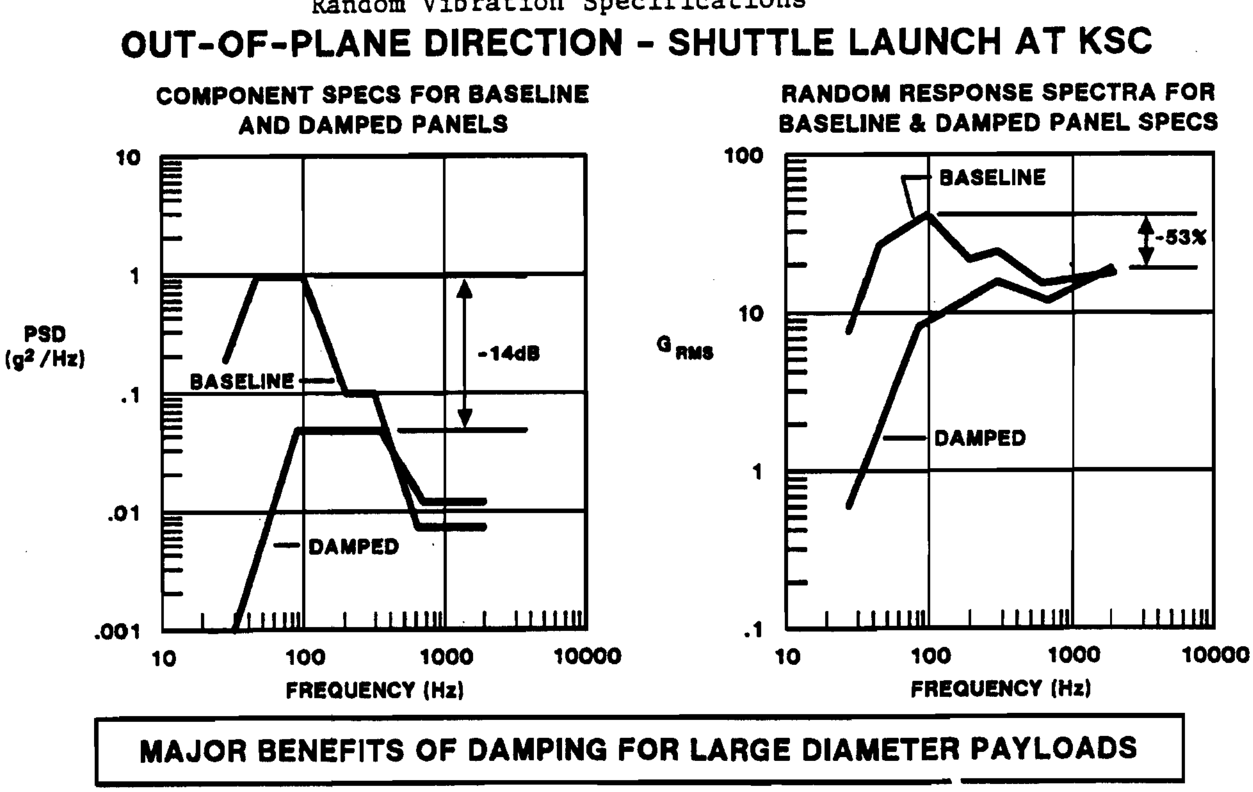

Figure 16. Random Vibration Specifications - 15 Ft. Diameter Payload

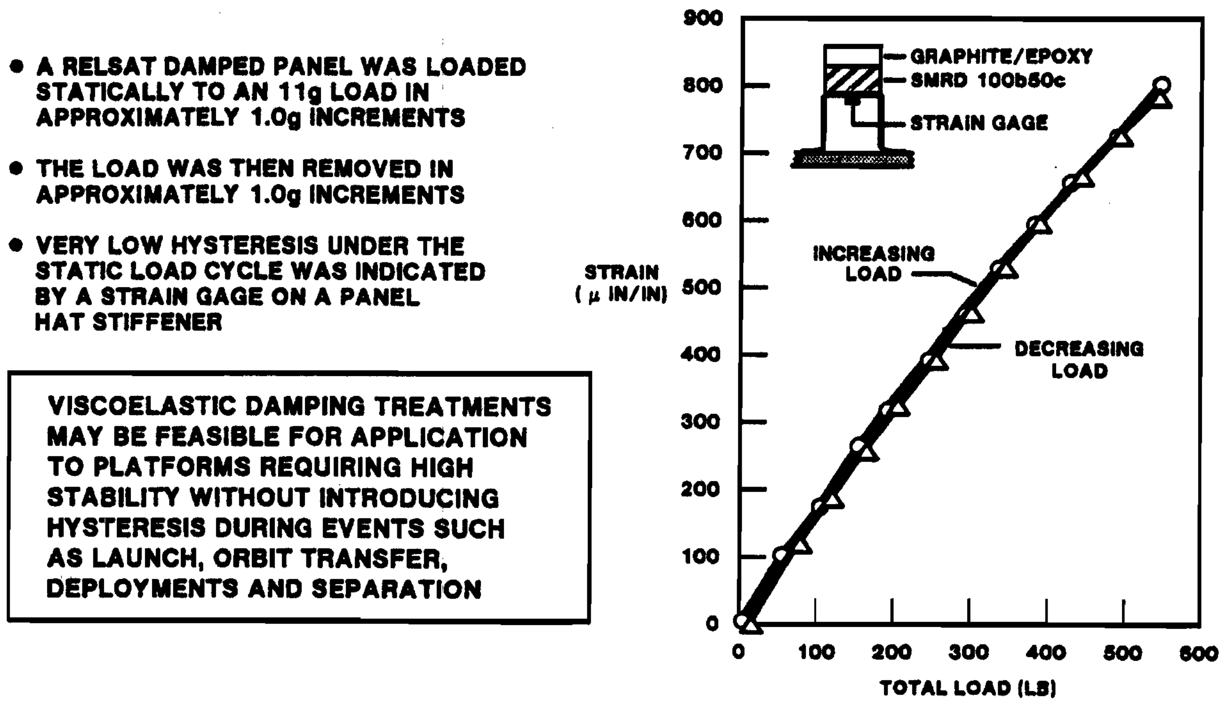

Figure 17. Static Test Hysteresis for a Damped Panel

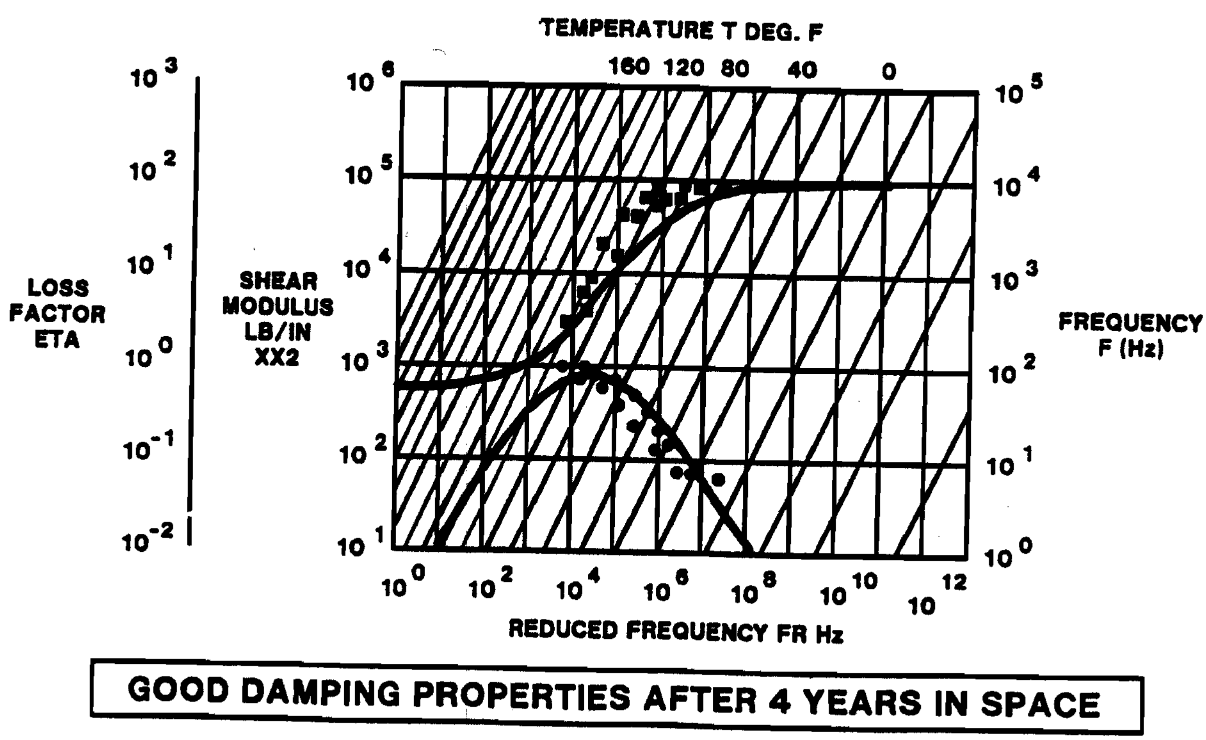

Figure 18. VEM Properties After Four Years in Space