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16. Abstract In June of 1989, the Texas Department of Transportation (TxDOT) contracted with the Texas Transportation Institute (TTI) to develop a set of performance specifications for truck mounted attenuators (TMA's). The objectives of this project were to (1) assess the performance of several truck mounted attenuators and then (2) develop and propose the criteria that define an "acceptable" TMA. These criteria will be used by the Equipment and Procurement Division (D-4) of the Texas Department of Transportation in setting minimum performance requirements for TMA's purchased by the Department. This report is the third of three volumes. The purposes of this report are to (1) describe the procedures for conducting vibration and moisture tests on TMA's, (2) discuss the plans for the construction of the necessary apparatus to conduct these tests, and (3) explain the procedures and protocols by which these tests are conducted.			
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**PROCEDURES AND EQUIPMENT FOR
CONDUCTING VIBRATION AND MOISTURE TESTS
ON TRUCK MOUNTED ATTENUATORS (TMA'S)**

by

Richard A. Zimmer

August 1991

Safety Division
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA				
in ²	square inches	645.2	centimetres squared	cm ²
ft ²	square feet	0.0929	metres squared	m ²
yd ²	square yards	0.836	metres squared	m ²
mi ²	square miles	2.59	kilometres squared	km ²
ac	acres	0.395	hectares	ha

MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft ³	cubic feet	0.0328	metres cubed	m ³
yd ³	cubic yards	0.0765	metres cubed	m ³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

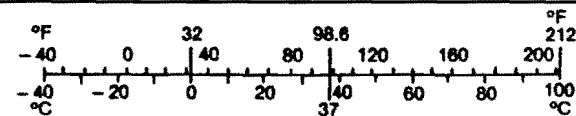
AREA				
mm ²	millimetres squared	0.0016	square inches	in ²
m ²	metres squared	10.764	square feet	ft ²
km ²	kilometres squared	0.39	square miles	mi ²
ha	hectares (10 000 m ²)	2.53	acres	ac

MASS (weight)				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m ³	metres cubed	35.315	cubic feet	ft ³
m ³	metres cubed	1.308	cubic yards	yd ³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
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These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

NOTICE

This report was prepared for the Texas State Department of Highways and Public Transportation (SDHPT) under the provisions of a contract to the Texas Transportation Institute (TTI) of the Texas A&M University System entitled "Development of Performance Specifications for Truck Mounted Attenuators" (Study Number 2-4-89-991). SDHPT assumes no liability for its contents or use thereof.

The contents of this report reflect the views of the author, who is responsible for the accuracy of the data presented herein. Any conclusions or opinions expressed in this report do not necessarily represent those of TTI, SDHPT or any other political subdivision of the state of Texas.

This report does not constitute a standard, specification or regulation.

PREFACE

In June of 1989, the Texas State Department of Highways and Public Transportation (SDHPT) contracted with the Texas Transportation Institute (TTI) to develop a set of performance specifications for truck mounted attenuators (TMA's). The objectives of this project were to (1) assess the performance of several truck mounted attenuators and then (2) develop and propose the criteria that define an "acceptable" TMA. These criteria will be used by the Equipment and Procurement Division (D-4) in setting minimum performance requirements for TMA's purchased by the Department.

This report is the third of three volumes. The purposes of this report are to (1) describe the procedures for conducting vibration and moisture tests on TMA's, (2) discuss the plans for the construction of the necessary apparatus to conduct these tests, and (3) explain the procedures and protocols by which these tests are conducted.

The first volume to this study [An Evaluation of Selected Truck Mounted Attenuators (TMA's) with Recommended Performance Specifications, by L.I. Griffin, R. A. Zimmer, W.L. Campise and K.K. Mak] details the work conducted during the course of the study and presents the study findings, conclusions and recommendations. More specifically, this first volume provides an overview of the study, along with the results obtained during crash, vibration and moisture tests on seven different makes and models of TMA's. Comparisons are drawn between the different attenuators that were tested, and a set of performance specifications for TMA certification is proposed.

In the second volume to this study [Comparative Crash Tests Conducted on Seven Different Makes and Models of Truck Mounted Attenuators (TMA's), by W. L. Campise], the procedures and protocols employed in the 21 crash tests conducted during the course of this project are presented, along with the ways and means by which test data were collected and analyzed. Results of the tests are presented photographically (before-and-after photographs of the TMA's and test vehicles; sequential photographs of the crashes) and graphically (vehicle deceleration by time plots; angular displacements by time plots). Performance measures based upon NCHRP 230¹ (occupant impact velocity and occupant ride down acceleration) and TRB Circular 191² (maximum 50 msec average longitudinal acceleration) criteria are provided.

¹Michie, J.D. Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances, National Cooperative Highway Research Program Report 230, Transportation Research Board, National Research Council, Washington, D.C., March 1981.

²Transportation Research Circular 191. Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances. Transportation Research Board, National Research Council, Washington, D.C., February 1978.

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INTRODUCTION AND BACKGROUND

The ability of truck mounted attenuators (TMA's) to save lives is a function of their initial design and their ability to maintain those attributes throughout the service life of the unit. Since the TMA must spend its operational life attached to the rear of a dump truck, it is exposed to extremes of vibration and weather. If the unit is under designed, structural failures could appear months or years after being placed in service, thereby reducing the safety benefits of the unit.

To determine if a TMA cushion is properly designed to withstand the rigors of field use for many years, accelerated fatigue and moisture testing should be preformed. These full-scale fatigue and moisture tests should be capable of producing the equivalent of many years of normal use within a few days.

California was the first state to develop fatigue (vibration) and moisture tests to evaluate TMA's. Current fatigue and moisture test requirements are contained in Caltrans Specification Number 90002-406-91.³ This detailed specification describes procedures that must be followed and passed before a TMA is eligible for purchase by the California Department of Transportation.

CALIFORNIA VIBRATION TEST

To determine the structural adequacy of a TMA, California vibrates the TMA box assembly (i.e., the cushion on a typical TMA instillation), in a sinusoidal manner at a constant frequency between 6 and 8 Hz (cycles per second) and a constant amplitude of 0.60 in (peak to peak). TMA's are tested in three different positions: horizontal, 60° and 90° (with respect to the horizontal). The test is run for a total of 40 hours in each position. At the end of the test, the unit is inspected and measured for any damage or position change greater than 0.50 inches.

CALIFORNIA MOISTURE TEST

In the California moisture test, the TMA box assembly is first sprayed for 24 hours in the standard, horizontal position. The spray completely covers the top and sides of the box assembly and simulates a 6 inch per hour rain. At the end of the 24 hours the unit is turned over and sprayed for another 24 hours. At the end of the 48 hours the unit is allowed to dry for 1 hour. The box assembly is then disassembled and inspected. It must be completely free of moisture to be judged acceptable.

TTI VIBRATION TEST: APPARATUS, PROCEDURE, PROTOCOL AND RESULTS

APPARATUS

The design of the TTI vibration test apparatus is, in general, similar to the California equipment. The TTI vibration device or 'shaker' does not incorporate the 139 in pivot arm, but moves the TMA mounting plate in a perfectly

³Specifications for "A Truck Mounted Attenuator Box Assembly" (Specification Number 90002-406-91), State of California, Department of Transportation, Division of Equipment, Sacramento, California.

vertical plane. This design, shown in Figure 1, uses heavy duty linear ball bearings at six locations on the 700 pound mounting plate. These bearings, also shown schematically in Figures 2 and 3, provide a very low friction motion along the axis of the precision rods over which they travel, while restricting movement in any other direction. The frame of the shaker is intentionally over designed using 6 in by 8 in steel box beams with $\frac{1}{4}$ in wall thickness. This is to preclude any structural fatigue in the testing machine after millions of cycles. The frame is anchored in 6 places to a 6 in thick concrete slab with heavy duty expansion bolts.

A vertical force, which follows a sine wave motion, is applied to the TMA mounting plate by a closed loop hydraulic servo system. This electro/mechanical system is powered by a 15 horsepower electric motor driving a 1500 psi, 15 gallon per minute hydraulic pump (Figure 4). The pump pressure is connected to an electronic servo control valve located on the hydraulic cylinder. This valve, based on the difference in displacement and command signal, applies pressure to the actuator to extend or retract. Physical displacement is measured by a precision transducer located between the frame and mounting plate. The sine wave command signal is produced by an electronic oscillator controlling frequency and amplitude of the mounting plate (Figure 4). When in operation the hydraulic system is required to provide a 2750 lbs upward force and a 550 lbs downward force, 7 times each second. To avoid cracking the 6 inch concrete slab under the hydraulic actuator, a four foot deep shaft was drilled and filled with concrete and steel to accommodate the actuator forces.

Since the shaker would be operated unattended at times, several safeguards were designed. Limit switches on the mounting plate shut down the hydraulic pump if the vertical operating displacement is exceeded in either direction, as might occur if any subsystem within the control loop malfunctioned. Temperature of the hydraulic fluid is monitored with an electronic readout and a thermocouple. When the fluid temperature reaches 100° F, water flows automatically to a heat exchanger. If the temperature reaches 150° F, the hydraulic power unit is shut down. Under normal operations the fluid temperature runs about 112°F.

Ancillary equipment provides for precise monitoring of the amplitude and shape of the motion and total time of test. Various hydraulic and electronic gages have also been incorporated to insure the health of the system.

PROCEDURE

Frequency: The rationale for the frequencies, amplitudes and total cycles used in the California vibration test were not apparent at the outset of this project. Therefore, a small study was undertaken at TTI to determine the forces at work on a TMA attached to a dump truck traveling over various surfaces. In this study, a standard dump truck used by the Texas State Department of Highways and Public Transportation (SDHPT) was ballasted with sand bags until it achieved a total gross weight of 14,000 lbs. The truck was then fitted with various manufacture's TMA's. Accelerometers, oriented in the vertical axis, were attached to the rear of the truck and the front of the TMA cushion. The accelerometer signals were telemetered to the data processing center and recorded on magnetic tape for later processing.

Figure 5 is an accelerometer trace of a worst case scenario (i.e., a very rough road). In fact, the "very rough surface" in Figure 5 was simulated by driv-

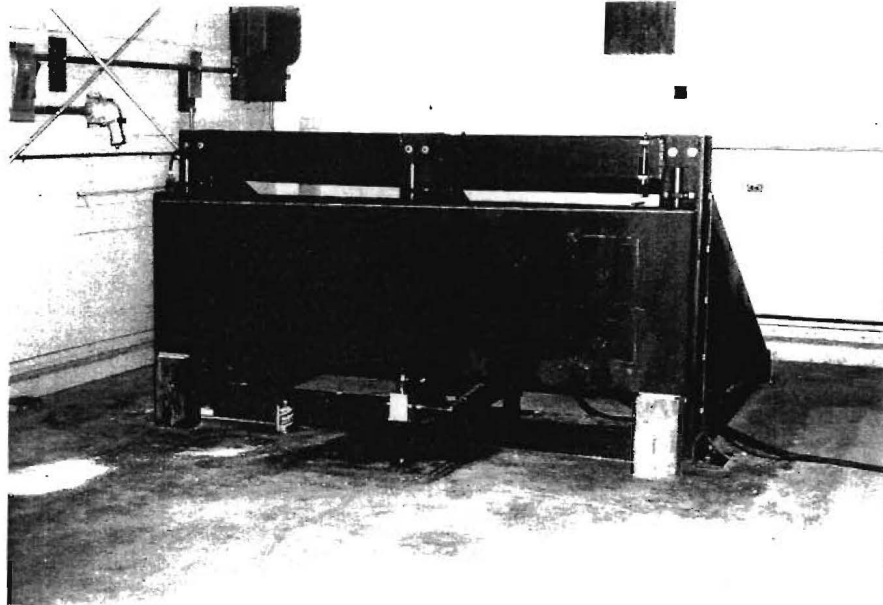


Figure 1(a): TTI Vibration Test Apparatus

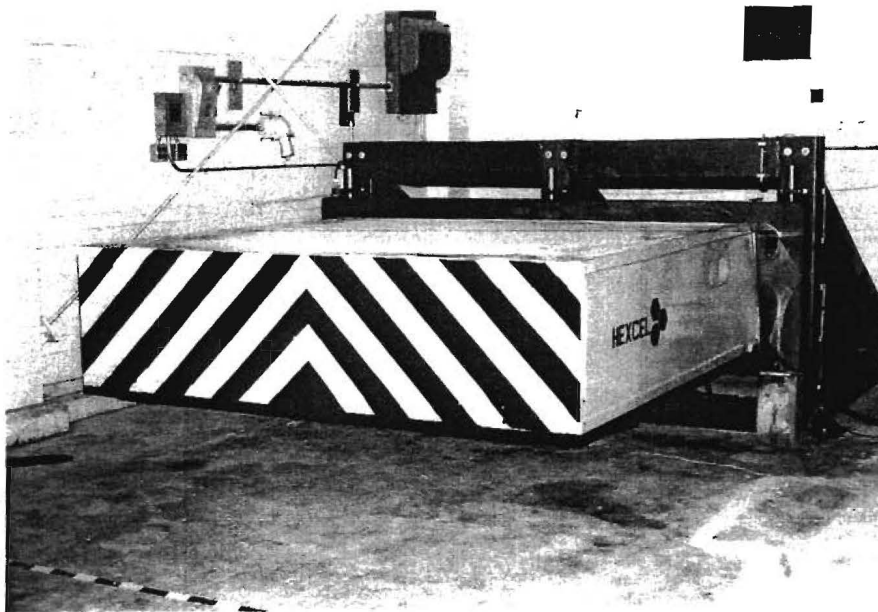


Figure 1(b): TTI Vibration Test Apparatus with a TMA Cushion Attached

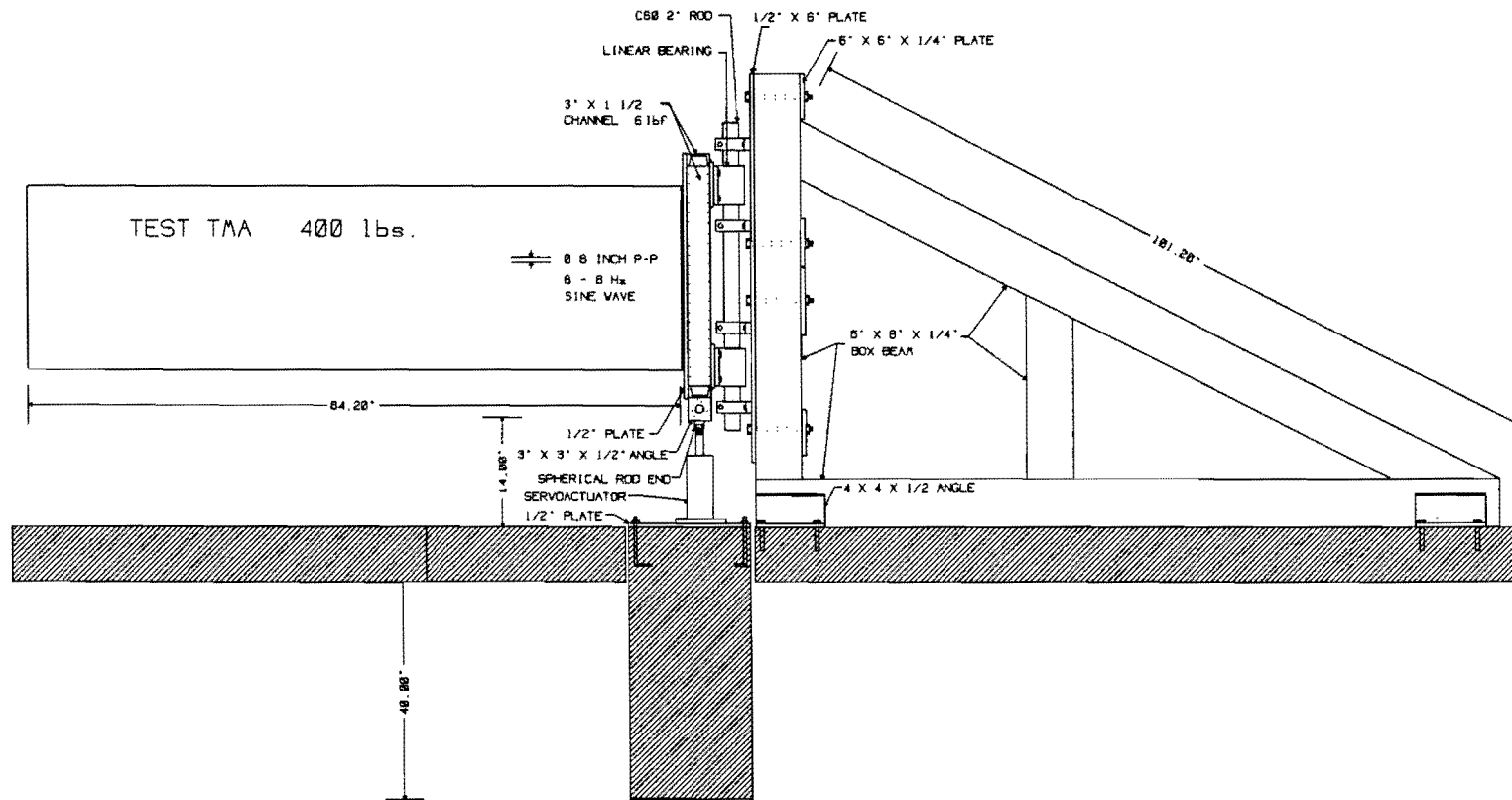


Figure 2: TTI Vibration Test Apparatus (Side View)

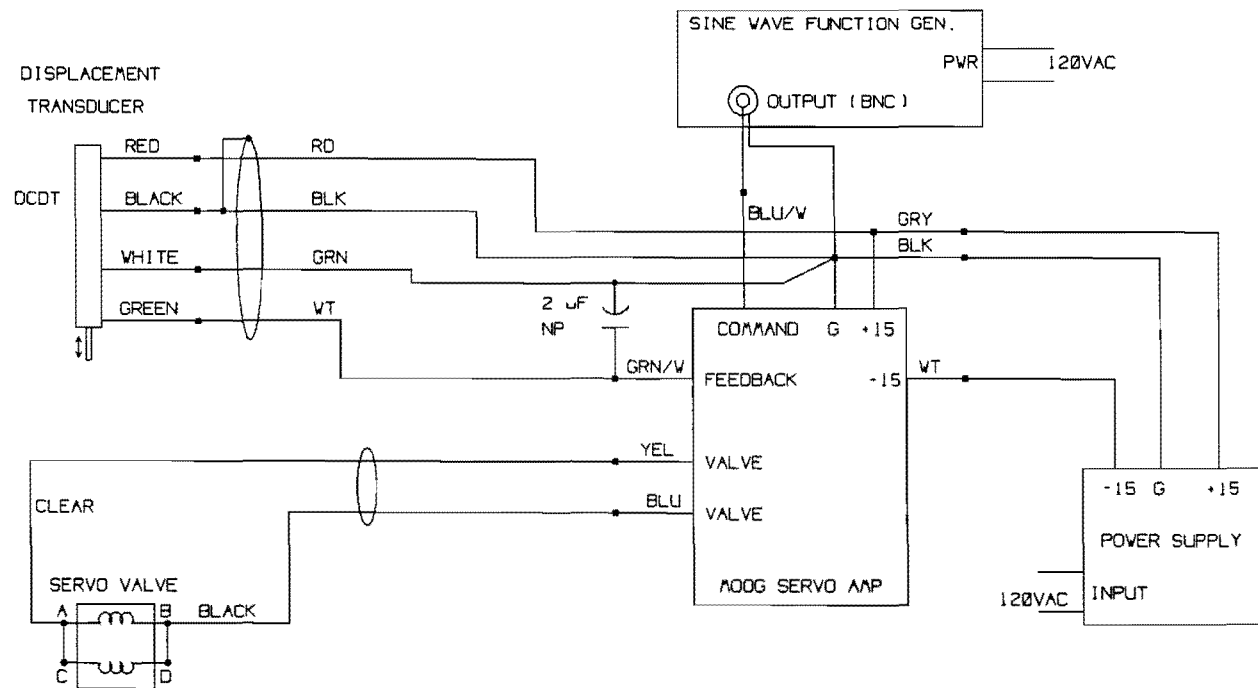
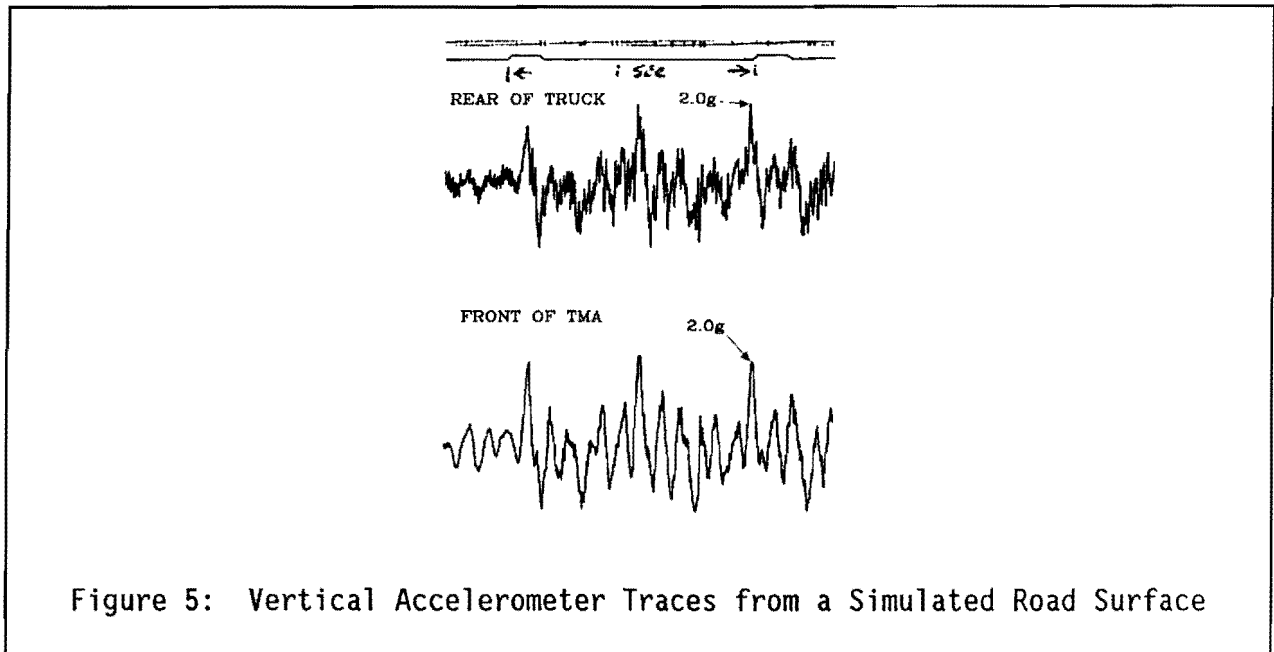


Figure 4: Electronic Servo Control System for the TTI Vibration Test Apparatus

ing over 1.5 in thick rubber strips placed at 6 foot intervals at 25 mph.⁴ This simulation might be likened to travel in a construction zone. The top trace represents vertical accelerations at the rear of the truck near the mounting point with the TMA. The bottom trace shows vertical accelerations at the front of the TMA cushion. Here the peak accelerations (about ± 2 g's) were the same at the two locations, with higher frequency components damped out across the mount.



Since most of the miles accrued by dump trucks supporting TMA's will not be in construction zones, but on primary and secondary roads, two additional tests were carried out on "typical" primary and secondary roads. The primary road was a smooth asphalt state highway with an AASHO present serviceability rating (PSR)⁵ of about 4. The secondary or rough road was also of asphalt construction, but with many potholes and patches, and a PSR of about 1 to 2.

Vertical accelerations were recorded for a TMA-equipped dump truck traveling over (1) the primary road at 55 miles per hour and (2) the secondary road at 10, 20 and 30 miles per hour, with only the 30 mph runs selected for analysis. The accelerometer was located at the front edge of the TMA cushion.

Data analysis began by first low pass filtering the raw TMA vibration data to remove any localized ringing above 100 Hz and then digitizing at 1000 samples per second. The digitized files were then processed to produce a power spectrum density plot. Figures 6 and 7 show typical plots of the relative vibrational acceleration over a frequency range of between 0 and 30 Hz. A top frequency of

⁴The frequency imparted to the dump truck at this speed (25 mph) and at this gap between the bumper strips (6 feet) is 6 Hz.

⁵Carey, W.N., Jr. and P.E. Irick. The Pavement Serviceability-Performance Concept (Bulletin 250). Highway Research Board, National Research Council, Washington, D.C., 1960.

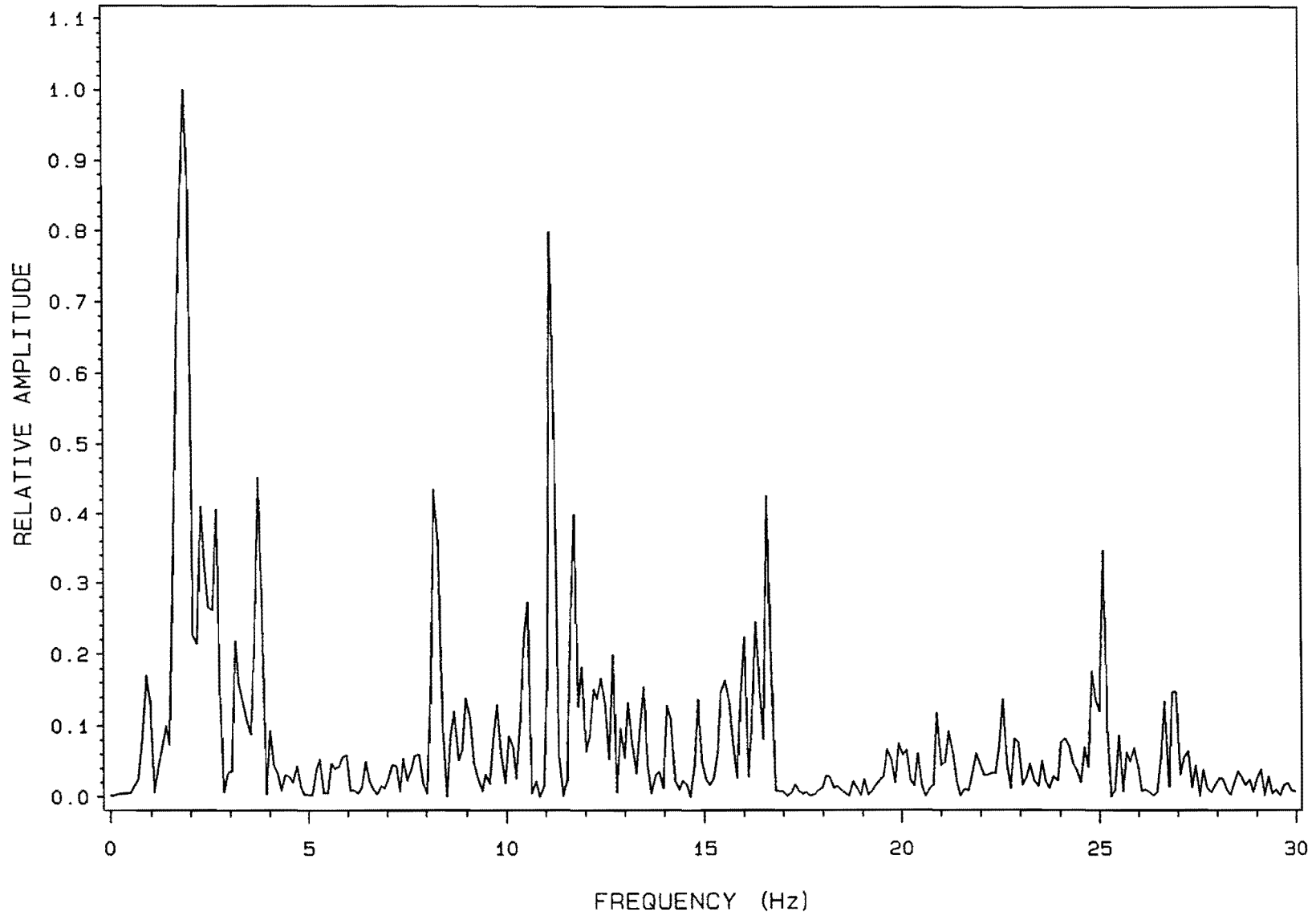


Figure 6: POWER SPECTRAL DENSITY FOR A TYPICAL TMA OPERATED ON A PRIMARY (SMOOTH) ROAD AT 55 mph

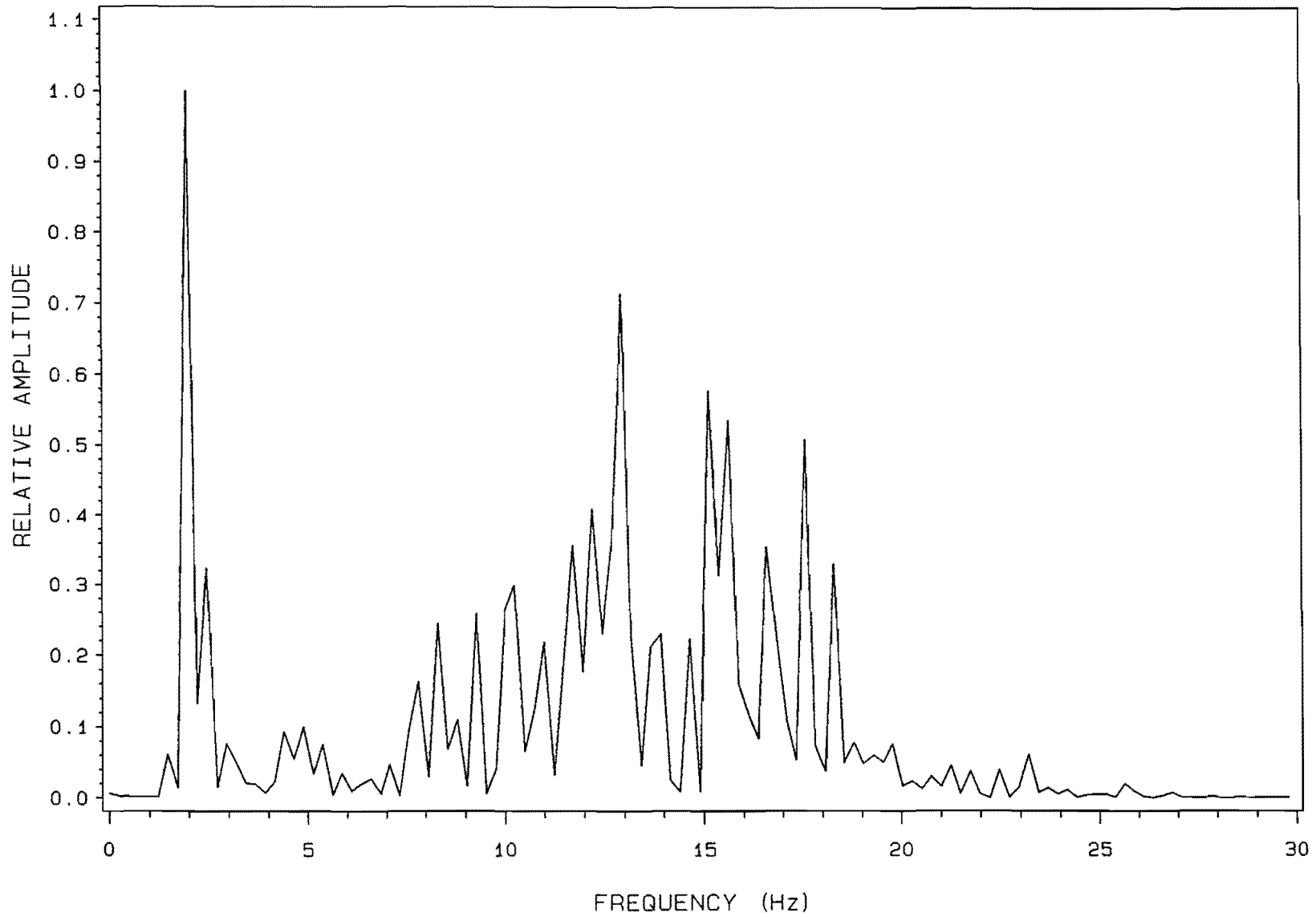


Figure 7: POWER SPECTRAL DENSITY FOR A TYPICAL TMA OPERATED ON A SECONDARY (ROUGH) ROAD AT 30 mph

30 Hz was chosen for these test since there appeared to be very little power above 30 Hz.

Even though total acceleration is much higher in the runs over the secondary (rough) road at 30 mph, the frequency distributions between roads (and among TMA types) were similar. The highest power density in Figures 6 and 7, and most other plots in this series of tests, was usually found around 2 Hz.⁶ This is the natural frequency of the dump truck suspension system. The remainder of the vibration power is spread out between 8 and 18 Hz. The largest peak in this range is the resonance of the cantilevered TMA cartridge. The remainder of the power is seen in various resonances in the truck, and TMA mounting hardware.

When a TMA is vibrated, the elements comprising the system (e.g., the truck, the attachment between the truck and cushion, the cushion itself, etc.) respond in a manner that depends on their natural frequencies compared to the frequency imposed. The closer an element is vibrated to its natural frequency, the higher the displacement amplitude observed.

Since TMA's are subjected to many frequencies while in service, and since these frequencies are different for each make and model of TMA, it does not seem prudent to select a frequency at one of the high power density points in the power spectral density (PSD) plots. The exception could be the 2 Hz value that equates to the truck suspension, but this frequency is removed from those found in the TMA system. To be impartial to variations in TMA design, it was decided to select a fixed test frequency in the area observed in the PSD plots that contained few resonances. This range is between 5 and 8 Hz, similar to the California range. To reduce the variability in testing it was decided that one value for test frequency should be used instead of a range from 6 to 8 Hz, as California uses. This is because the acceleration or force of the tester is determined by the square of the frequency as shown in the following equation.

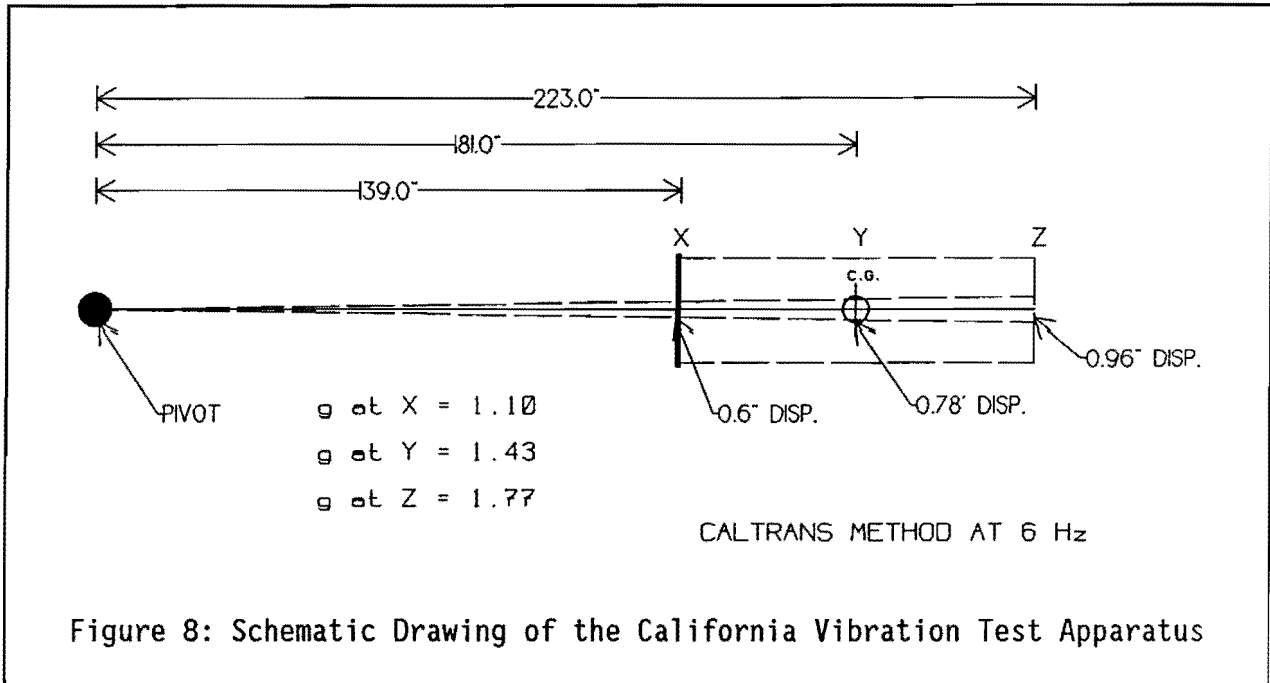
$$a = 4\pi^2 f^2 A$$

Where: a = Peak test acceleration (feet per second²)
f = Vibration frequency (cycles per second)
A = Peak displacement (feet)

Amplitude: The amplitude or severity of the vibration test is measured in terms of the peak vertical acceleration on the TMA at the mounting plane. In the California procedure this acceleration, using the above formula, could vary from ± 1.1 g's to ± 1.96 g's using a 0.6 in displacement and a frequency of 6 to 8 Hz. The California test also requires that this vertical acceleration be applied to the TMA mounting plate at the end of a 139 in arm shown in Figure 8. This arm provides some degree of amplification of vertical acceleration because the displacement is higher toward the end of the TMA. The example used in Figure 8 shows that at a typical test frequency of 6 Hz and 0.60 in total displacement at

⁶in these plots the highest power density frequency is set to 1.0.

the mounting plate, the acceleration at the that point would be ± 1.1 g's. The displacement at the rear of the TMA would be a total of 0.96 in with an acceleration of ± 1.77 g's. The acceleration at the center of mass, assuming constant distribution, would be ± 1.43 g's.



During the development of the TTI vibration device, it was decided that there was no strong justification for the 139 in arm used by Caltrans. The design of the system could be somewhat simplified, and the mass of the test apparatus could be greatly reduced, if the TMA mounting plate vibrated in a pure vertical plane. With this design philosophy adopted, thought was given to the vibration amplitude. To stay somewhat compatible with California test parameters (which seemed reasonable based upon the previously described road surface tests) the range of accelerations between 1.1 g's and 1.9 g's was considered. To verify that this range is similar to the worse case vibration a TMA would see during its life, an amplitude analysis was done on the vertical acceleration data obtained for the frequency analysis. These digitized data were processed with simple software developed for this purpose. The primary and secondary road data used in the vibration test were used for this evaluation. The software scanned the raw data and reported the percentage of time selected g-ranges occurred. Two of these tests are shown in Figures 9 and 10. These tests suggest that the vertical g-loadings at the front of a TMA traveling over a relatively smooth primary highway may range up to 0.4 g's, while the same TMA traveling over a rougher secondary road may experience g-loadings of up to 0.6 g's. In the simulated construction zone tests (Figure 5), the vertical accelerations recorded were up to 2 g's.

Based on these tests it was decided that the highest vertical g-level a TMA might ordinarily see during its life would be about ± 1.5 g's. This value, which is close the value at the C.G. in the Caltrans tests, was chosen for the TTI testing.

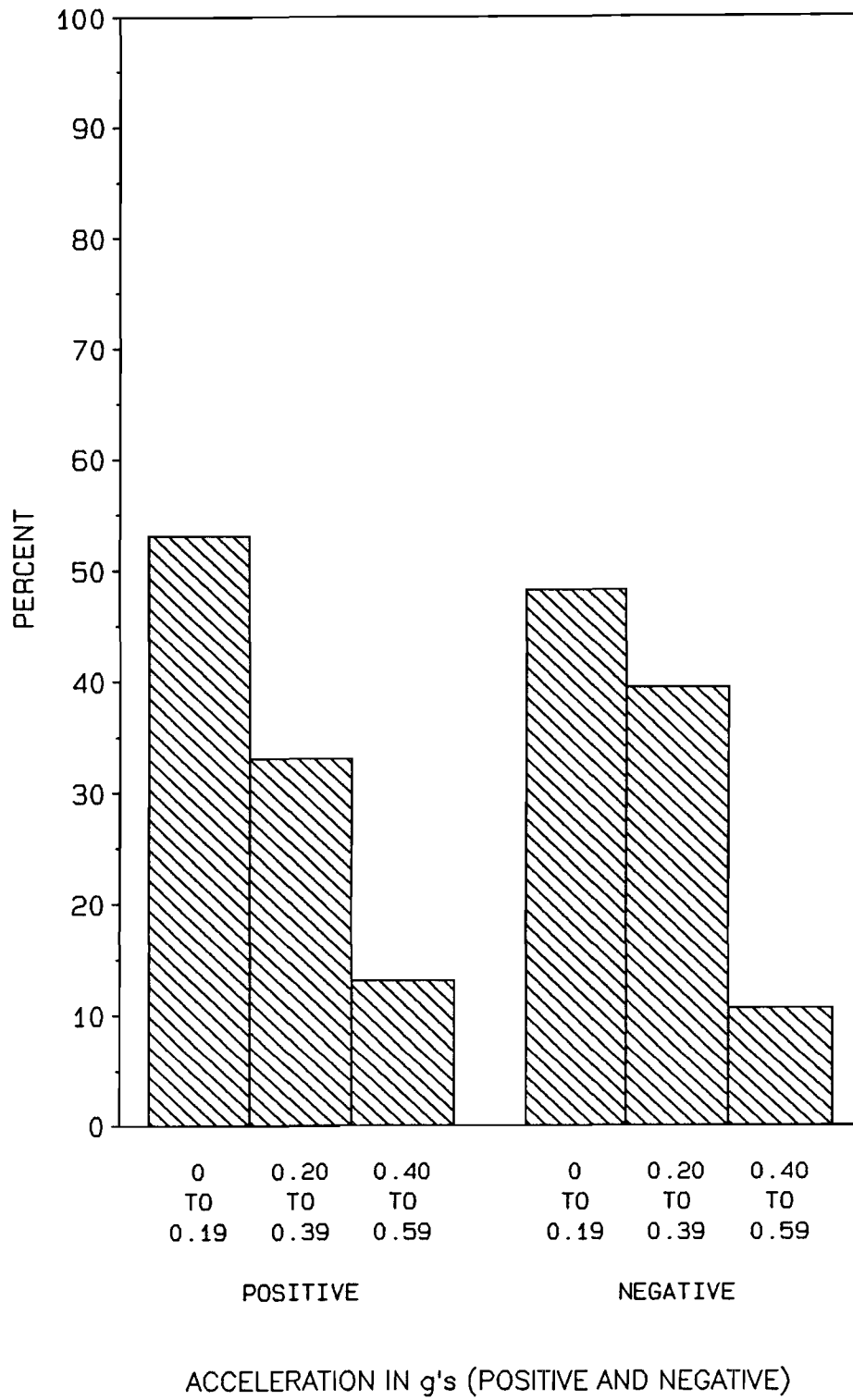


Figure 9: PEAK VERTICAL ACCELERATIONS RECORDED ON A TMA TRAVELING ON A ROUGH ROAD AT 30 MILES PER HOUR

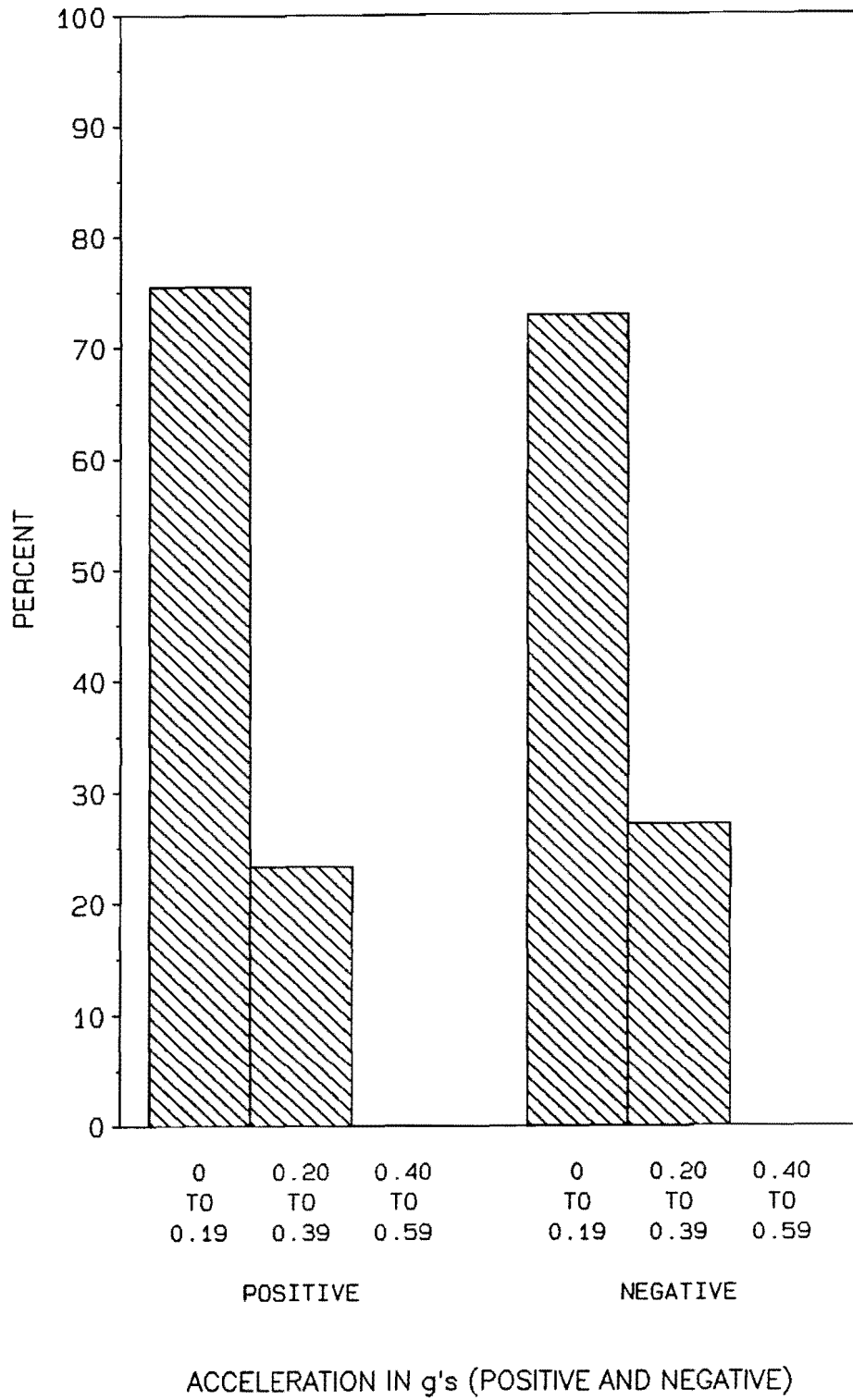


Figure 4: PEAK VERTICAL ACCELERATIONS RECORDED ON A TMA TRAVELING ON A SMOOTH ROAD AT 55 MILES PER HOUR

Duration: The duration of the vibration test is the third element in full scale fatigue testing. Test duration is usually specified in terms of total cycles. Figure 11 represents the typical relationship between stress amplitude and cycles-to-failure for repeated reversals of stress. The stress corresponding to the "knee" of the fatigue curve is referred to as "endurance limit stress." This means that stresses below this level may continue forever with no structural damage.

The TTI test is run for 40 hours, the same as California (for a given orientation of the TMA cushion). If the test is run at 7 cycles per second for 40 hours, a total of 1,008,000 cycles are completed. This value falls close to the typical "knee" in Figure 11. To correct for the typical endurance limit being at 4 million cycles one could assign a value of ± 1.5 g's at the 1 million cycle point and determine that the stress would be less by about 64 percent at the endurance limit or ± 0.95 g's. This level is still less than the peak values seen on the primary and secondary roads.

PROTOCOL

Each TMA cushion assembly was tested in the horizontal position. All testing was done at a frequency of 7 Hz at a null-to-peak displacement of ± 0.3 in at the mounting plate. This level of vibration applied a dynamic load of ± 1.5 g's to the unit. To pass the test a TMA cushion was required to vibrate at this level for a total of 40 hours (approximately one million cycles). The 40 hours of testing were usually completed over a 4 to 5 day period, 8 to 10 hours of testing per day.

At the end of each day the TMA would be carefully examined for structural damage. Vertical measurements between reference marks at the rear of the TMA and the floor were also taken and compared the pretest values. A drop, on either side of more than 0.5 in constitutes a failure.

RESULTS

Table 1: Results of Vibration Testing on Five Makes and Models of TMA's

Manufacture	Total Hours	Right Droop	Left Droop	Condition	Pass Fail
Markings & Equipment	40	0.13"	0.13"	No structural damage	Pass
Hexcell	40	0.38"	0.38"	Minor buckles and cracks in the skin	Pass
Energy Abs. Alpha	40	0.03"	0.0"	No structural damage	Pass
Energy Abs. Foam	16.2	5.0"	5.0"	Failed in area of upper mounting bolts	Fail
Renco	4.1	1.13"	1.06"	Large split all the way across the top of cushion	Fail

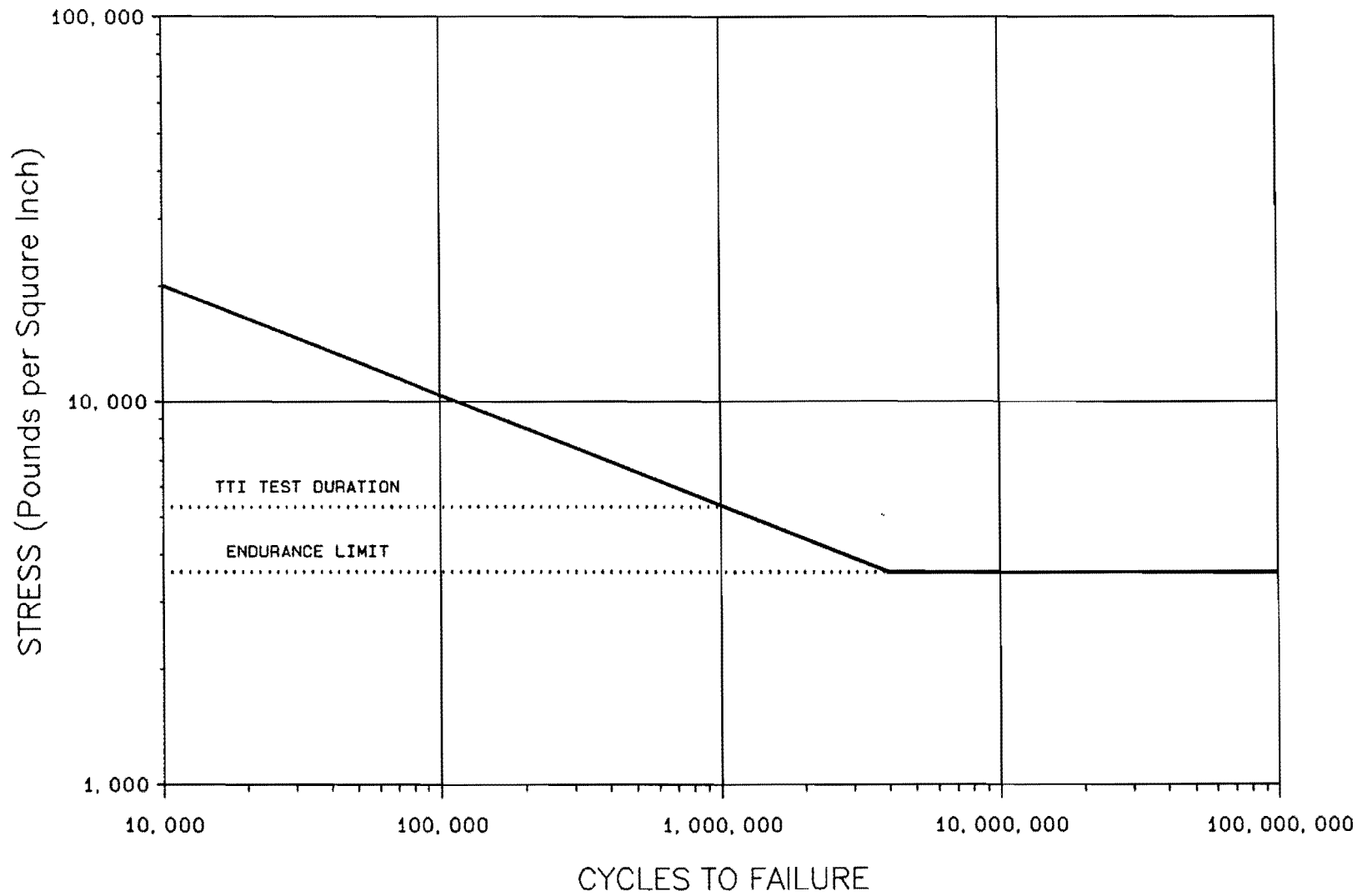


Figure taken from 'Full-Scale Fatigue Testing of Components and Structures,' edited by K.J. Marsh, 1988 (Butterworths: Boston)

Figure 11: TYPICAL RELATIONSHIP BETWEEN STRESS AND CYCLES TO FAILURE

TTI MOISTURE TEST: APPARATUS, PROCEDURE, PROTOCOL AND RESULTS

APPARATUS

The TTI moisture test facility was designed to produce an uninterrupted water spray over the top and sides of TMA's for 24 hours. The TMA is positioned, on metal rails, over the water tank, Figure 12. Water is pumped from the tank, through a flow control valve, through the spray nozzles onto the TMA and returned to the tank. The nozzles are of special design to provide a solid cone of droplets with a 90° divergence. The 8 nozzles are positioned so that the spray cones overlap and cover the entire surface of the TMA. To contain the over spray and return it to the tank, plastic shower curtains were used. The tank was fabricated at TTI for this purpose using plywood and lumber. Once completed the tank was fiberglassed on the inside to prevent any leaks. A mechanical flow meter was inserted in the water line just ahead of the nozzles. See Figure 12.

PROCEDURE

Each TMA to be moisture tested was first weighed and then moved to the spray facility and placed on the tank rails. The TMA was spray tested in its natural condition with no holes or cracks covered. Once in place, the spray and timer was started. By collecting water over several locations on the TMA within a given time period, a valve setting was found that provided a 6 inch per hour spray. The flow meter reading was set at that rate for use in future tests. After a total spray time of 24 hours the pump was turned off and the TMA allowed to drain for 1 hour. At the end of that time it was removed and reweighed just as in the pretest.

PROTOCOL

Since the only data obtained during the spray test was the weight of the TMA before and after testing, it was considered to be of the utmost importance. The method used to weigh each TMA was to suspend it from an overhead crane by nylon straps. Between the straps and the crane hook was a precision, strain gage load cell. The cell was connected to a digital readout with better than one pound resolution. The difference in the pre- and post-test weights was attributable to the amount of water retained.

A TMA is considered to pass the moisture test if at the end of the hour drain period the weight did not increase by more than 5 percent. For example a 400 pound TMA cannot retain over 20 pounds of water (2.4 gallons).

RESULTS

Table 2 and Figures 13 and 14 summarize the results of the moisture tests. Since the Renco and Energy Absorption/Alpha units did not pass the vibration test because of cracks in the surface, they were not moisture tested.

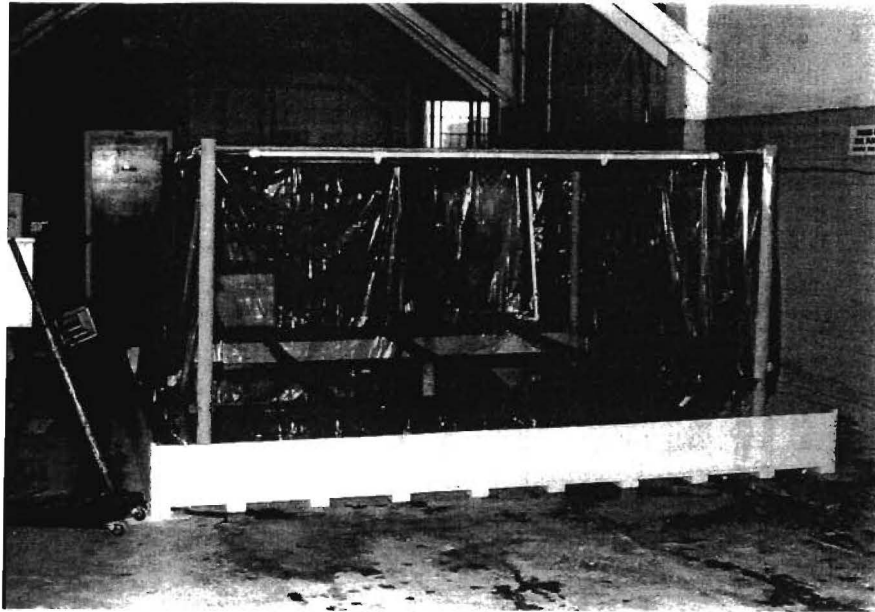


Figure 12(a): View of the TMA Moisture Testing Facility

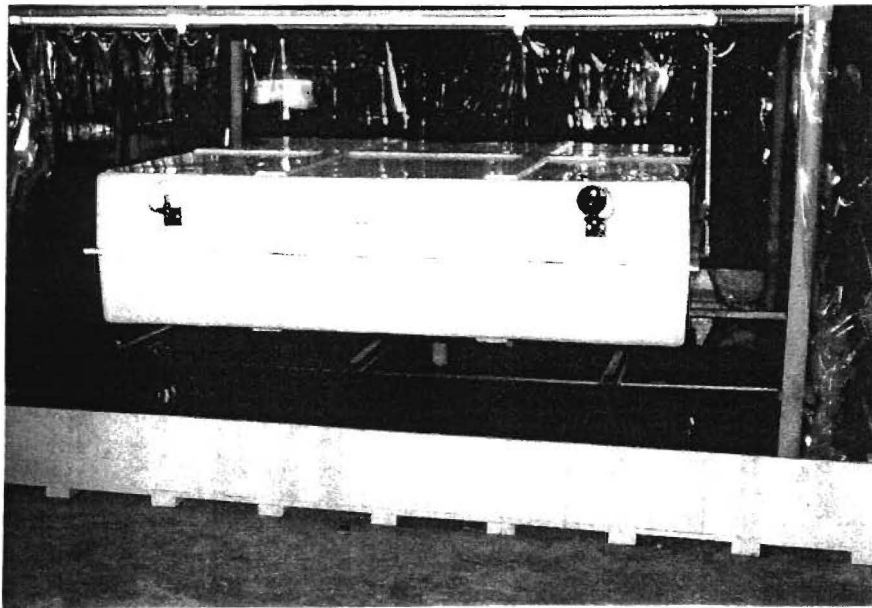
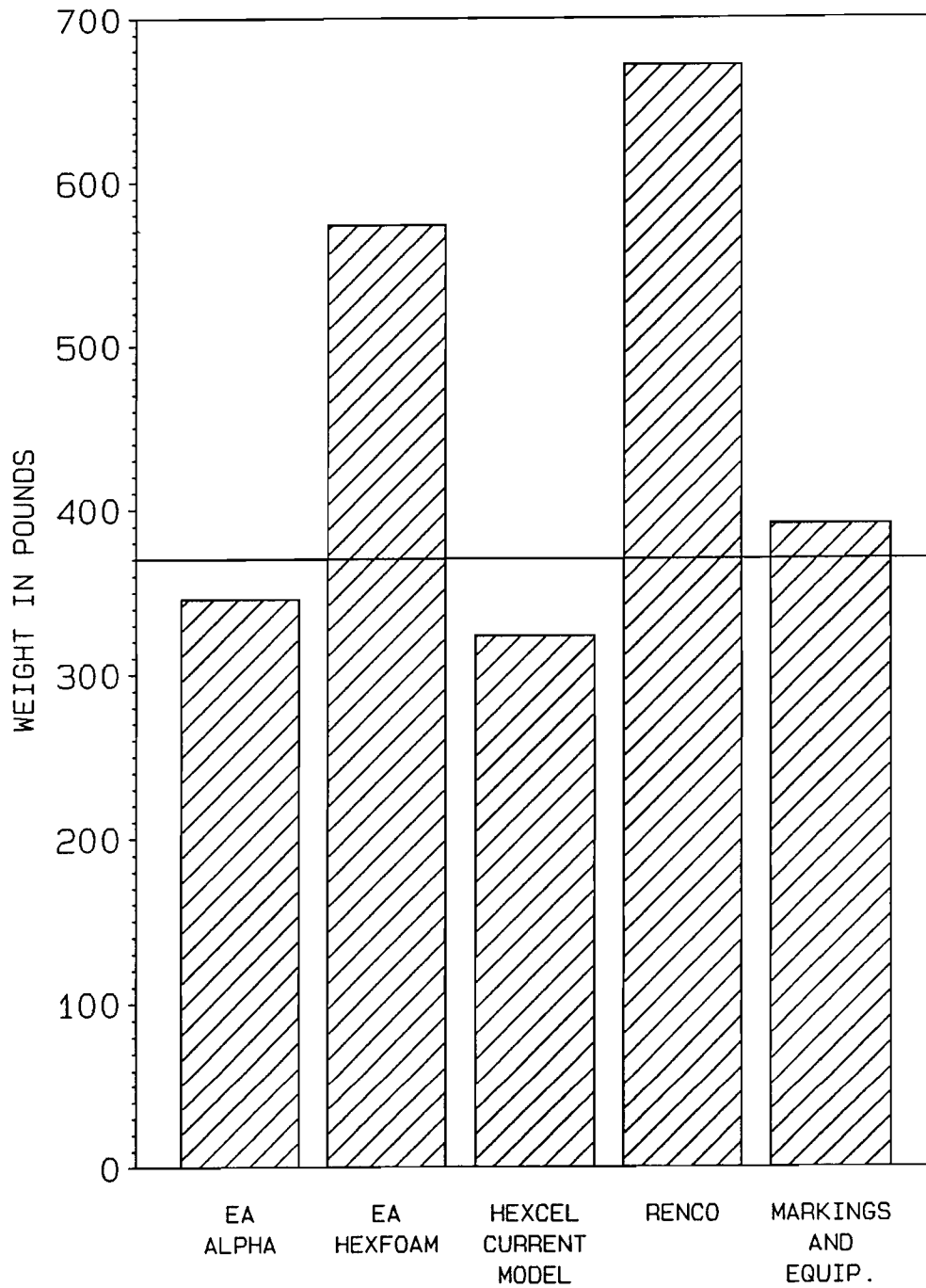


Figure 12(b): View of TMA Moisture Testing Facility
with a Unit in Place

Table 2: Results of Moisture Testing on Three Makes and Models of TMA's

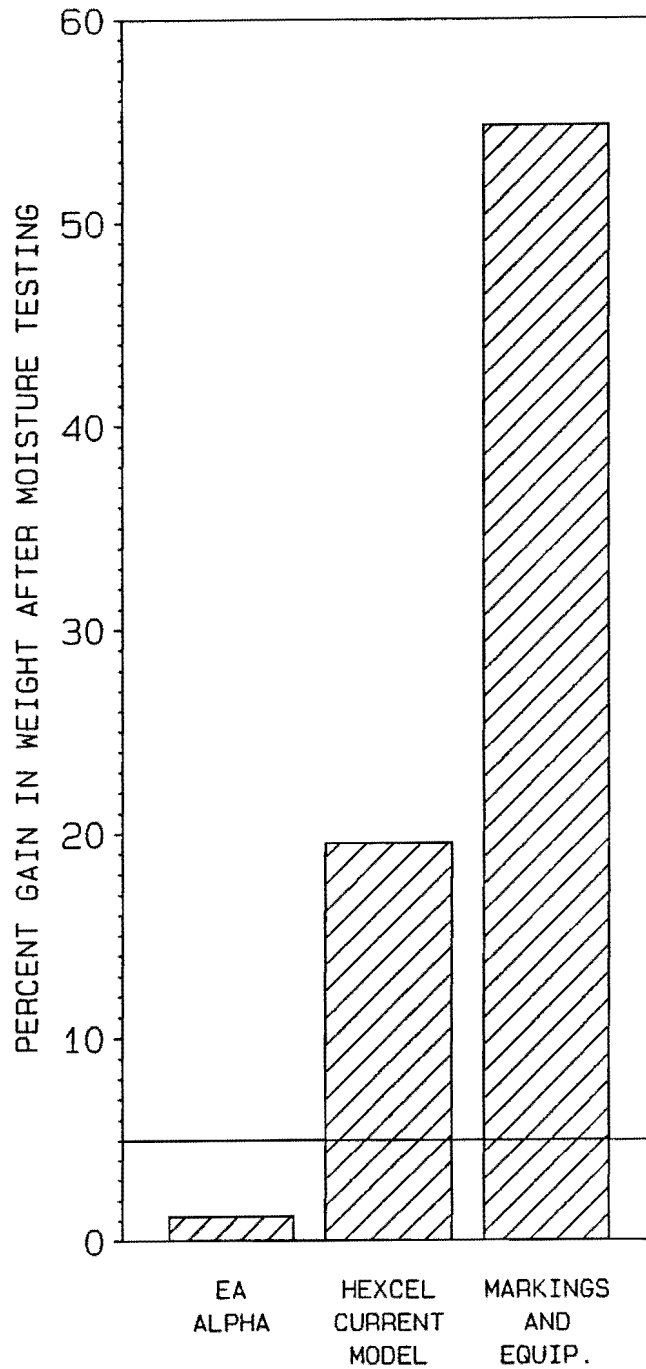
Manufacture	Dry Weight (Lbs.)	After Spray (Lbs.)	Increase	Pass Fail
Markings & Equip.	391	605	54.7%	Fail
Hexcell	323	386	19.5%	Fail
Energy Abs.- Alpha	346	350	1.2%	Pass
Energy Abs.- Foam	574	-	-	-
Renco	671	-	-	-



MAKES AND MODELS OF TRUCK MOUNTED ATTENUATOR'S

NOTE: California specifications require that TMA cushions not weigh more than 370 lbs.

Figure 13: WEIGHTS OF TMA CUSHIONS BEFORE MOISTURE TESTING



MAKES AND MODELS OF TRUCK MOUNTED ATTENUATOR'S

NOTE: The tentative 'percent weight gain' specification for the moisture test discussed in this report in five (5) percent.

Figure 14: PERCENT WEIGHT GAIN IN TMA CUSHIONS FOLLOWING MOISTURE TESTING