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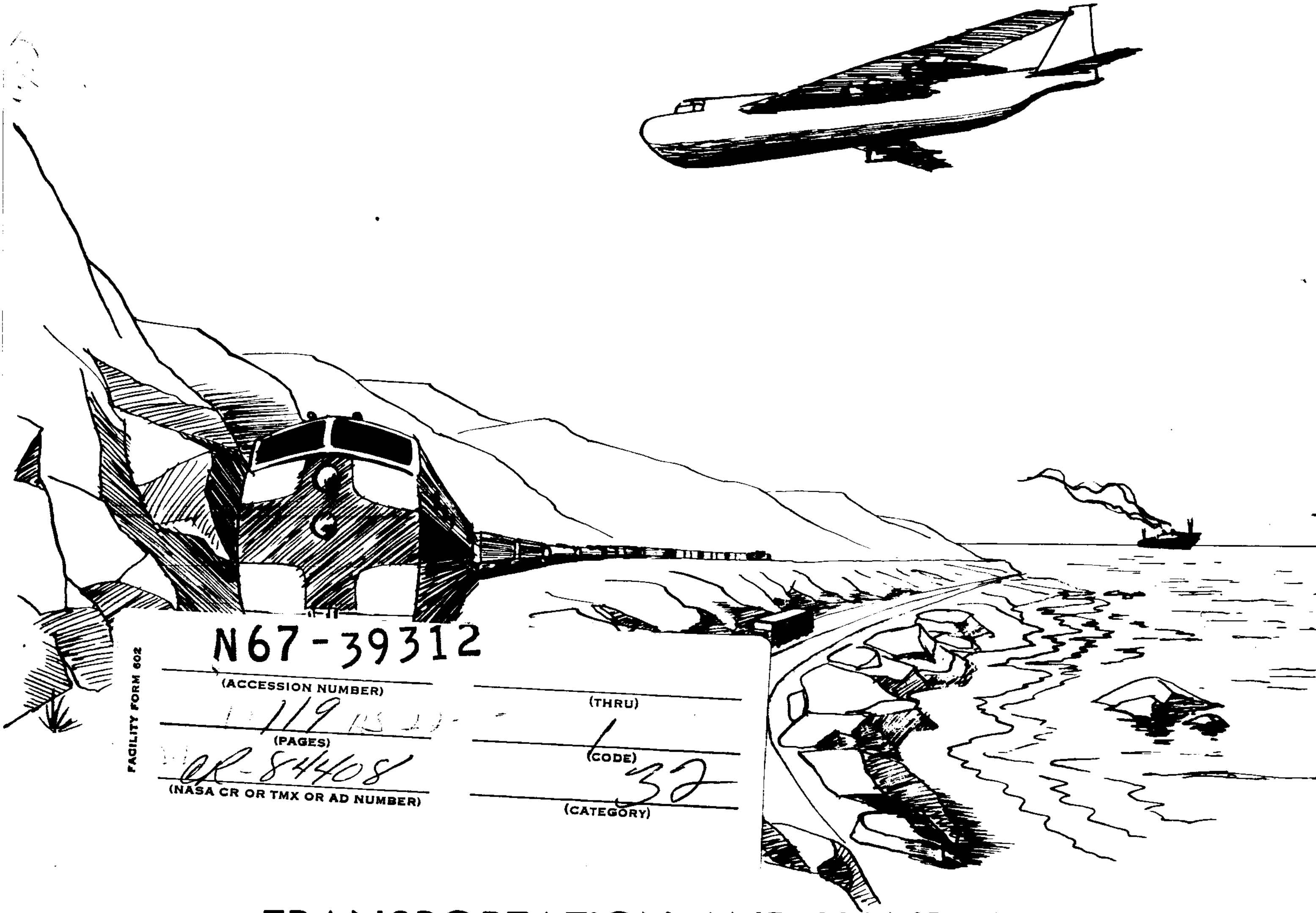

TRANSPORTATION AND HANDLING
SHOCK AND VIBRATION
DESIGN CRITERIA MANUAL

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Final Report

3 TRANSPORTATION AND HANDLING SHOCK AND VIBRATION ENVIRONMENTAL CRITERIA

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ABSTRACT

A comprehensive literature survey and search was conducted for data and information applicable to the cargo handling environment. Approximately 150 reports and articles were reviewed and over 50 agencies or organizations concerned with problems of this nature were contacted. The information compiled is summarized to show the distribution of drop heights for particular packages, distribution systems, and handling operations. Other information on the handling environment such as the number of drops received per package per trip, the distribution of the drops over the faces, edges and corners, the effect of package size and weight, the effect of the distribution system and the effect of labels and handholds are also presented. A case history for paper sacks is presented which describes the complete drop height history from manufacturer to customer. Applications of the data to typical package design problems are discussed. Results of recent measurement programs of the transportation shock and vibration environment are also presented.

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SECTION 1

INTRODUCTION

The shock and vibration environment encountered by items and equipment during shipment can be severe enough to cause damage. This, of course, depends upon the input motions resulting from the shipping environment and the fragility levels of the item or equipment. Packaging and design engineers, faced with the problem of shipping a product or piece of equipment must have detailed information concerning the environment (and the fragility levels of the equipment or product) in determining if an item requires protection. If protection is required, the information is used for designing protective packaging or isolation systems.

A very useful report would be provided if all available data concerning the shipping shock and vibration environment were available in condensed form in one source. Providing such a source was the main purpose of this program.

In this report, the shipping shock and vibration environment is defined to include both the intransit environment and the handling environment. The intransit environment includes those motions resulting from movement on transport vehicles (truck, ship, railroad, and aircraft). The handling environment includes those motions resulting from operations such as physical handling, loading and unloading, and movement within storage or warehouse areas.

SECTION 2

TRANSPORTATION SHOCK AND VIBRATION ENVIRONMENT

The intransit shock and vibration environment has been measured extensively for the four major transportation modes (rail, truck, ship and aircraft). The results of these measurement programs have been reviewed and are summarized in an earlier report.(1)* In an effort to make the description of this environment complete and up-to-date, the search for new data applicable to the transportation environment continued during the current study. Following are summaries of recent measurement programs in the four major transportation modes.

It should be mentioned that the information provided by these field measurement programs does not affect the peak envelope curves developed previously(1). The additional data merely describes the shock and vibration environment in greater detail.

2.1 Truck

A study of the truck transportation shock and vibration environment(2) has recently been completed by the Sandia Corporation, Albuquerque, New Mexico. The measurements of the dynamic environment recorded on the cargo floor of a semi-trailer during a transcontinental shipment from Wilmington, Delaware to Albuquerque, New Mexico are reported. The measured data has been processed and presented in terms of acceleration peaks versus frequency. The distributions of the acceleration peaks in selected frequency bandwidths are tabulated

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*Denotes Bibliography Reference

for each road condition and speed encountered during the trip. Only the summary composite plots for the loaded and unloaded vehicle are presented in this report. Data for specific road speeds, road types and their frequency of occurrence can be obtained from the original report. (Mechanical impedance measurements of the load and unloaded truck are also reported as is a method for applying the data to other loads which might be carried on the vehicle.)

The summary plots of the above tests are presented in Tables 1 and 2. Peak acceleration envelopes of the data are shown in Figure 1. They include vertical measurements only (these were proven to be the maximum) recorded at the forward, center, and aft cargo floor locations for the loaded and unloaded condition. The data are presented in terms of probability of occurrence (%) of acceleration levels within selected frequency bands. The plots have been summarized by Sandia to include the probability of occurrence of the road speeds and road types encountered in the transcontinental trip. The circled values are defined as shocks. The others are defined as vibrations.

It was concluded from the above study that the environment over most roads consists of a low level complex vibration upon which are superimposed a great number of repetitive shocks.

This form of data presentation provides not only information on the peak accelerations encountered but provides information on the levels of vibration below the peaks and their probability of occurrence. For example, accelerations in the frequency band 0-2 1/2 cps occur at a level of .23 g's for .51% of a trip while .1 g levels occur during 90.2% of a trip. For a 1000 mile trip at an average speed of 50 mph, (20 hour trip) a vibration level of .23 g's

TABLE 1

Truck - Semi Trailer
Composite Plot
Vertical Axis
(Front, Center, Aft Locations)

Overall Trip Composite Amplitude Distribution
for an Unloaded Truck

Probability of Occurrence, Percent
(-) (Probability less than 0.1% is not reported)

O-Peak Acceleration, G													
3.2	4.18						-	-	-	-	0.25	0.14	2.48
2.3	-						-	-	-	-	-	-	-
1.65	-	-			-		-	-	-	-	-	-	-
1.2	-	-	-		-		-	-	-	-	-	-	-
0.86	0.12	-	-		-	-	-	-	-	-	-	0.12	-
0.62	0.12	-	-	-	-	-	-	-	-	0.12	-	0.18	-
0.45	1.89	-	0.20	-	0.10	-	-	-	-	0.54	-	0.23	0.19
0.32	-	0.33	0.20	0.24	0.28	-	-	-	-	1.67	0.16	0.47	0.44
0.23	0.51	3.03	1.33	0.99	1.63	0.47	0.17	0.16	0.10	5.22	0.93	2.14	1.57
0.17	0.86	10.52	7.33	2.91	4.46	1.97	1.52	0.40	0.15	8.12	3.55	5.67	4.06
0.12	2.05	16.87	11.68	8.56	7.94	4.69	9.61	0.96	0.34	9.11	8.34	8.06	9.26
0.1	90.21	69.12	79.23	87.21	85.55	92.70	88.48	98.21	99.14	74.99	86.57	82.94	81.80
Frequency, cps:	0-2 1/2	2 1/2-5	5-10	10-15	15-23	23-30	30-44	44-63	63-88	88-125	125-175	175-238	238-313

Total Peak Accelerations Used in this Summary: 700,909

Notes:

1. This summary accounts for probability of occurrence of road speeds and road types encountered in a typicak transcontinental trip.
2. The circled values are those which may be considered to be "shocks". The uncircled values are those considered to be "vibration".

TABLE 2

Truck - Semi Trailer
Composite Plot
Vertical Axis
(Front, Center, Aft Locations)

Overall Trip Composite Amplitude Distribution
for a Loaded Truck

Probability of Occurrence, Percent
(-) (Probability less than 0.1% is not reported)

0-Peak Acceleration, G													
3.2	3.85						-	-	-	-	0.20	0.19	0.90
2.3	-												
1.65	-						-	-					-
1.2	0.52		-	-	-		-		-	-	-		
0.86	0.82	-	-	-	-	-	-	-		0.12	-	-	-
0.62	19.06	-	-	0.11	-	-	-	-	-	0.91	0.10	-	0.17
0.45	3.11	-	-	0.70	0.15	-	-	-	-	3.58	0.83	1.36	1.60
0.32	7.16	0.21	0.26	1.99	0.71	0.32	-	-	-	6.71	3.12	5.51	4.92
0.23	18.14	1.35	2.05	5.66	3.33	2.12	0.66	0.53	-	10.59	8.92	16.48	11.86
0.17	15.24	3.24	4.87	7.71	6.85	4.54	2.47	1.24	0.19	8.89	11.28	15.97	13.51
0.12	7.24	7.02	10.27	10.01	12.82	7.52	6.88	2.86	0.95	9.17	12.87	17.65	16.12
0.1	23.33	88.11	82.50	73.78	76.09	85.42	89.90	95.25	98.65	59.96	62.63	42.71	50.66
Frequency, cps:	0-2 1/2	2 1/2-5	5-10	10-15	15-23	23-30	30-44	44-63	63-88	88-125	125-175	175-238	238-313

Total Peak Accelerations Used in this Summary: 2,253,493

Notes: 1. This summary accounts for probability of occurrecne of road speeds and road types encountered in a typical transcontinental trip.

2. The cricled values are those which may be considered to be "shocks". The uncircled values are those considered to be "vibration".

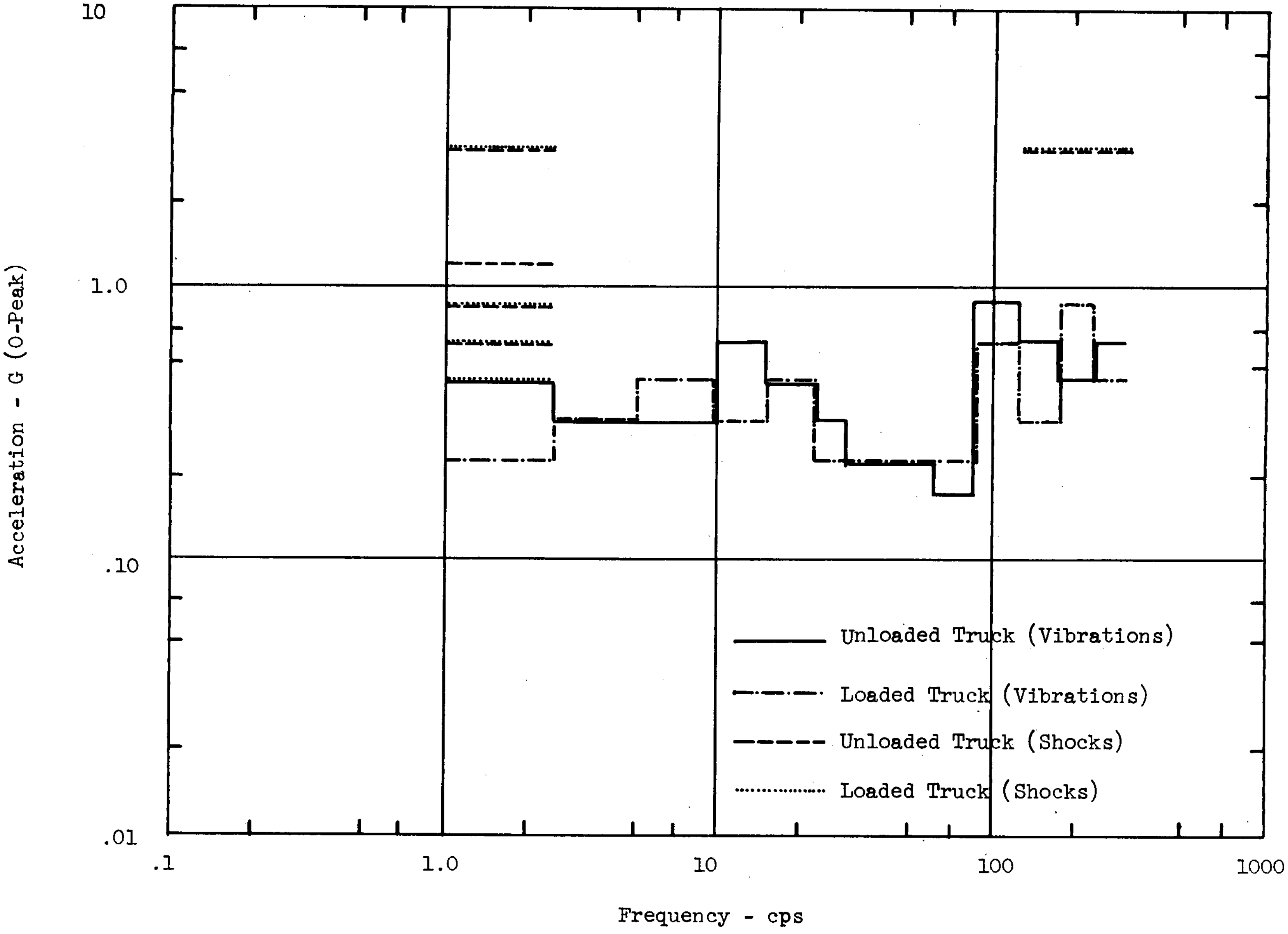


Figure 1 SHOCK AND VIBRATION ENVIRONMENT - FLATBED TRACTOR TRAILER, VERTICAL (FRONT, CENTER AND AFT LOCATIONS)

would occur for .51% of the time or 6 minutes. This format represents the most extensive and descriptive method for processing and presenting transportation shock and vibration environmental data. Additional studies are being conducted by Sandia on other transport vehicles. The data for these vehicles will be processed and presented in the same format.

Other recent studies pertinent to the truck shock and vibration environment include a study of an air ride suspension van(3). Power spectral density and shock spectrum analysis plots are presented for data recorded during rough road and smooth highway operations. The scales used on the plots, however, make the conversion to g_{rms} vs. frequency difficult and for this reason they have not been included. Some of the conclusions from this study are as follows: Equipment should be hard mounted to the floor of the van if the dynamic characteristics of the shock isolation system or support structure have not been accurately determined. (If the system is tuned to the input, the response is amplified.) The amplitudes on the van floor rarely exceeded 1-g peak. At low frequencies the center of the van floor lengthwise and widthwise is less severe. The shock spectra plots indicate that shock mounted equipment should have a system resonant frequency well below 18 cps. A peak response occurs at 18 cps and may be associated with the phenomena of wheel bounce.

2.2 Rail

Additional data concerning the railroad shock and vibration environment has been obtained from tests conducted by the United Technology Center(4). Their studies cover measurements recorded during transcontinental shipment of a large solid propellent motor case. The data resulting from these tests are reported in terms of peak acceleration and frequency. These results do not alter the summary plots developed previously.

Railroad Coupling - The severest shock environment on railroads occurs during coupling operations. Numerous shock mitigating devices have been developed but detailed information on their performance could not be found. Comparative performances of a number of the devices, however, are presented in a recent New York Central railroad report(5). Peak acceleration as a function of coupling speed is used to compare the devices.

The conventional railroad draft gear (the shock absorbing device behind the coupler) produces the severest coupling shock environment. Shock spectrum plots for this environment were presented earlier(1). However, some organizations have commented that this form of data is not suitable as a test specification for performing laboratory tests. It is preferred that the coupling shock data be presented in simpler parameters. For these situations, the shock can be related to equivalent pulses by enveloping the coupling shock spectra with spectra for standard pulses eg. 1/2 sine, square, saw tooth. (This enveloping process, however, usually results in a more severe test.)

For coupling speeds of 6 and 11 miles per hour the following pulses have been suggested:

6 mph	13 g's zero to peak	43 msec duration
11 mph	47 g's zero to peak	17 msec duration

The shock spectra for these pulses, Figure 2, envelope the computed spectra from the actual coupling measurements at most frequencies. The very high frequencies are not enveloped since they are considered less damaging than the lower frequencies. Further, complete enveloping would result

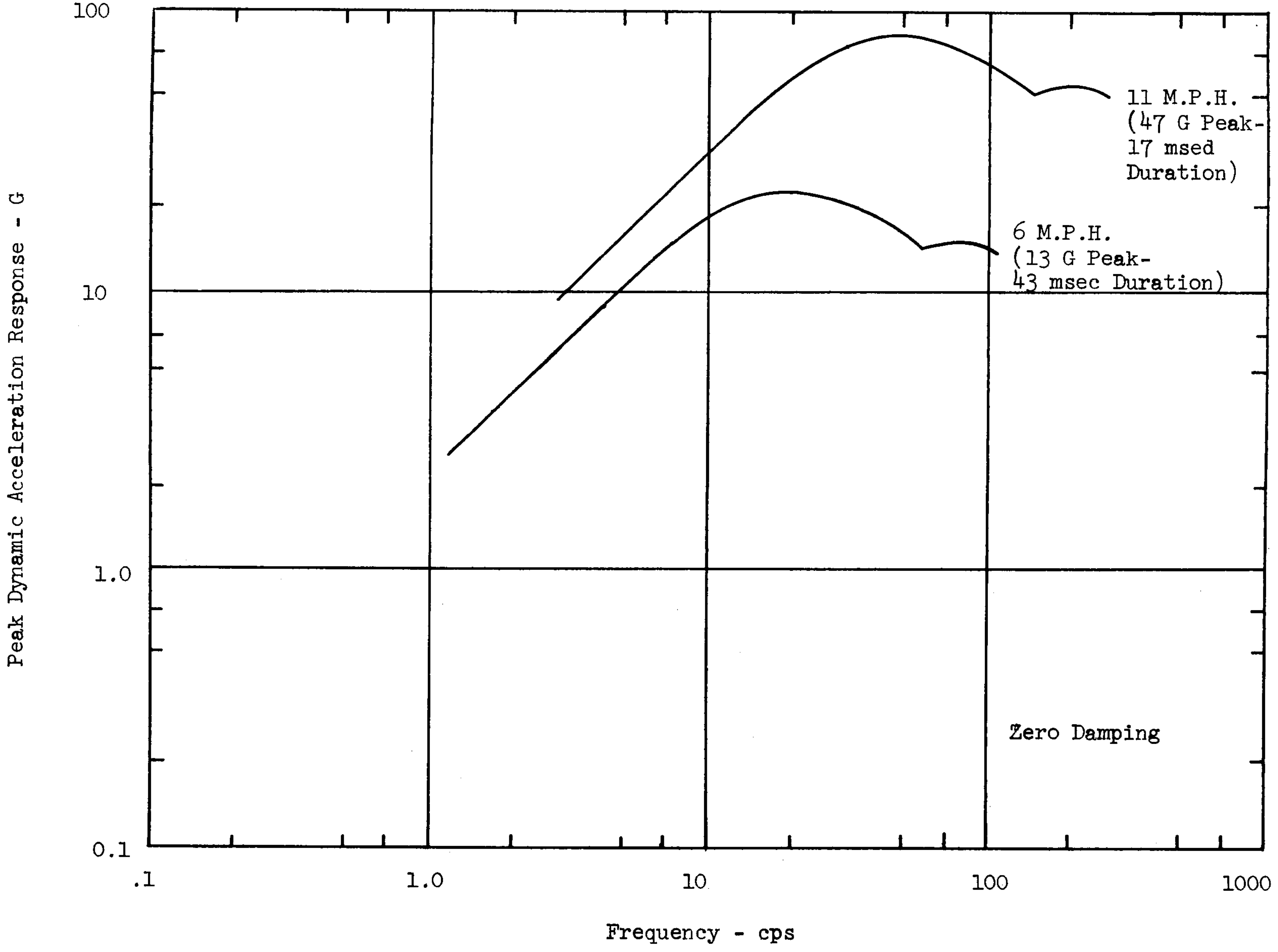


Figure 2 SHOCK SPECTRUM FOR 1/2 SINE PULSES CORRESPONDING TO 6 MPH AND 11 MPH RAILROAD COUPLING SPEEDS

in unrealistic impact velocities. Integration of the above pulses results in impact velocities of 7.8 and 11 mph respectively.

2.3 Aircraft

Additional data concerning the aircraft shock and vibration environment could not be found. The Sandia Corporation has reported that a program is in progress on a version of the Boeing 707 jet. The data from this study will be reported in the same format used for the truck data (i.e. distribution of peaks within selected bandwidths and their probability of occurrence).

2.4 Ship

Shock and vibration measurements in the cargo area of ships are insufficient at the present time to define the environment. Data recorded at the fantail are still the most complete and should be used as an upper bound on the environment.

The relationship between vibration measurements in the cargo hold and the aft perpendicular has been determined for discrete frequencies.(18, 19). These results indicate that the vibration levels in the cargo hold range from 1/2 to 3/4 the levels measured at the aft perpendicular. These factors can be applied to the vibration data previously presented for the ship environment.(1)

SECTION 3

HANDLING ENVIRONMENT

As mentioned earlier, the handling environment is defined to include those motions resulting from operations such as physical handling, loading and unloading and movement thereof in the storage area. In general, the shocks received by packages and equipment during handling operations are greater than those experienced on a vehicle in transit.

The intensity of the handling shocks will be influenced by such factors as the distribution system (railroad, truck, air freight, railway express, full carload shipments, mixed consignments, etc.) and the characteristics of the package (size, shape, weight, etc.). Detailed information describing these effects would be extremely useful to all engineering personnel involved in packaging and testing.

3.1 State of the Art

The environment resulting from handling operations has not been measured extensively. Some of the reasons for this are that accurate self-contained instrumentation capable of recording unattended for long periods was not available and secondly successful, although overdesigned, packages had been shipped by conservatively estimating the environment.

An early approach to the package design problem was to construct a package or container and submit it to field trials. If the item arrived intact, the packaging was considered adequate. If the item arrived damaged, additional packaging was provided until an acceptable design was obtained. This method is time consuming, costly and often results in overpackaging. Another disadvantage is that information is obtained only if damage occurs. Further it is not always possible to relate the damage to a package to the particular shocks which have been imposed. Another method for evaluating packages was to compare the performance of a new package with that of a package which had been proven successful. This again can result in overpackaging with resulting economic losses.

Later, laboratory tests were developed for evaluating the performance of packages. The test conditions proposed were roughly related to conditions occurring in the field. Typical of these are the recommended maximum drop heights shown in Table 3. It can be seen that the drop heights are related to package size, weight and method of handling. In addition to the drop test, other laboratory tests for evaluating packages prior to shipment were developed. These include the rotating drum test, the pendulum impact test, and the inclined impact test. The latter tests attempt to simulate the damage rather than duplicate the shipping environment.

Recently, field measurement programs have been initiated in an attempt to accurately define the handling environment. These measurement programs have employed both instrumentation and observation techniques.

3.2 Measurement Programs

3.2.1 Instrumentation Studies

In most of the early instrumentation measurement programs, the peak acceleration response of a packaged item to a handling shock was measured. Data of this type provides information on the relative severity of different handling operations but does not provide information on the input shock

TABLE 3

RECOMMENDED DROP HEIGHTS

Package Weight (lbs)	Type of Handling	Drop Height (inches)
0-20	One man throwing	42
21-50	One man carrying	36
51-250	Two man carrying	30
251-500	Light Equipment Handling	24
501-1000	Light Equipment Handling	18
1000 up	Heavy Equipment Handling	12

Notes:

1. The above drop heights are also related to package size. For example, the size of the package classifies the type of handling it receives into one man, two man, light equipment or heavy equipment with the corresponding drop heights.

2. The orientation of the package at impact varies with package size and weight. Small light-weight packages are subjected to free falls onto sides, edges and corners. Larger heavier packages handled by light or heavy equipment are dropped where one end rests on the floor and the other end is dropped. (Heavier packages may also be rolled over if manually handled.)

excitation. This information cannot be determined from the component response unless the system parameters are known. Unfortunately, most reports do not contain this information.

More recent measurement programs have attempted to measure the environment in terms of drop height. The use of drop height to express the handling environment is considered of more importance than the commonly used acceleration because of (1) the standard package drop testing methods and (2) a knowledge of the energy to be absorbed can be readily determined from drop height.

The main obstacle in the performance of field measurement programs has been the lack of self-contained instrumentation. The requirements for an instrument to be used for this purpose would include its ability to accurately measure height of drop, angle of impact, nature of impact surface, surface of package impacted (side, top, bottom, edge, or corner), time reference to determine when and where impacts occurred, and an internal storage capability for recording unattended for periods up to two weeks.

A number of instrument development programs have been initiated for the purpose of developing instruments with the above capabilities. Organizations which have reported activity in this area include Wright Air Development Center, Air Force Packaging Research and Development Branch (Brookley), U. S. Army Engineering Research and Development Laboratories, Army Ballistic Missile Agency, Quartermaster Food and Container Institute, Sandia Corporation, the Packaging and Allied Trades Research Association (Surrey, England), and Tektronics, Inc. Some instruments were developed from these studies and used in various field measurement programs. None of those developed, however, meet all of the specified requirements. Discussion of these instruments and some of the results obtained are reported in later sections of this report.

The procedure used in conducting instrumented field measurement programs is as follows: The recorders are housed inside a package, calibrated in controlled tests, and then sent through various shipping routes. The drop heights, distribution over the faces, and other related information is recorded at the end of a trip. The package is then sent on a return trip or to an alternate destination and the above information recorded. The shipping is continued until adequate statistical data is obtained.

3.2.2 Observational Studies

The difficulties involved in developing instrumentation have been circumvented in some instances by employing observational techniques for monitoring the handling environment. In this approach the handling of packages is observed at the different handling points. The drop height for each package handled is estimated as is the angle of impact and the nature of the impact surface.

This method is efficient when applied to a given depot or handling point which considers all of the packages handled there. The complete handling over a trip for a given type of package requires that observations be made at all transfer points, depots and other handling points so that the factors affecting the drops can be determined. Factors such as package weight and size as well as characteristics of the handling operation (handling aids, etc.), can be determined by this method. If a particular handling operation has not been observed, it is estimated from those handling operations which are similar.

(Instrumented studies cannot provide this information since the method of handling is unknown.)

From the above discussion it is obvious that the observational method is efficient for studying all types and sizes of packages including those of awkward shape such as long thin packages. It is limited, however, by the difficulty of access and the volume of packages handled. If only a few packages are handled the presence of an observer may inhibit normal handling; whereas a large volume of packages enables more data to be collected and allows the observer to become part of the surroundings. It gives information on the impact between packages and the characteristics of the handling operation (i.e. height and distance carried, use of mechanical aids). It is inefficient, however, in that it requires extensive study to determine the drops received by a particular package over a complicated trip. This is more easily obtained in instrumented packages.

3.3 Summarization of Available Data

Field measurements of the dynamic environment encountered by packages during handling operations have been reported in various forms. Typical forms of the data are peak acceleration, zones of shock, drop height, and shock spectra. Because of the sparse amount of data available, the results of some of the more extensive studies have been summarized. These studies present the data in the above forms.

It should be noted that in most of the investigations, the handling operations encountered by instrumented packages were not always well defined so that it is difficult to determine what percentage of the handling shocks, if any, occurred as a result of fork truck or crane hoisting operations.

The data reported in terms of drop height has been organized to show the drop height probability, the number of drops likely to occur during a trip, and the distribution of the drops over the faces, corners and edges. The effect of the distribution system, handholds and labels on the package, and the effect of package size and weight are also described.

3.3.1 Zones of Shock

The pioneer investigation of the handling environment was conducted by the National Safe Transit Committee(5). In this study, commercial impact recorders were mounted in wooden boxes and shipped as ordinary products. These instruments record the shocks encountered during shipment by the displacements of spring-mass systems. The systems are linked to recording pens which record the deflections on a recording paper driven by a clock mechanism. The pen deflections are recorded in zones of shock from 1 to 5 with the 5th zone representing the severest shock. The results of this study provide information on the relative severity of the transportation and handling environment but do not provide quantitative data on the drop heights during handling. No relationships were given in the report between the zones-of-shock and drop height.

The shocks received by a package shipped via air cargo from Cleveland to New York to Cleveland are shown in Figure 3. The results of numerous test shipments for all modes of transportation are shown in Figure 4. These results point out that the severest environment, regardless of the type of carrier employed, occurs during handling operations.

SHOCKS AS RECEIVED BY A PACKAGED PRODUCT SHIPPED AS AIR CARGO FROM CLEVELAND TO NEW YORK TO CLEVELAND, INCLUDING TRUCK TRANSPORTATION FROM LAGUARDIA AIRPORT TO NEWARK AIRPORT (N.S.T.C.)

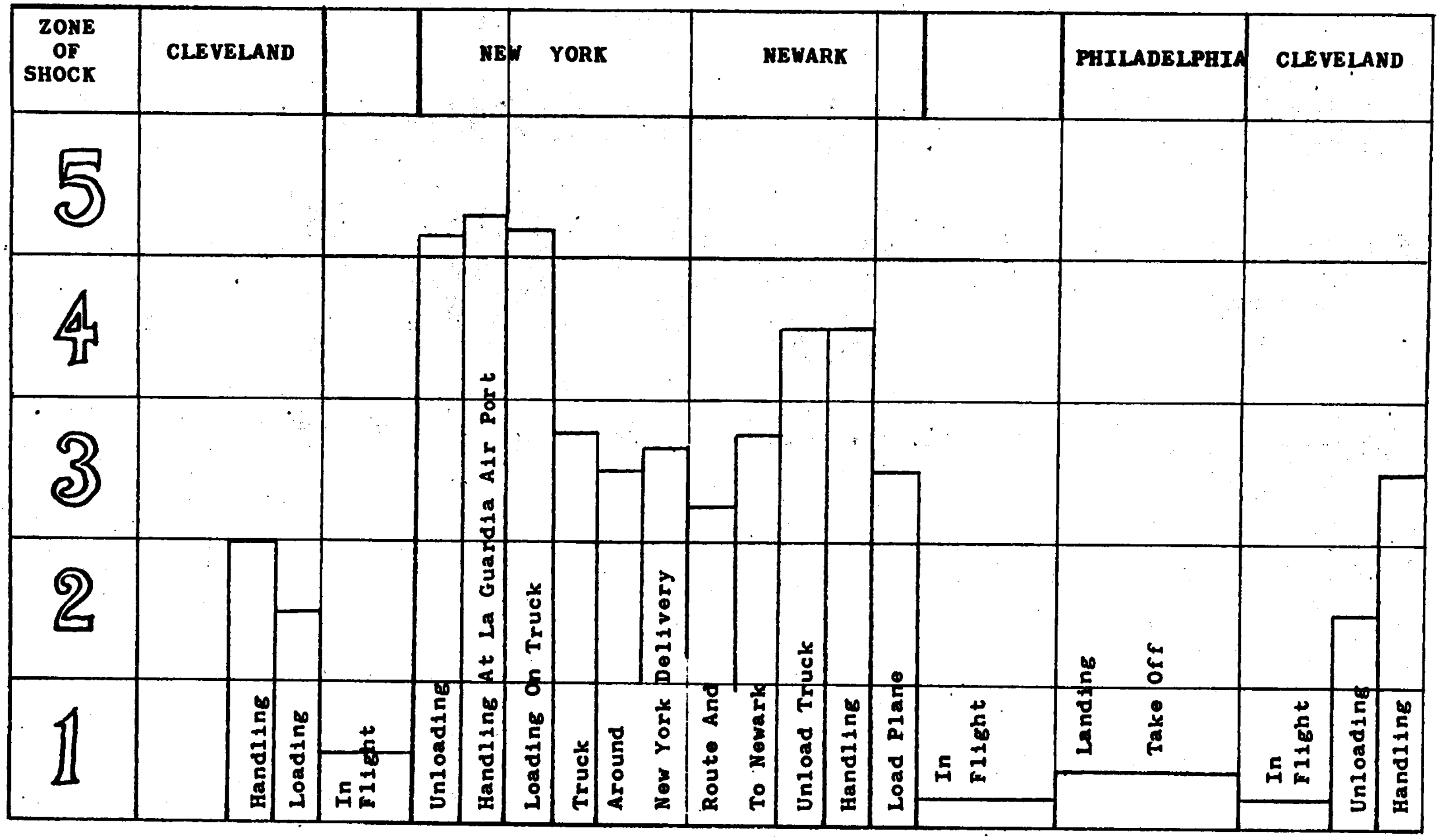


Figure 3 NATIONAL SAFE TRANSIT COMMITTEE MEASUREMENTS - AIR CARGO

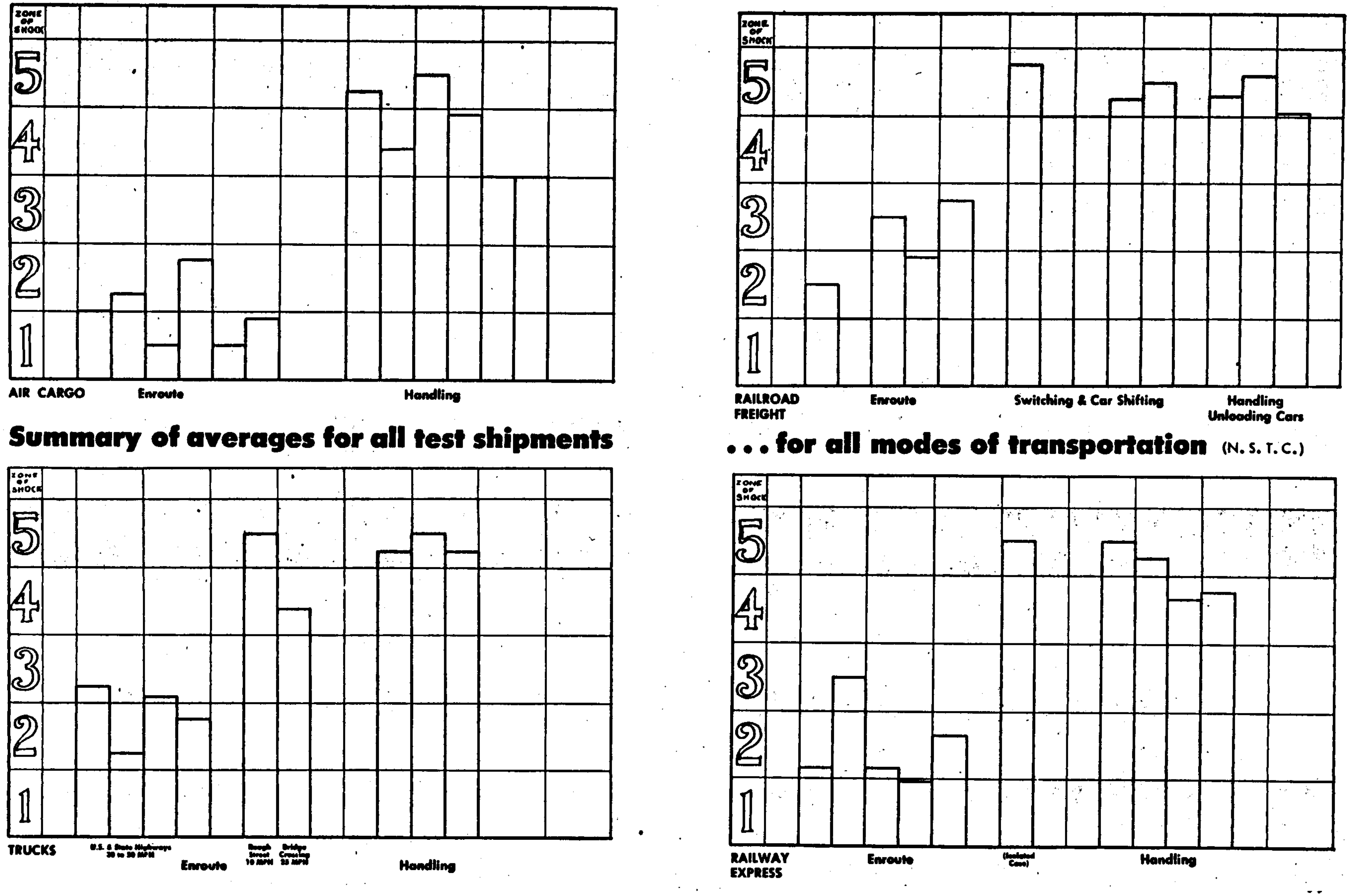


Figure 4 SUMMARIES OF NATIONAL SAFE TRANSIT COMMITTEE MEASUREMENT PROGRAMS

3.3.2 Peak Acceleration

Another extensive measurement program employing commercial impact recorders has been reported by Packaging Consultants Incorporated, Washington, D. C.(12). In this study thirty-three shipping containers of various shape ratios, (long 3:1:1, average 3:2:2 and tall 1:1:2) and weights (small 60 and 90 lbs., medium 150 and 250 lbs., and large 500 and 1500 lbs.) were fabricated and instrumented with Impact-O-Graphs. The packages were shipped via air, truck, ship and air modes of transportation within a radius of 200 miles of Washington. The measured field data is reported in terms of peak accelerations (Table 4). Laboratory tests to correlate instrument peak acceleration readings with drop heights are shown in Table 5. The wide variations in the instrument recordings (range) makes any correlation with drop height difficult.

Based upon the field studies, it was concluded that the rough handling tests for packaged electronic equipment are too severe. A proposed rough handling specification for packaged electronic equipment was recommended. A review of the principal rough handling specifications (Table 6) showed a wide variation in the test requirements.

3.3.3 Drop Height

3.3.3.1 Drop Height Distribution

Packages can be dropped every time they are handled and for a given handling operation or trip there is a probability of the package being dropped from a given height. The distribution of drops has been measured for particular packages, distribution systems, and handling points. Typical results are shown in Figures 5 to 9. The data is plotted on log-normal probability

TABLE 4

FIELD TEST RESULTS

PEAK ACCELERATIONS

(Figures in "g's")

	Small (60-90#)	Medium Small Skid-Mounted (150-250#)	Medium Skid-Mounted (250-500#)	Large Skid-Mounted (500-1500#)
Average (3:2:2)				
Mean (a)	41	31	14	21
Range	3-144	4-131	3-24	3-43
Long (3:1:1)				
Mean (b)	30	20	19	18
Range	4-50	3-38	4-35	3-14
Tall (1:1:2)				
Mean (c)	29	22	17	9
Range	3-76	3-41	3-50	3-17

TABLE 5

LABORATORY TEST RESULTS

PEAK ACCELERATIONS

Drop Height (Inches)		60-90# Flat Drop 6-12-24	150-250#	250-500#	500-1500#
			Edgewise Rotation Drop		
			12-18-24	12-18-24	12-18-24
(a)	Mean	57/78/77	31/38/47	39/47/70	40/41/61
	Range	(32-104)	(22-50)	(35-74)	(39-64)
(b)	Mean	39/51/90	39/47/56	54/45/43	60/73/83
	Range	(28-108)	(36-64)	(39-66)	(46-88)
(c)	Mean	74/88/114	Data here are not included since tall containers could not be subjected to corresponding drop tests without tip-over. Shocks produced at maximum height of rotational drop tests averaged less than 17 "g".		
	Range	(52-139)			

TABLE 6

ROUGH HANDLING REQUIREMENTS

	JAN-P-100	MIL-P-116	MIL-E-4970A*	MIL-P-7936A	ASTM	NSTC
(1) **FREE-FALL DROP:** Weight Max.	1) 50# or less 2) 100# " "	200#	200#	200#	Not stated	100#
Minimum Drop Height	1) 30 In. 2) 24 In.	30 In.	50# - 30 In. 100# - 21 In. 150# - 18 In. 200# - 16 In.	Level A, Level B 50# 30 22 100# 21 16 150# 18 14 200# 16 12	12 In.	over 50# - 12 In under 50#- 18 In
Number of Drops	8	8	8	8	8	10
Type and number of Drops	Once each corner	Once each corner	Once each corner	Once each corner	Once each corner	corners, edges, & flat face
(2) **FACE DROP TEST:**	None	None	Once each major face	None	None	See above
Height of Face Drop			50# - 30 In. 100# - 21 In. 150# - 18 In. 200# - 16 In. 600# - 14 In. 3000# - 12 In. No limit-12 In.			
(3) **EDGEWISE ROTATIONAL DROP TEST:**	None	200# & up more than 60 In.	600# & up	600# & up - not over 72 In.	1000# & up more than 48 In.	None
Height of Edgewise Drop		5 In.	5 to 6 In.	5 to 6 In.	Predetermined & Increased by 1" Increments. Constant.	
Number of Drops		Twice opp. ends	Once ea. end	Once		
Height of Edgewise Drop In relation to weight		200-250#-30 250-500#-24 500-1000#-18 over 1000#-12	600# - 36 In. 3000#- 24 In. no limit - 12 In.	Level A, Level B 600# 36 27 3000# 24 18 No limit - 12 9		

TABLE 6 (Cont'd)

		JAN-P-100	MIL-P-116	MIL-E-4970A*	MIL-P-7936A	ASTM	NSTC
(4)	CORNERWISE ROTATIONAL DROP:	None	200# & up more than 60 in.	600# & up - less than 72 in.	600# & up - less than 72 in.	1000# & up more than 48 in.	None
	Number of Drops		2 ea. opposite corner	1 ea. opposite corner	1 ea. opposite corner	Repeated at ea. height	
	Height of block		5 & 12 in.	5 & 12 in.	5 & 12 in.	4 & 10 in.	
	Height in relation to weight		same as edgewise drop test	same as edgewise drop test	same as edgewise drop test		
(5)	PENDULUM-IMPACT TEST:	None	200# & up - more than 60 in.	200# & up - more than 60 in.	200# & up - more than 60 in.	None	None
	Distance of travel of c.g. (in inches)		200-250#-14" 250-500#-11" 500-1000#-8" over 1000#-5"	9 in.	9 in.		
	Number of impacts & location		once each on 2 opposite ends	once ea., side and end, if less 9'5".	once ea., side and end, if less 9'5".		
(6)	INCLINE-IMPACT TEST: (CONBUR)	None	200# & up. ASTM D880	200# & up. ASTM D880	200# & up. ASTM D880	ASTM Method D880 No min. weight	100# & up.
	Velocity ft. per sec.		200-250#-7.0 250-500#-5.5 500-1000#-4.0 over 1000#-2.5	7.0	7.0	6 in. increments	1st Qtr of 5th zone
(7)	ROLL-OVER or TILT-OVER TEST:	300# to 600#	None	None	None	None	None
(8)	PUSH-OVER TEST:	100# up to 300#. 42" drop. Twice top up and bottom up.	None	None	None	None	None
(9)	VIBRATION TEST:	None	None	*This spec covers environmental testing, therefore does require vibration tests. If adequate machines are not available, drop tests are recommended in lieu thereof.	None	ASTM D999	100# & up.

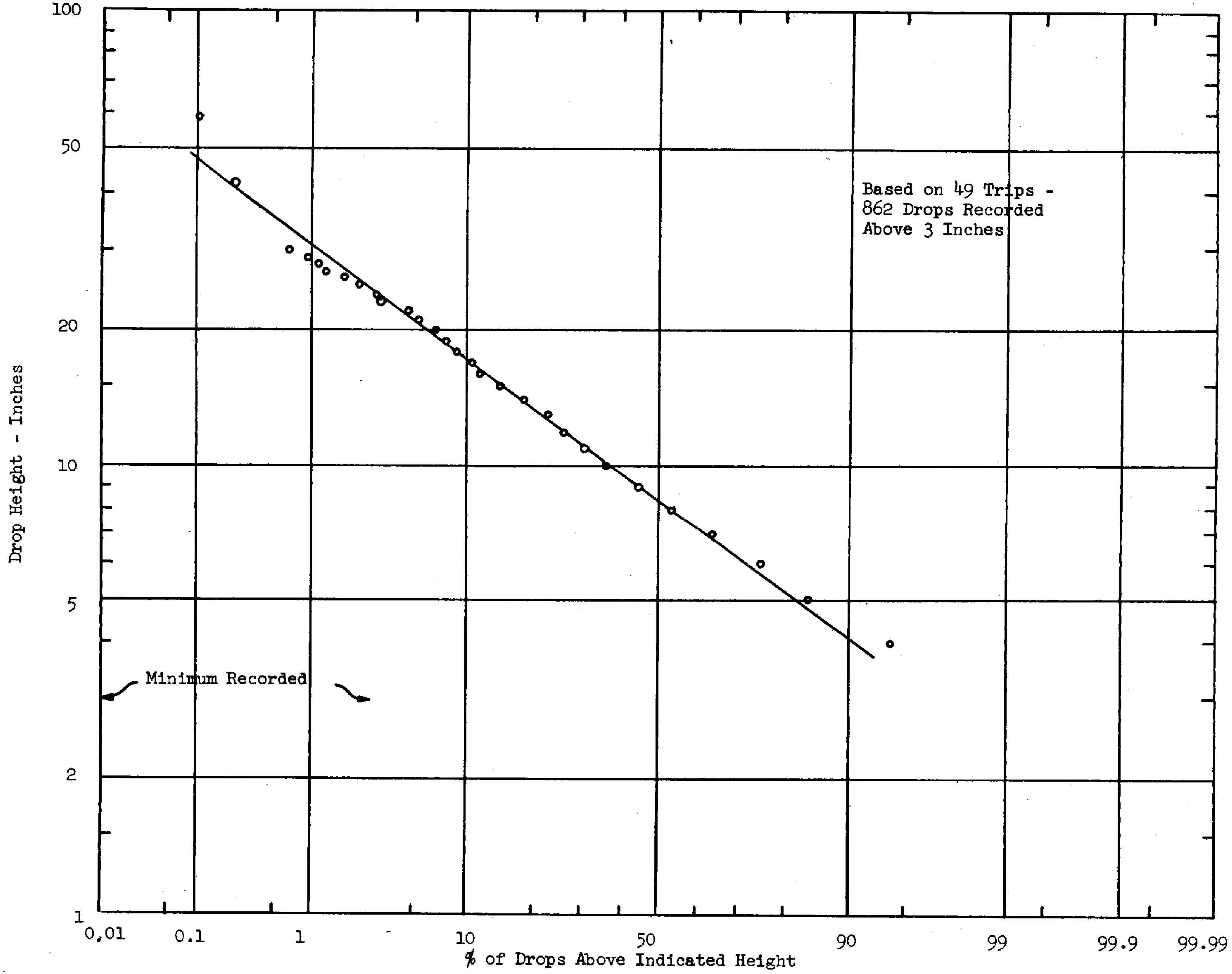


Figure 5 43 LB CLEATED PLYWOOD BOX SENT BY RAILWAY EXPRESS (19" x 19" x 19")

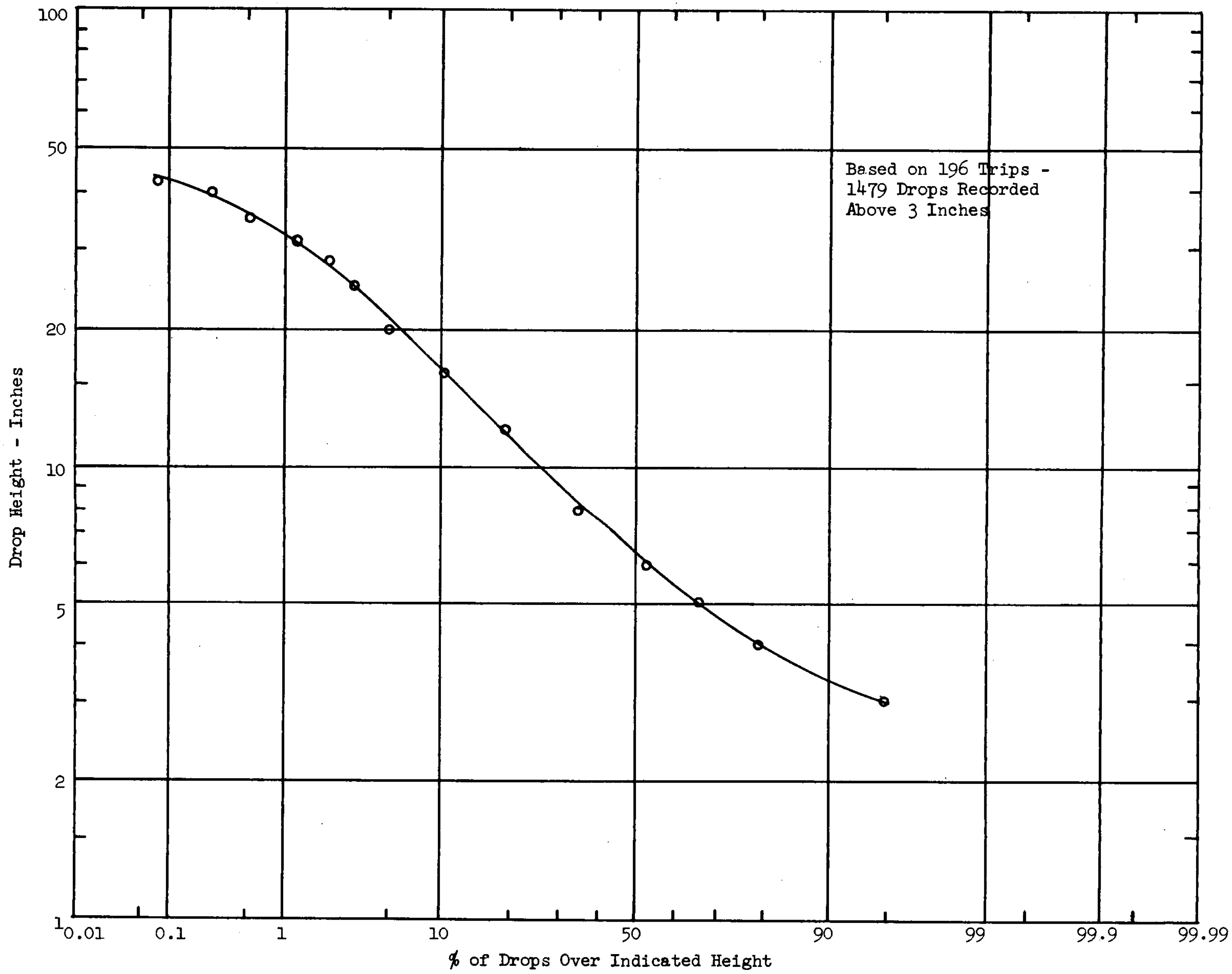


Figure 6 22 LB CORRUGATED FIBRE BOARD BOX SENT BY RAIL (MIXED GOODS)

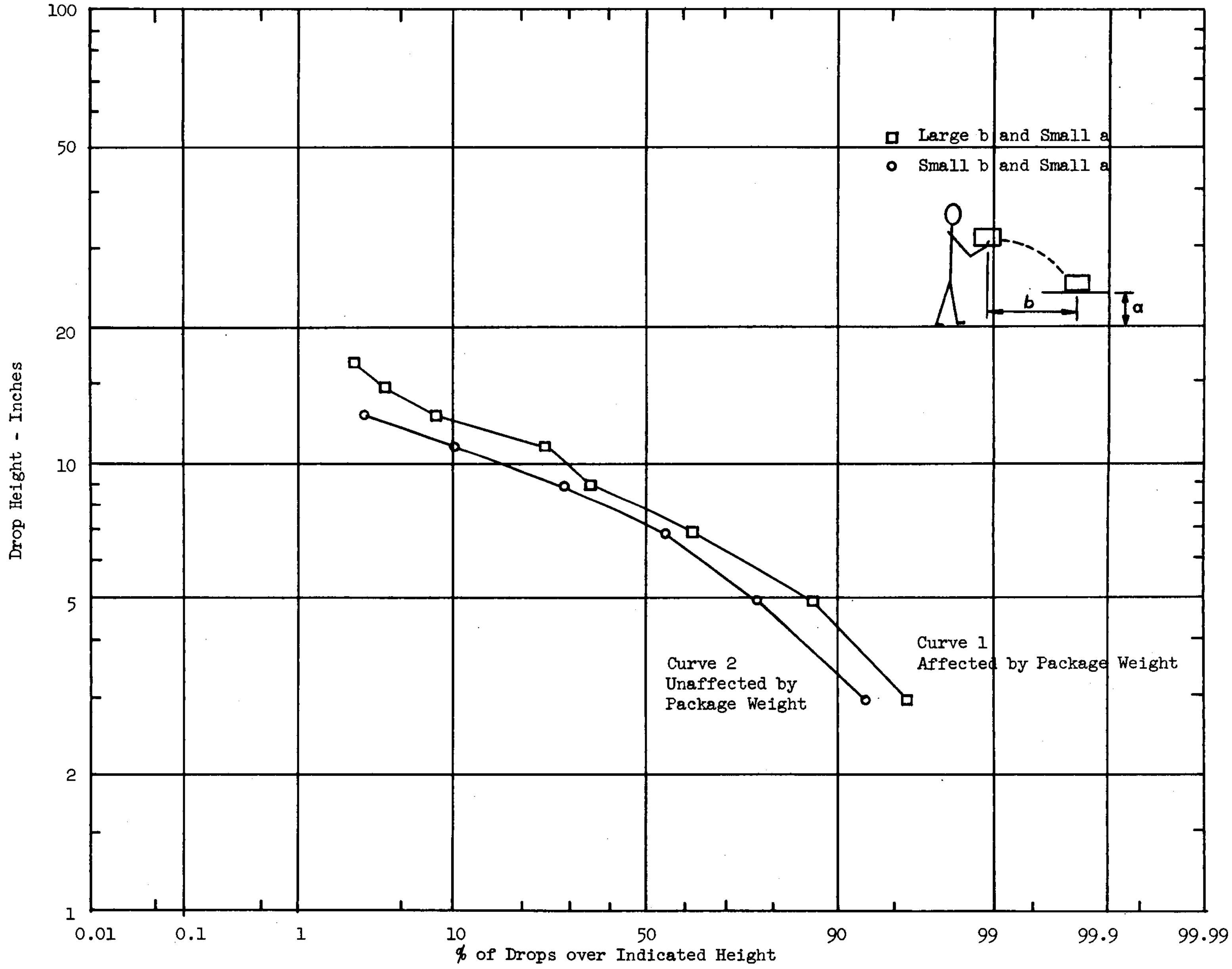


Figure 7 RAILROAD DEPOT LOADING OPERATION - SEVEREST HANDLING OPERATION

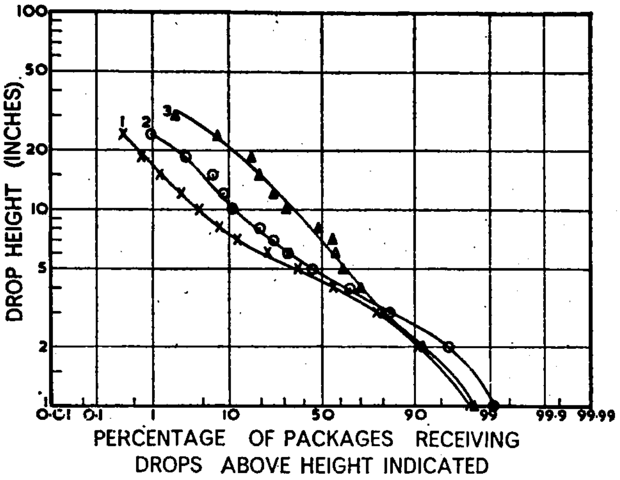


Figure 8

Curve 1 - Loading Handcart from Railroad Car
Mean Weight 32.5 lb.
n = 310

Curve 2 - Sorting Prior to Loading Cart
Mean Weight 35.3 lb.
n = 113

Curve 3 - Loading Railroad Car from Truck
Mean Weight 31.2 lb.
n = 74

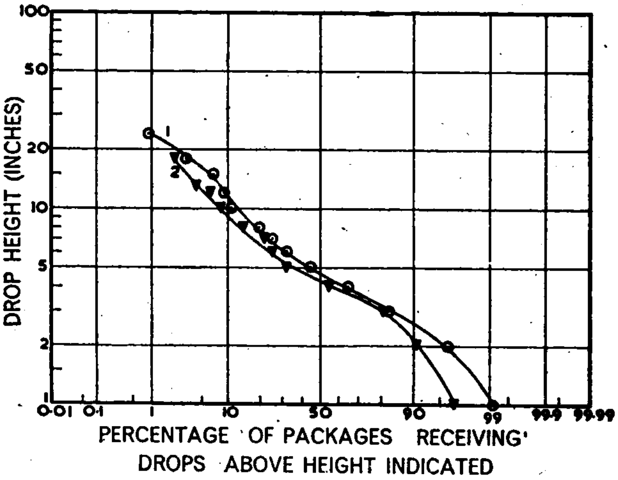


Figure 9

Curve 1 - Sorting Prior to Loading Cart
n = 113

Curve 2 - Sorting Prior to Loading Truck
n = 47

paper which presents the statistical probability of a package receiving a drop at or above the height indicated, during a trip or handling operation.

Data for the 43 pound 19 inch cubical cleated plywood box was obtained from tests conducted by Wright Air Development Center(7). Instrumentation consisted of a commercial Impact-O-Graph used in conjunction with a cubical spring suspension system. The purpose of the spring suspension system was to control the input to the recording instrument such that the instrument is independent of the type of surface impacted, i.e. compressibility of the surface. This study was restricted to routes involved in shipments from one Air Material Area to another Air Material Area via Railway Express (although some shipments were made via Air Freight). The data is based on 49 trips involving 13 packages. (862 drops were recorded above 3 inches.) The data shows that only 5% of the packages received drops in excess of 21 inches.

Data for the 22 pound 17-1/2" x 12" x 11-1/2" corrugated fibreboard box was obtained from tests conducted by the Packaging and Allied Trades Research Association, Surrey, England(8). The PATRA Drop Recorder was used in this study. This instrument consists of an arrangement of weights pivoted about an axis perpendicular to a recording chart and so arranged that each is sensitive to shocks along one of the three sensitive axes. Three recording pens record the drops on opposite pair of faces of the container. Drops are recorded on a waxed paper chart which is driven at a constant speed. On impact the paper is accelerated by a shock operated drive. This separates the shock traces and makes it easier to read successive drops. The recorder is mounted inside a package with a 2 inch layer of polyurethane foam around it. The results presented in Figure 6 were obtained from packages shipped via railroad in mixed goods consignments. The curve is based on measurements recorded on 192 packages. (Three out and return trips from a large railroad goods depot.)

Figure 7 presents the data for two transfer points at a large railroad depot. The data was obtained from observational studies conducted by the Swedish Packaging Research Laboratory, Stockholm, Sweden(9). Seven handling operations were observed at a large railway goods depot handling express freight weighing less than 80 pounds. The severest handling operation (Curve 1) consisted of transferring the packages from a conveyor to a hand cart. Drop heights were observed only during the loading of the first layer on the cart on the far end. These packages received the highest drops and occurred during 5% of the loading time.

A second handling operation was observed in transferring the packages from a railroad car to a hand cart (Curve 2). Packages loaded on the bottom layer received the highest drops as in the previously described operation and were the only ones recorded. These two curves demonstrate the effect of horizontal distance on drop height. They show that the severity of the drops increase with the horizontal distance through which the packages are thrown.

Other reported PATRA studies include direct observation of the handling operations associated with loading and unloading of a railraod car(8). The drop heights recorded during the unloading of a railroad car onto a pushcart are shown in Figure 8, Curve 1, which is based upon 310 observations. The packages ranged in weight from 10 to 100 pounds with the most common weight between 30 and 39 pounds. The curve shows that 5% of the packages had drops over 8 inches and 1% over 16 inches. The sorting (according to destination) of packages prior to loading the pushcart is shown as Curve 2. This curve is based upon 113 observations. Higher drops occurred during this operation with 5% being dropped over 16 inches. It was found that one in three packages are handled for sorting while all packages are loaded on the cart.

Handling operations where packages are thrown result in higher drops. This is shown by Curve 3 in which the unloading from trucks directly into railroad cars (walking to and fro) was observed. Here 5% of the drops were over 26 inches.

Drops occurring during two different sorting operations are shown in Figure 9. Curve 1 applies to sorting prior to unloading railroad cars and Curve 2 applies to sorting prior to loading a truck. It can be seen that the drop height distributions are similar for the two operations.

3.3.3.2 Number of Drops Received per Package

Damage to packaged items from drops incident to the handling environment can be cumulative. For packages of this nature the number of drops at different heights which the package receives as well as the maximum drop height must be known.

The number of drops recorded above a given height (3", 6", 12" and 24") are presented in Figure 10 for a 43 lb. container shipped via railway express(7) and in Figure 11 for a 22 lb. container shipped via railroad (mixed goods consignments)(8).

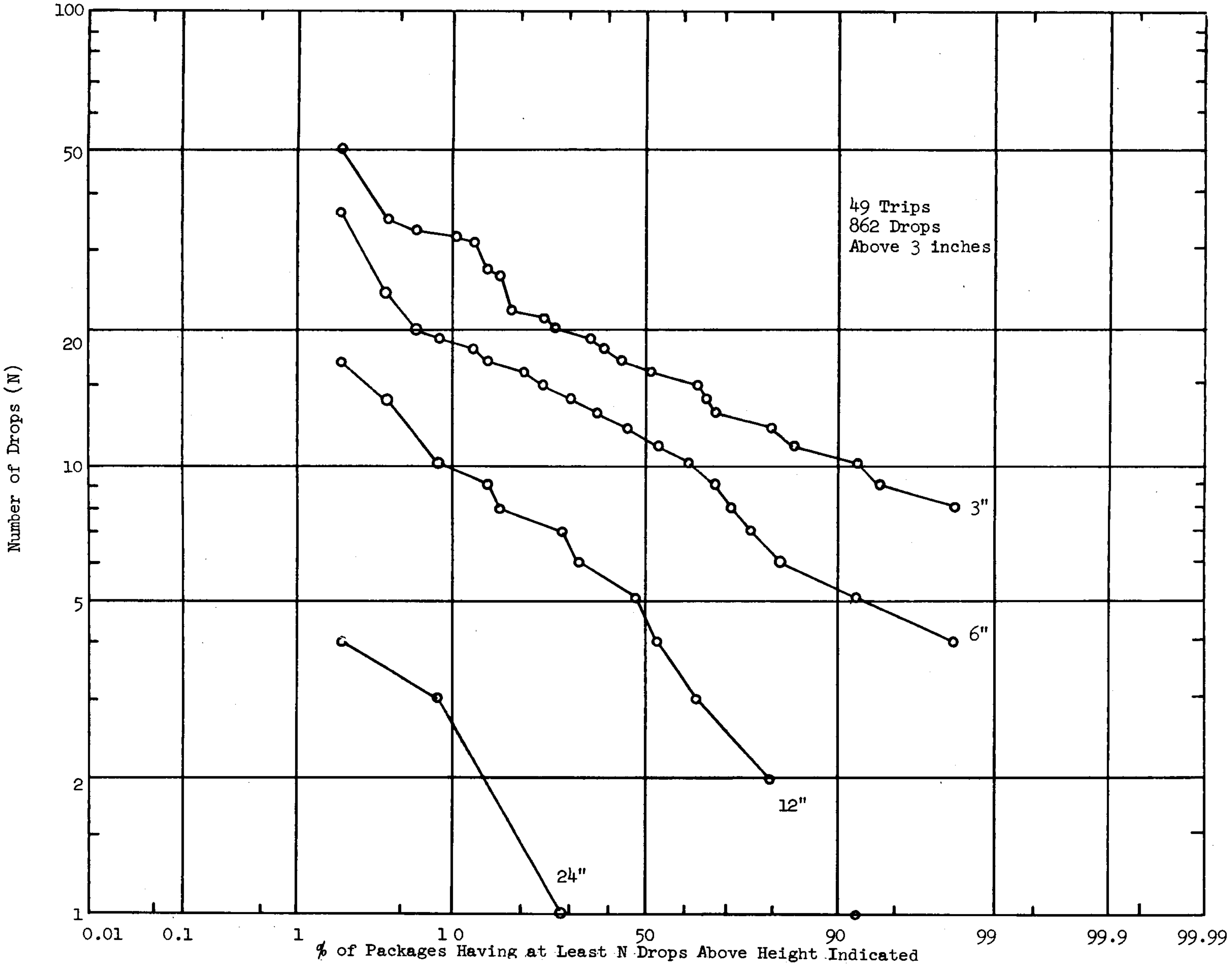


Figure 10 43 LB CLEATED PLYWOOD BOX SENT BY RAILWAY EXPRESS (19" x 19" x 19")

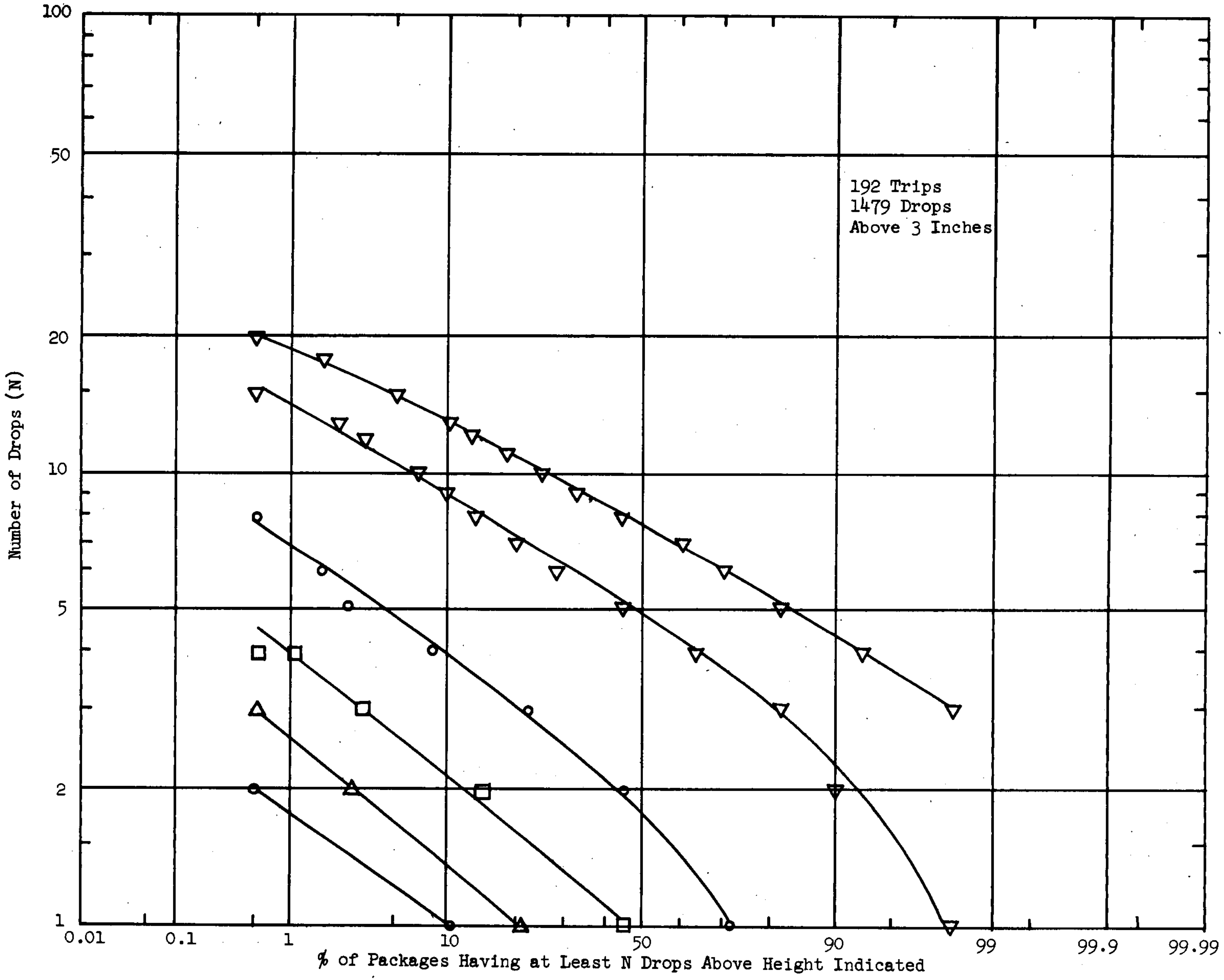


Figure 11 22 LB CORRUGATED FIBREBOARD BOX (17-1/2" x 12" x 11-1/2")
SEND BY RAILROAD (MIXED GOODS)

Other studies yielding information on the number of drops have been conducted by the Packaging and Allied Trades Research Association employing the PATRA Journey Shock Recorders(8, 10, 11). This instrument consists of a mass-spring system attached to a counter unit and immersed in oil. Each unit has uni-directional sensitivity and counts the number of drops above a preset height on a given face of the package. By using a number of counters, covering the different faces and set to record at different heights, the drops can be estimated between the heights set for the different counters. This instrument is also packed with a 2 inch layer of cushioning around the recorders. The cushioning makes the acceleration pulse acting on the recorder independent of the compressibility of the surface on which the package is dropped. Thus the response of the recorder is primarily a function of drop height and secondarily by the angle of the package on impact.

Results conducted with these instruments are shown in Figure 12 for passenger train shipments and in Figure 13 for mixed good railroad shipments. The instrumented packages weighed 52 pounds and measured 17" x 12" x 13". Twenty-four packages were shipped over six different routes (144 package-trips). A total of 653 drops were recorded for the mixed goods consignment and 798 for the passenger train shipment.

3.3.3.3 Effect of Distribution System

The distribution system will influence the drops received by packages. Shown in Table 7 are the mean number of drops received per package for rail (mixed good consignments and passenger), road, and overseas shipments. These results show that 52 pound packages shipped by passenger train are exposed to the severest handling followed by truck and mixed goods rail shipments.

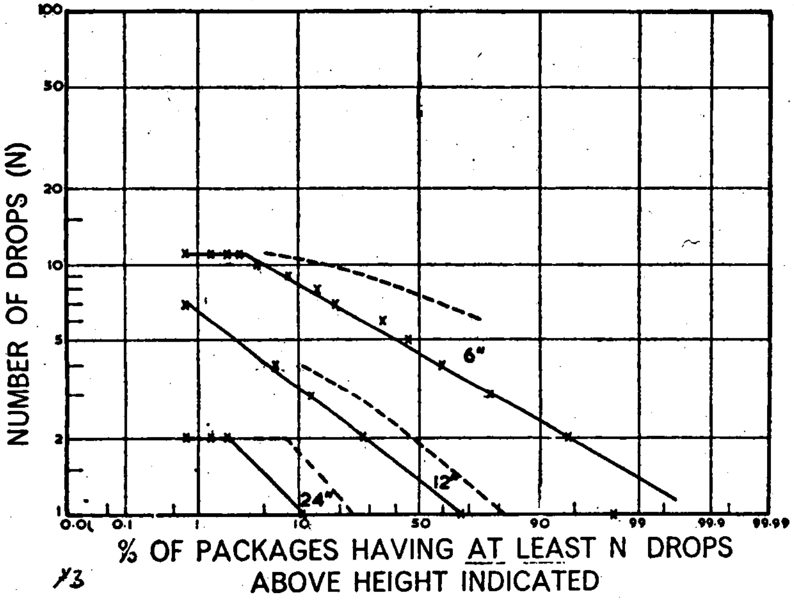


Figure 12. 52 LB FIBREBOARD BOX SENT BY RAIL (MIXED GOODS).

Solid Line - Combined Results of Six Routes

Dashed Line - Results for Route with Most Severe Handling

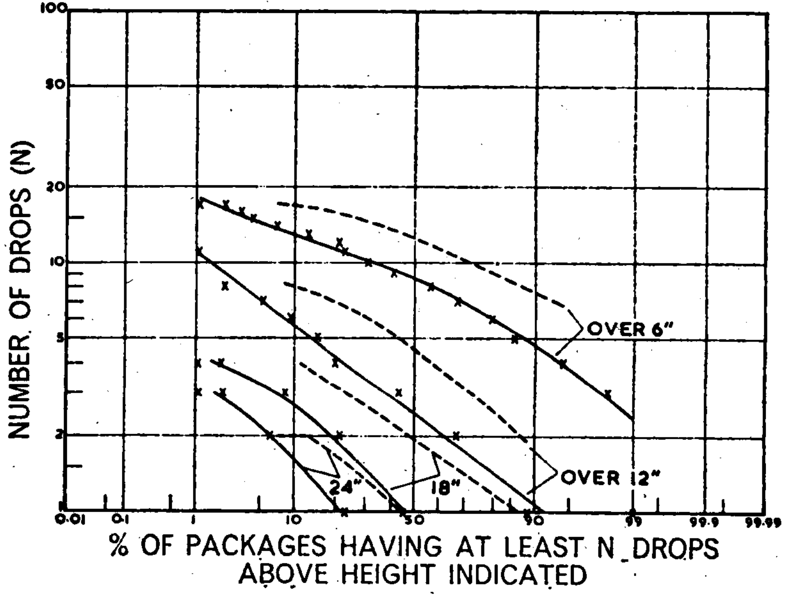


Figure 13 52 LB FIBREBOARD BOX SENT BY PASSENGER TRAIN

Solid Line - Combined Results for Six Routes

Dashed Line - Results for Route with Most Severe Handling

The effect of mixed good consignments via railroad as opposed to full container loads is shown in Figure 14(11). This data is based upon six shipments of four instrumented packages. The outgoing shipment was in packages in full load consignments and the return shipment was as mixed goods. These results show that mixed goods shipments received on the average more severe handling than full load consignments. It further shows that the handling received by individual packages is variable and that misleading information can result if only a few packages are monitored.

The 22 lb. package showed less variation in handling between passenger train and mixed goods train shipments than the 52 lb. package. This is attributed to the choice of routes which did not cover as wide a range for the lighter package.

The mean number of drops received in overseas shipments(10) are much lower than the other distribution systems. This is due in part to the weights of the packages shipped. Results of a series of overseas shipments are shown in Table 8. The shipments were from the United Kingdom to Cyprus to Aden to Bahrein to Aden to Cyprus to the United Kingdom. Crane operations and off loadings from ships to lighters were involved. It can be seen from these results that as the weight of the package increases, the maximum drop height decreases.

3.3.3.4 Distribution of Drops over the Faces

The distribution of drops over the faces of packages have been determined in most studies(8). Table 9 is a listing of the reported distributions. Although these results apply to a limited range of package sizes,

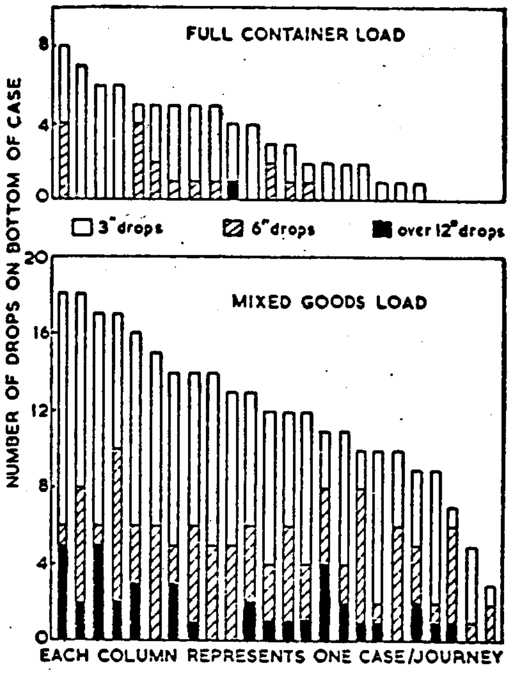


Figure 14 VARIABILITY IN HANDLING OF CASES

Outbound - Full Contained Railroad Shipment 24 Trips (4 Cases in 6 Shipments)

Inbound - Mixed Goods Railroad Shipment 24 Trips

TABLE 7

EFFECT OF DISTRIBUTION SYSTEM

Mean Number of Drops per Trip per Package

52 lb Package (17" x 13" x 12")

Drop Ht.	Passenger Rail	(Mixed Goods) Rail	Truck
Over 6"	8.3	3.4	4.1
12"	2.5	1.1	1.4
18"	.8	NR	NR
24"	.3	.12	.2
36"	NR	0.0	0.0

Drop Ht.	(Mixed Goods) Rail	(Full Container Load) Rail
Over 3"	12	5.3
6"	3.2	1.6
12"	1.6	.71

22 lb Package (17 1/2" x 12" x 11 1/2")

Drop Ht.	Passenger Rail	(Mixed Goods) Rail
Over 6"	5.7	4.6
12"	1.8	1.5
18"	0.7	0.6
24"	.34	.24
30"	.13	.10
36"	.06	.03

NR - Not Recorded

TABLE 7 (Con't)

43 lb Package (19" x 19" x 19")

Drop Ht.	Railway Express
Over 6"	11.5
12"	4.9
18"	1.6
24"	.52
36"	.01

Overseas Shipment

Drop Ht.	80#	150#	250#	500#	800#
Over 6"	1.4	2.3	.45	.23	1.9
9"	NR	NR	.22	.25	.083
12"	.43	.47	NR	.104	0
18"	NR	NR	.017	0	0
24"	.11	.012	0	NR	NR
36"	0.0	NR	NR	NR	NR

NR - Not Recorded

TABLE 8

SUMMARY OF OVERSEAS SHIPMENTS

Weight lb.	Pack Journeys	Recorder Readings					
		6 in.	9 in.	12 in.	18 in.	24 in.	36 in.
80	72	122	NR	31	NR	8	0
150	84	194	NR	40	NR	1	NR
250	60	27	13	NR	1	0	NR
500	48	11	12	5	0	NR	NR
800	24	46	2	0	0	NR	NR

TABLE 9

DISTRIBUTION OF DROPS OVER THE FACES

	52# Package (17" x 13" x 12")			22# Package (17 1/2" x 12" x 11 1/2")	
	Rail (Mixed goods)	Passenger Rail	Road	Rail (Mixed Goods)	Passenger Rail
Top	5%	3%	5%	9%	8%
Bottom	52%	77%	44%	45%	43%
Sides	43%	20%	51%	49%	49%

TABLE 10

ANGLE OF IMPACT

	Sorting and Loading		Unloading and Stacking			
Top	5.1%	7%	75%	93%	89%	76%
Bottom	48 %	60%				
Sides	40.6%	30%				
Edges	5.1%	1%	25%	7%	11%	22%
Corners	1.4%	2%	0%	0%	0%	0%

TABLE 11

EFFECT OF HANDHOLDS

Drop Height	Without Handholds	With Handholds
Over 6"	100%	100%
12"	30.5%	24.4%
18"	9.4%	7.2%
24"	3.7%	1.8%

52 lb Package

Passenger Rail

Number of Drops

6"-11"	555	501
12"-17"	168	114
18"-23"	45	36
24" and over	30	12
Total	798	663

weights and distribution systems, the results indicate a general trend. That is, few drops are recorded on the top of a package (10%) with the remaining drops divided approximately equally between the bottom and sides. These results would not apply to very large containers where drops would occur more frequently on the base.

3.3.3.5 Angle of Impact

The angle of the package at the instant it strikes the ground depends on the type of handling operation. Typical data is shown in Table 10. In loading and stacking it is reported that the lower drops are at a slight angle. Usually one edge is lowered near the stack and then the case dropped. The higher drops are closer to being flat (to prevent toppling). More corner and edge drops are received by packages which are thrown. Edge and corner drops are defined as those with the impact face at more than 10° with the ground. These results indicate that no more than 25% of the total drops received by a package are angle drops.

3.3.3.6 Effect of Handholds

The effect of handholds on packages sent by passenger train is shown in Table 11. In this program (8) a number of packages (52 lb. 17" x 12" x 13") were fitted with handholds on the ends and shipped in pairs. The results showed a significant reduction in the number of drops with greater difference over 12". The overall reduction was 17%, whereas drops over 12" were reduced by 33%. One reason stated for the reduction is that the handholds lowered the bottom of the case by about 10 inches.

3.3.3.7 Effect of Labels

Labels on packages will influence the manner in which they are handled. Investigations conducted by PATRA(8) have shown that the position of the address labels affects the handling. For example, address labels affixed to the top of packages tend to be handled with the label on the top, i.e. face up. In the studies conducted 50 to 60% of all drops occurred on the face opposite the label (designated the base).

Packages with warning labels such as Handle-With-Care and This-Side-Up were studied on packages shipped by railroad. The results indicated a greater portion of base drops and lower drops in general. The overall effect, however, was small. One reason for the small influence of warning labels is that they are currently misused. Warning labels can be applied by shippers to any package. Further, the carriers load their vehicles to their advantage to attain the maximum payload.

3.3.3.8 Effect of Package Weight

The effect of package weight on drop height is shown in Figure 15. The data used in constructing this plot was obtained from observational studies at a large railroad goods depot(9). It represents the severest handling operation at the depot which consisted of loading a hand cart from a conveyor. Only fibreboard boxes less than 80 pounds were handled. The maximum drop height recorded was 24 inches. As would be expected, heavier packages were dropped from lower heights.

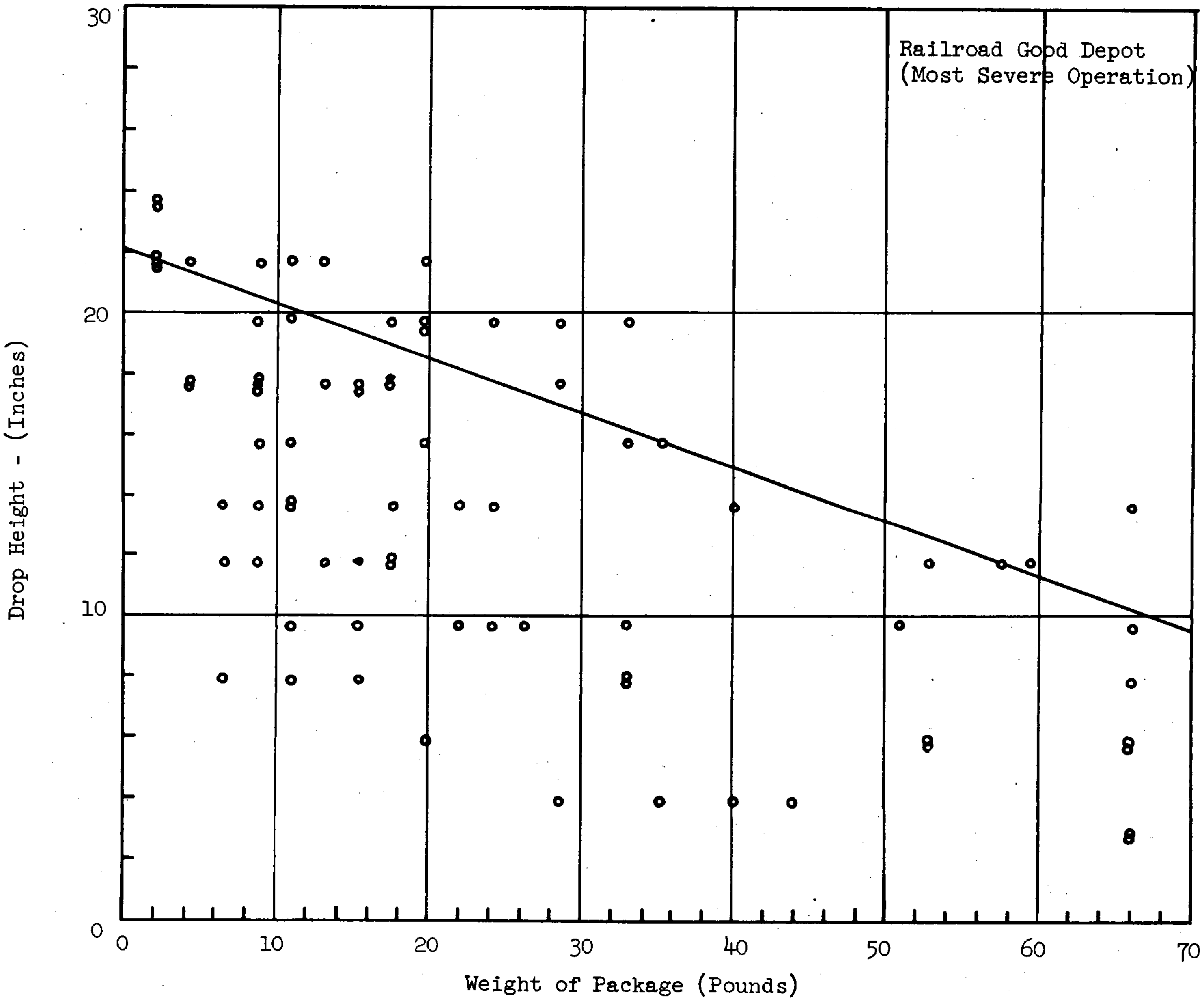


Figure 15 DROP HEIGHT VERSUS PACKAGE WEIGHT

For the packages studied, drop height was related to package weight by the following,

Drop Height = 22 lb. - .18 W, where drop height is in inches and W is in pounds.

In another study(8) in which packages were unloaded from trucks, the mean drop height was related to package weight by the following relationship

Drop Height = 17.1 - .26 W

This relationship is based upon measurements of 71 packages between 20 and 75 pounds.

The effect of package weight on drop height for very large containers can be noted from the tests conducted on overseas shipments (Table 8). Maximum drop height for 80 pound containers was 24 inches while maximum drop height recorded for 800 pound containers was 9 inches.

3.3.3.9 Effect of Package Size

The effect of package height on drop height is shown in Figures 16. These results apply to the same loading operation described for determining the effect of package weight, ie., unloading packages from a conveyor onto a handcart. Here again, the maximum recorded drop height was 24 inches. For this loading operation, the drop height is related to package height by the following:

Drop Height = 25.5 - H, where drop height is in inches and H is package height in inches.

As expected, the drop height decreases with increasing package height.

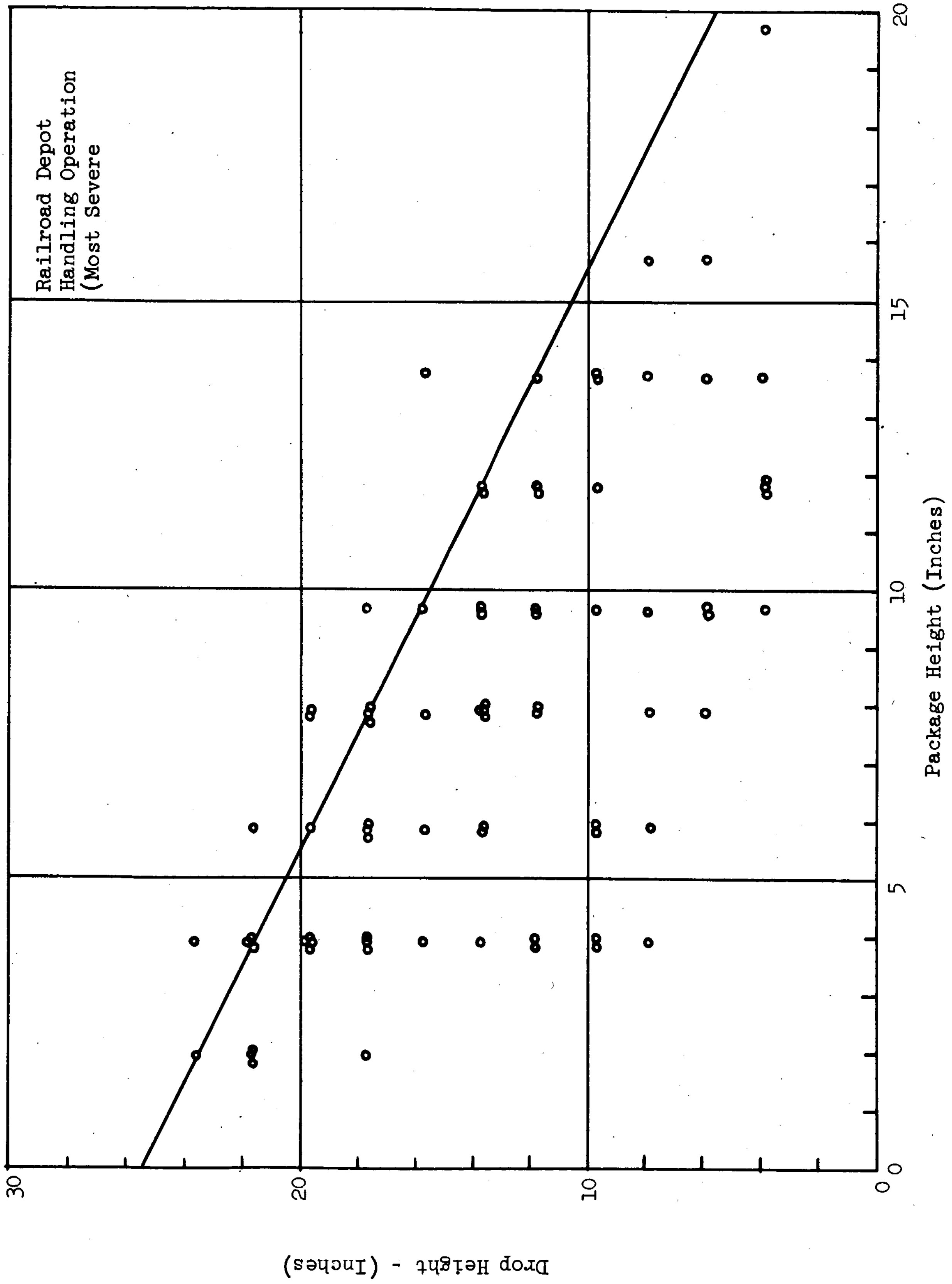


Figure 16 DROP HEIGHT VERSUS PACKAGE HEIGHT

3.3.3.10 Case History

A case history for paper sacks is presented as an illustration of a program to determine the drop height history over a complete trip from manufacturer to customer(13). The information obtained in the study was obtained by systematic observation of all stages in the manufacturing plant and distribution system.

Two product lines were investigated, one packing product in 112 pound sacks and the other packing product in 56 pound sacks. The distribution systems were similar with shipments sent to the customer by truck in either palletized or unpalletized loads.

In most of the handling operations observed, there was an upper limit to the drop height as a result of the method of carrying the sack, the sack weight, and the height of the impact surface. This can be seen in the leveling of the drop height curves at higher drop heights and should be remembered when attempting to extrapolate any of the data to an upper limit. The drops received at the different operations are shown in Tables 12 and 13. The number of observations recorded, the maximum drop height, and the height of drop exceeded by various percentages of the sacks from 5 to 90% are tabulated. Figure 17 shows the distribution of drop heights recorded during the palletizing of 112 pound sacks. The results are plotted for two observers and show the consistency which can be obtained by observational technqiues.

The drop height distribution associated with palletizing 56 pound sacks is shown in Figure 21. A depalletizing operation is shown in Figure 20. In

TABLE 12

Summary of drops received in different operations, 56 lb sacks
Expressed as percentages of sacks receiving drops at or above given heights

No.	Operation	Sack	Face	Scale	N	Max	Drop heights						Notes
							5%	10%	30%	50%	70%	90%	
1	From filling head	OM	B				Constant height 4 in.						
2	on to check weigher	OM	B	L	61	10	7·4	6·4	4·6	3·7	2·9	2·2	Up to 6 tamping drops
3	on to stitcher	OM	B	L	154	6	5·6	5·0	4·2	3·6	3·1	2·6	Slatted wood belt 18 in. high
4	on to conveyor	OM	F	A	146	17	15·8	14·5	11·8	9·7	7·7	4·8	Rubber fabric belt 21 in. high
5	on to conveyor	V	F	A	201	15	11·7	10·4	7·7	6·0	4·3	2·7	Slatted wood belt 18. in. high
6	on to check weigher	V	G	A	136	7	6·8	5·7	3·4	1·8	—	—	Metal platform 18. in. high
7	on to pallets all operations	OM & V	F	L	749	35	16	12·7	8.0	5·8	4·2	2·6	Stacked 5×8 or 4×10, pallet 5 in. high
8	Depalletising on to lorry	OM & V	F	A	666	40	31·4	27	17·4	10·5	6.0	3.0	Up to 10 high
	Unloading lorries												
9	on to stillage	V	F	A	117	72	64	57	43	33	23	8.0	Some thrown off lorry; 13 sacks high. Highest drops on top layers of stillage
10	on to trolley	OM	F	L	189	20	12·5	10·5	7·4	5·8	4·5	3·2	Small trolley; 12 in. high Stacked 7 high
11	by rope sling	V	F	L	83	12	11	9·5	7.0	5·8	4·7	3·5	Stillage 15 in. high. Stacked 13 sacks high
12	Drops on lorry prior to lifting off	OM	B	L	107	18	15	11	5·4	3·3	2·0	1·0	Stacked 5 high×2 wide on sling
	Stacking												
13	Large stack with all sacks carried		F	L	224	25	20	17	10·5	7·0	4·6	2·4	Up to 15 high
14	Large stack with some sacks thrown from lorry		F	L	226	60	48	34	16	9·4	5·6	2·8	Up to 15 high
15	Constricted stack, all sacks carried		F	L	75	18	15·2	12·5	8·2	6·2	4·6	3·0	Lack of headroom or space between stacks

B = Butt
F = Face
G = Gusset
L = Logarithmic height scale

A = Arithmetic height scale
N = Number of observations
Max = Maximum height observed
5-90% = Percentage of sacks receiving drops at or above heights given in table.

TABLE 13

Summary of drops received in different operations. 112 lb sacks

No.	Operation	Sack	Face	Scale	N	Max.	Drop heights						Notes
							5%	10%	30%	50%	70%	90%	
1	On stitcher	OM	B	A	281	8	6·5	6·0	4·9	4·2	3·4	2·4	1-man operation (Tamping drop)
2	Palletising	OM	F	L	133	15	12·5	10·5	7·3	5·8	4·5	3·1	2-man operation
3	Palletising	V	F	A	421	30	22	19·2	12·8	8·5	4·5	2·0	1-man operation
	Loading lorries												
4	Depalletising on to lorry	OM & V	F	A	422	39	35·5	31·5	23	17	11·5	5·5	1-man operation
5	Depalletising on to lorry	OM & V	B	L	83	30	30	26	15·5	11	7·6	4·7	1-man operation
6	Loading by conveyor. Stacked vertically	—	B	A	99	39	37	34	28·5	24·5	20	14·5	Differences between crews. Sacks received at waist level and stacked 2 high
7	Loading by conveyor. Stacked vertically	—	B	A	74	27	26	23·5	18	13·5	6·0	50	
8	Loading by conveyor. Stacked flat	—	F	A	78	30	28	25	14	9·0	7·0	4·0	1-man operation
9	Loading by conveyor. Flat on to layer of vertical sacks	—	F	A	101	12	12	10·5	7·5	6·0	4·5	3·0	1-man operation
	Unloading lorries												
10	by sling. 1 man	—	F	L	273	27	24	20	12·5	9·5	6·8	4·9	
11	by sling. 1 man at docks	—	F	L	53	24	23	20	12·5	8·5	5·0	—	
12	by sling. 2 men at docks	—	F	L	39	15	14	12·5	8·5	6·0	4·2	2·4	
	Stacking												
13	From sling to stack	—	F	A	233	36	27	23	15	9·0	6·5	4·0	Sling on truck, 19 in. above ground. Handled by 2 men.
14	Stacking on floor some sacks thrown	—	F	A	290	78	58	54	43	32	18	10·5	No attempt to build a neat stack.
15	Stack all sacks carried. 1 or 2 men	—	F	A	144	30	24·5	24	14	11	7·5	4·5	
16	Operation performed by 1 man	—	F	A	921	39	31	27	17·5	12	6·2	2·5	
17	Operation performed by 2 men	—	F	A	445	27	20	17	11·6	9·0	7·0	5·0	

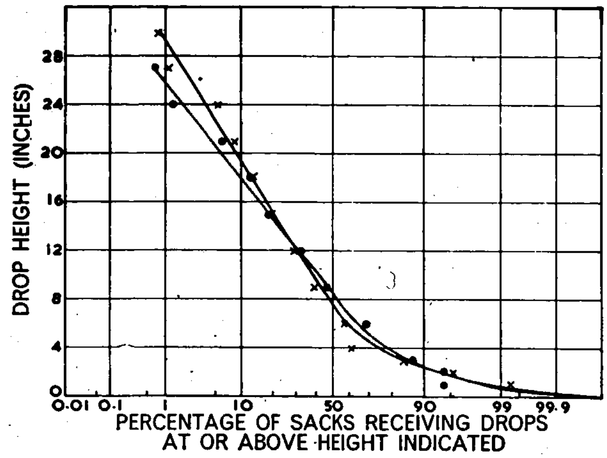


Figure 17 COMPARISON OF THE RESULTS OBTAINED BY TWO OBSERVERS ON THE PALLETISING OF 112 LB SACKS. FACE DROPS.

Observer 1 n = 149 Observer 2 n = 272

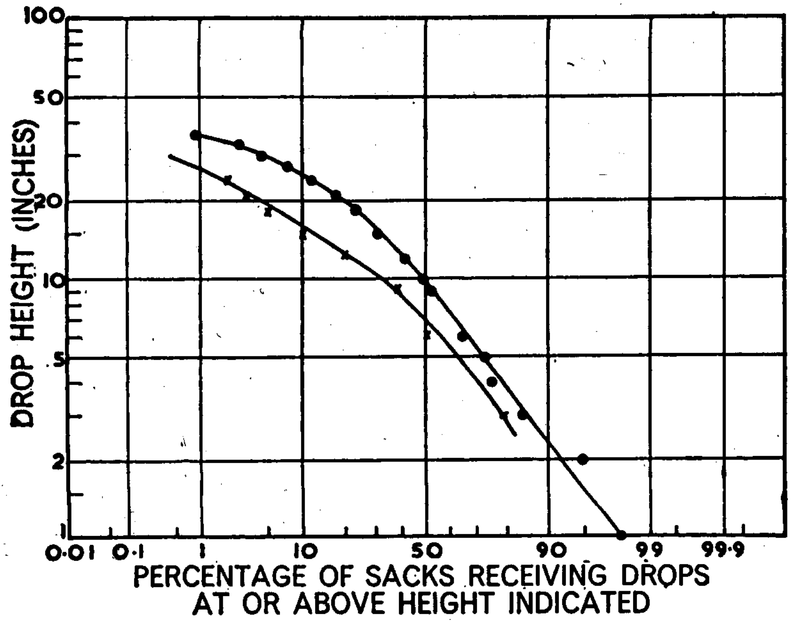


Figure 18 STACKING 112 LB SACKS, SHOWING DIFFERENCE BETWEEN OPERATIONS IN WHICH SACK IS HANDLED BY 1 AND 2 MEN. FLAT DROPS ONLY.

(Upper line) 1 man operations n - 921. Operations include palletizing, conveyor loading of truck and depalletizing on to truck

(Lower line) 2 man operations n = 445. Operations include palletizing and loading into slings.

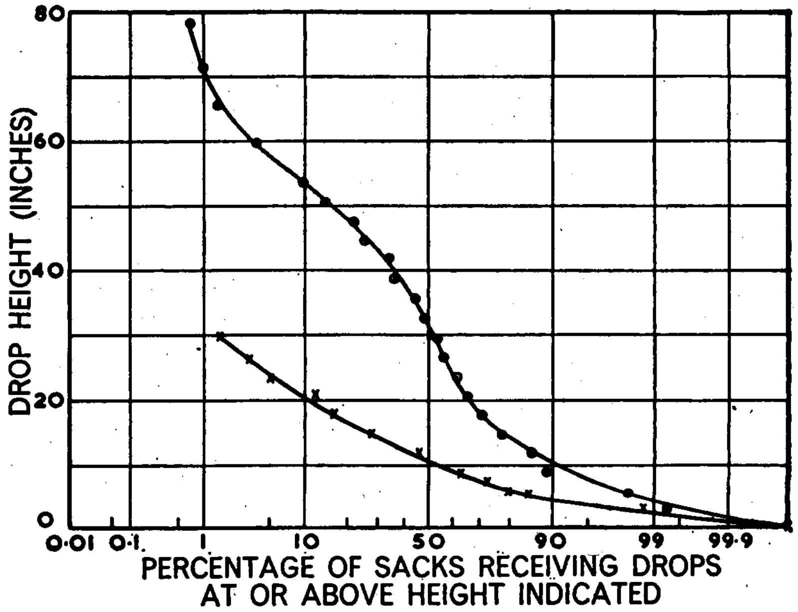


Figure 19 UNLOADING 112 LB SACKS FROM LORRY.

(Upper line) Unloaded by throwing off truck on on to stack n = 290.

(Lower line) Passed to ground crew and then stacked n = 144.

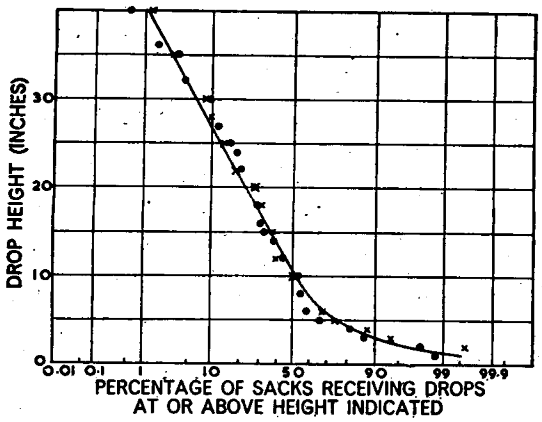


Figure 20 DEPALLETISING 56 LB SACKS ON TO TRUCK. FACE DROPS.

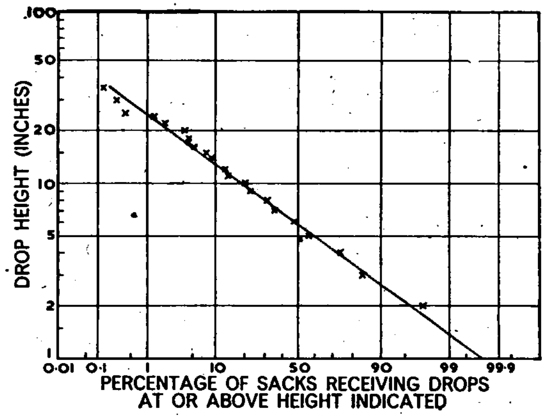


Figure 21 PALLETISING 56 LB SACKS. COMBINED OBSERVATIONS FOR ALL SUCH OPERATIONS. FACE DROPS, N = 749.

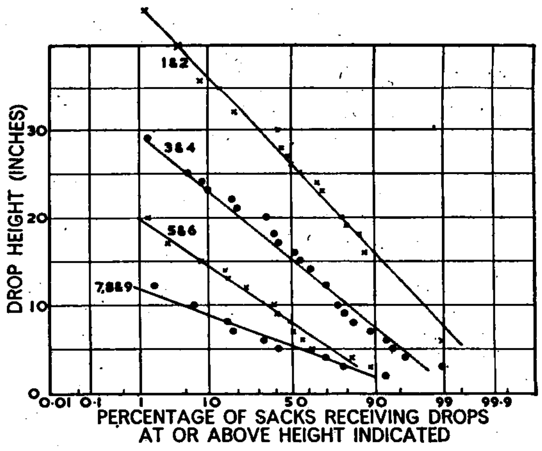


Figure 22 EFFECT OF POSITION IN STACK ON DROP HEIGHT WHEN DEPALLETISING 56 LB SACKS ON TO TRUCK. FACE DROPS.

Tiers 1 and 2 n = 77
Tiers 3 and 4 n = 71
Tiers 5 and 6 n = 75
Tiers 7, 8 and 9 n = 61

this operation a full pallet is lifted by a lift truck to the side of a truck and manually unloaded onto the truck. The effect of position on the stack in the truck is shown in Figure 22. As would be expected, the highest drops are experienced by the sacks on the lowest levels.

Stacking operations with 112 pound sacks have been observed in which the sack is handled by 1 and 2 men. In one man operations the drops are more severe since the sacks are received at waist level, carried and then dropped. In the two man operations observed, the sacks were seldom lifted above knee height and the drops were therefore lower. Drop heights received by 112 lb. sacks during unloading from trucks is shown in Figure 19. Two methods of unloading are described. Those in which the sacks are thrown from the truck and those in which the sack is passed to a ground crew and then stacked. It can be seen that considerable variation in drop heights results.

In another case study conducted by the Eastman Kodak Company, the results shown in Table 14 were obtained. In studying the various products through production, packaging case loading, storage and shipping, it was reported that after the products were loaded into cases for shipment, the handling from that point was common to all products which fell into prescribed weight limits and types of containers. Seven handling tests were developed by Kodak from these studies for various classification of containers. Typical of these is the test sequence shown in Table 15. The test gives values to each step in the handling cycle for containers under 75 pounds.

TABLE 14

EASTMAN KODAK TEST PROCEDURE

Testing Procedures II and IIa for Shipping Containers Under 75 Pounds

	Actual Condition	*Laboratory Simulation*
1.	Onto roller conveyor	4" flat drop on any surface
2.	Onto and down spiral chute	3" edge drop
3.	Onto belt conveyor	1" impact
4.	Onto skid	4" flat drop on bottom
5.	Skid onto truck	2" flat drop on bottom
6.	In truck to Shipping Dept.	1 minute vibration 1' Impact
7.	Skid off of truck to temporary storage	2" flat drop on bottom
8.	Stacked in freight car	24" flat drop on any surface
9.	In freight car to branch	10 min. vibration 3-3' impacts
10.	Onto two wheel truck	6" flat drop on best stacking surface
11.	Stacked in truck	10" flat drop on best stacking surface
12.	In truck to Branch	1 min. vibration 1' impact
13.	Onto chute	6" flat drop on best stacking surface
14.	Down chute to conveyor	(2 tumbles) see note.
15.	Onto roller conveyor	1-3' impact
16.	Onto skid	6" flat drop on best stacking surface
17.	Off skid into storage	4" flat drop on bottom
18.	Onto skid	4" flat drop on bottom
19.	Onto belt conveyor	3" drop on edge
20.	On belt conveyor	1' impact
21.	Stacked in truck	6" flat drop on best stacking surface
22.	Onto skid	4" flat drop on bottom
23.	Stacked in truck	6" flat drop on best stacking surface
24.	In truck to Express Depot	2 min. vibration 1-2' impact
25.	Onto floor	6" flat drop on best stacking surface
26.	Onto conveyor truck	4" edge drop
27.	Onto floor	6" flat drop on best stacking surface
28.	Stacked in truck	6" flat drop on best stacking surface
29.	In truck to Express Depot	2 min. vibration 1-2' impact
30.	Onto floor	6" flat drop on best stacking surface
31.	Onto conveyor truck	4" edge drop
32.	Onto floor	6" flat drop on best stacking surface
33.	Stacked in freight car	12" flat drop on any surface
34.	In freight car to dealer	10 min. vibration 3-3' impacts
35.	Transfer point	6" corner drop 12" flat drop on best stacking surface
36.	Onto two wheel truck	6" flat drop on best stacking surface
37.	Stacked on floor	6" flat drop on best stacking surface
38.	Onto two wheel truck	6" flat drop on best stacking surface
39.	Stacked in truck	6" flat drop on best stacking surface
40.	In truck to dealer	2 minutes vibration 1-2' impact
41.	Onto dealer's receiving platform	24" flat drop on bottom
42.	Into dealer's storage	4" flat drop on bottom

* NOTE: *IIA—Procedure II with Step No. 14 omitted.*
Step No. 14 applies only to cubical shaped containers, simulates tumbling down a chute or conveyor.

3.3.4 Shock Spectra

High cost research items such as missiles and spacecraft are usually monitored through all phases of transportation. Once the normal environment has been determined, measurements continue only to monitor the loadings during accidents. The shock and vibration environment on large equipment is generally monitored by accelerometers mounted at various locations. Recordings are made either intermittently or continuously during the shipment (intransit and transfer operations). The data is reviewed and where significant levels are produced, shock spectra are computed. Typical of these is the shock spectrum shown in Figure 23. It was computed from data recorded during a transfer operation of the Saturn rocket stage. The shock was produced when the forward end of the stage dropped from a height of 3 inches. The plot envelopes the shock spectrum at four locations on the rocket. This form of data gives the maximum dynamic acceleration response which can be expected on components mounted at the instrument locations. A .03 damping factor was used since this represents a lower limit for nonisolated support structure.

3.4 Future Handling Studies

Because of the very sparse amount of data available, field measurement programs of the handling environment are being planned by various organizations. Some of the organizations are the Sandia Corporation, the U. S. Army Natick Laboratories, the Swedish Packaging Research Institute, and the Packaging and Allied Trades Research Association (England). (The investigations will employ both the observational method and instrumented packages.)

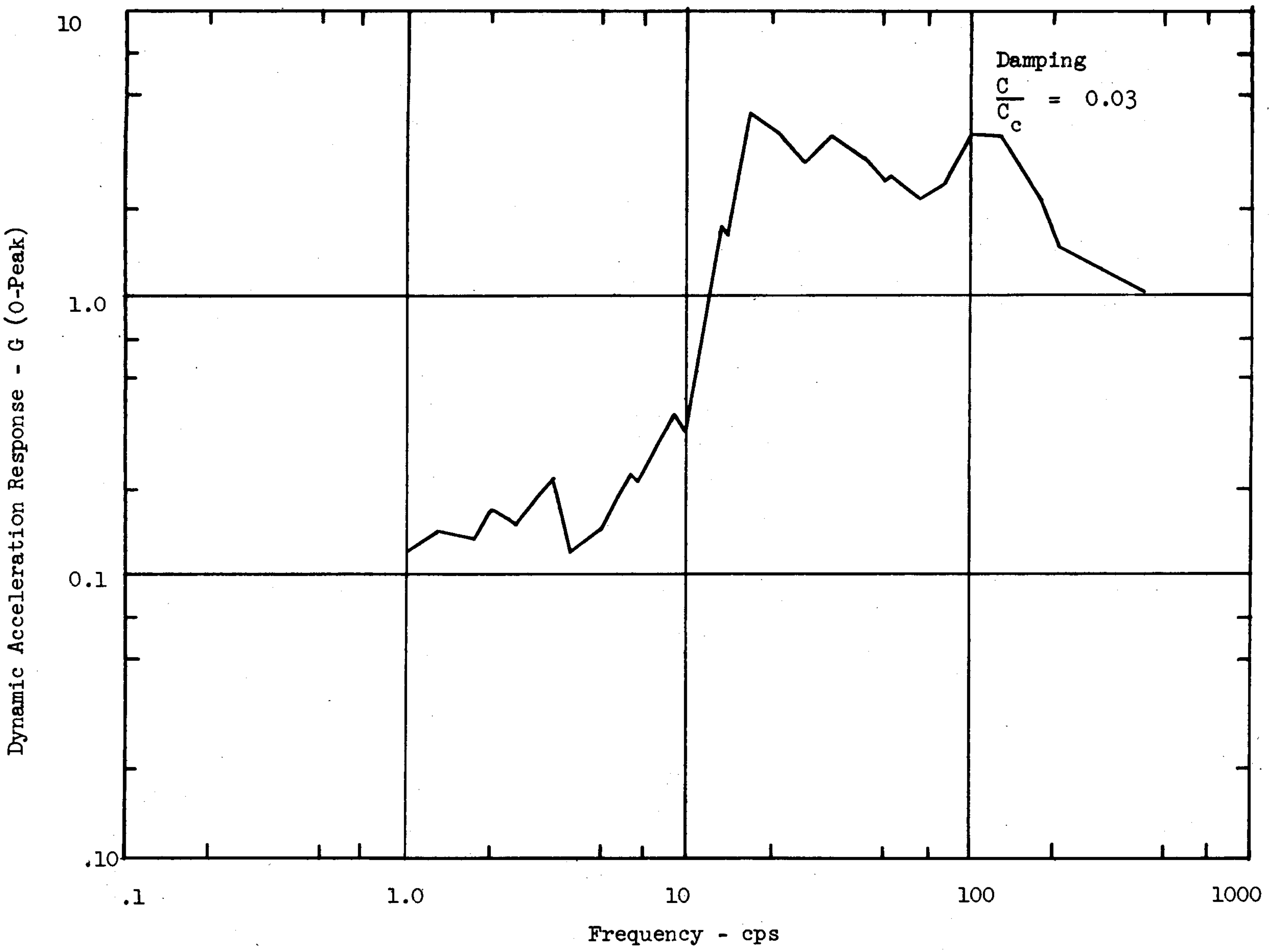


Figure 23 SHOCK SPECTRUM OF HANDLING SHOCK - 3 INCH DROP OF SATURN ROCKET STAGE

The Natick Laboratories has reported the completion of a self contained drop recorder(15). The recorder is a solid state electronic unit capable of recording unattended for periods up to six months. Impacts are sensed by a transducer consisting of a magnetic rod which rides within a rigid nylon tube. The magnet is connected at both ends to coil springs. Upon impact, the relative motion of the magnetic rod relative to coils of wire wrapped around the tube produces a voltage which is proportional to the impact velocity. (The impact velocity can be related to drop height.) The recording unit can record the voltage signals from three mutually perpendicular transducers. A fourth recording channel is used to record a timing mark. This instrument should be extremely useful in future measurement programs of the cargo handling environment.

SECTION 4

DESIGN OF PACKAGE CUSHIONING

4.1 Introduction

4.1.1 Nature of Handling Environment

A functional item is subject to forces due to the following three sources:

1. forces involved in the manufacturing processes
2. forces associated with its use
3. forces encountered during shipment

The design of the item, so that it can withstand stresses of the first and second types, is the task of its designer. As a result of this design, the item may also be able to withstand loadings of the third type. The analysis of this source of potential damage, and the specification of any necessary protection, is in the province of the packaging engineer.

The shipping of cargo from one point to another may be separated into the following two stages:

1. the handling of the cargo before loading onto the transporting vehicle at the point of origin and after unloading at the point of destination
2. the movement of cargo by the transporting vehicle between terminals.

In order to ensure that the cargo will not be damaged, it is necessary to know the shock and vibration levels to which it may be subjected.

A summary and discussion of the shock and vibration environment to which items are subjected during transportation by the four major modes was given in an earlier report(1). The environment within the cargo space of a vehicle is dependent upon such factors as the speed, power plant, vehicle structure, and the medium through or on which the vehicle travels. The vibration may consist of deterministic components such as the contribution from the power plant, and of random components, such as the effect of road surface, wind, etc. The underlying physical mechanisms, however, are deterministic. That is, given some knowledge of the condition of the road (or sea), the engine, and the vehicle structure, it is theoretically, if not practically, possible to compute the essentials of the cargo area vibration.

In this report, the shock environment encountered during the handling stages is considered. Handling involves moving, stacking, and loading of packages at terminal points. The shock loadings which occur during these operations are of a different nature than the vehicle shock and vibration environments. The handling loads are the result of human error, accident, or expediency, and result in dropping a package or in applying a sudden push or pull during machine operations. Therefore, the environment is a chance phenomenon and the magnitudes and frequency of occurrence of the loadings can only be found from experience and described on a statistical basis.

Because of the difference between the nature of the vehicle environment and the nature of the handling environment, the philosophy of design should be different for the two cases. In the case of the vehicle environment, all packages are subjected to the same levels of shock and vibration (approximately), while in the latter, the load which one unit receives is independent of the loads which other units receive (assuming the packages are handled individually), and the packages are only subjected to the same <u>possibility</u> of receiving a handling shock of a given magnitude. Therefore, the design of package protection for in-transit vibration can be effected by considering one unit only. If this survives, all survive. The design for handling loads, however, must be done on a statistical basis. Experience will indicate the frequency of occurrence of shocks of given magnitudes. If a shipment contains a large number of units which are to be handled individually, these statistics can be used to predict how many units can be expected to receive loads above various levels.

The principle governing specification of protection for handling loads should therefore be the balancing of the cost of ensuring the survival of an additional percentage of the shipment against the value of this additional percentage. That is, it is conceded that it is impractical to try to design against any load and the goal becomes the minimization of the net loss. This, of course, assumes that all considerations can be reduced to financial terms.

The ideal form of data for design against handling loads is a set of statistics giving magnitudes and frequencies of occurrence of shocks for the various operations involved. Very few measurement programs having this goal have been performed and these have been described earlier in this report. Lacking these statistics, a common practice, particularly by the military, has been to establish arbitrary, but reasonable, drop tests for packages dependent upon their size and weight. For example, small and lightweight packages are easily and commonly tossed onto stacks while medium size packages can be dropped from waist or shoulder height dependent upon how many men are required to carry such a package. Heavy items which must be lifted by a hoist may be bumped against a wall. Thus, the types and extent of the abuse which a package must endure is related to its shape and weight. Some specifications for drop tests in use were presented earlier.

In summary, then, the following information is of value in designing for loads encountered during handling:

1. approximate size and weight of package
2. routing of package and handling operations to be performed
3. statistics of handling loads
4. estimates of costs of cushioning materials, estimates of shipping costs as a function of size and weight, and cost of item shipped.

In addition, the physical characteristics of the packaged item must be known so that the effect of the loads can be predicted.

4.1.2 Dynamic Considerations

Whether the packaging engineer has an ample set of statistics or must work from an essentially arbitrary specification, he must be able to compute the response of the packaged item to the loads which will be encountered. The first step is to idealize the input to the package. The simplest form of excitation to work with is the step change in velocity. This is also a reasonable approximation because the loads due to handling are sudden changes in velocity due to drops, bumps, sudden movement by machine, etc.

The velocity step is applied to the container in which the packaged item is enclosed. If it were rigidly attached to the container, the item would experience the full effect of the input. Thus, it is necessary to isolate the item from the outer container by a suitable cushioning material. Selection of the proper material involves considerations such as mechanical effectiveness, pertinent nonmechanical properties, volume needed to provide a certain degree of isolation, and cost.

There are two basic methods of determining the effectiveness of a given cushioning material. The first, presented by Raymond D. Mindlin(16), involves the analytical representation of the load-deflection characteristics of a cushioning material, and using this function in the equation of motion to find the displacement or acceleration transmitted to the packaged item when a given load is applied to the container. A second approach, given in a report by the Forest Products Laboratory(17), involves obtaining sets of curves of maximum acceleration of a packaged item as a function of cushioning material, depth of cushioning, weight of packaged item and its bearing area, and the height of drop (which is equivalent to a velocity step). If the set of curves is complete enough, it is possible to choose the best cushioning for a given application.

In order to assess the damage potential of a given loading, a failure criterion must be formulated. One commonly used is the fragility rating. This is the maximum acceleration which the packaged item can withstand before failing in some manner. In certain instances, the item may have an element which is particularly susceptible to failure through over-stressing. It then becomes necessary to examine the relative displacement of this critical element with respect to the main body.

In order to illustrate some of the points made and to bring out additional features of the problem, a specific, although oversimplified, example will be considered.

An article weighing twenty pounds is to be packaged so that it will survive handling. Lacking any better data, it is decided that a drop of three feet is a reasonable estimate of the maximum abuse to which the package will be subjected.

The article itself must not experience an acceleration greater than 50 g's. In addition, a critical element weighing one half pound and having an equivalent spring constant of 10^5 lbs/ft must not be displaced more than .005 inches.

For simplicity, the interior of the package will be represented by the arrangement shown in Figure 24.

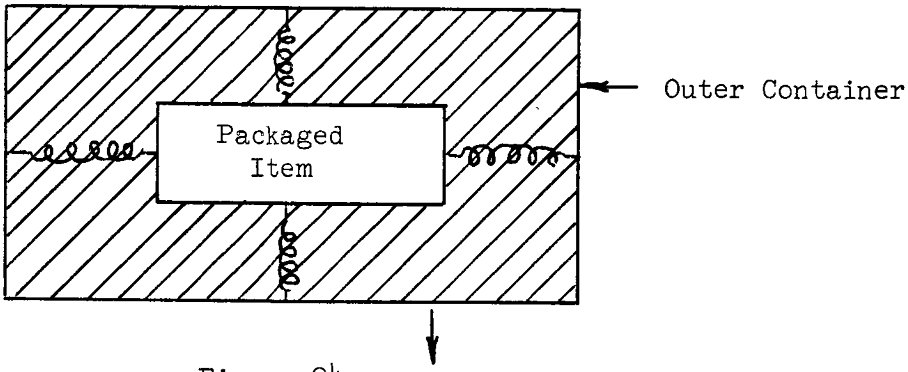


Figure 24

The cushioning, which is usually a distributed, nonmetallic material, is represented by the four springs shown, each of which is assumed to be linear and undamped. This is not typical of most cushioning. The following assumptions will be made:

1. The cushioning can be represented by the four equal linear and undamped springs shown (with spring constant k). In practice, distributed materials are used which are nonlinear and damped. The horizontal springs do not affect the vertical motion.
2. The package is assumed to be dropped in the direction of the arrow and the bottom of the container is assumed to hit flat on the floor. This is not likely to happen, but tests have shown that a flat drop is usually more severe than a corner or edge drop.

3. There is no relative motion between the item and the outer container while the package is dropping. The floor is assumed to be rigid and the impact of the container on the floor is perfectly plastic. This means that the velocity of the container becomes zero upon impact and its kinetic energy is completely dissipated. The packaged item has the same velocity as the container just before impact and its kinetic energy is transformed into potential energy of the spring and gravitational potential energy of the item.

On the basis of the third assumption and the assumption that the springs are undamped, it is possible to use the principle of the conservation of energy to find the maximum travel of the packaged item within the container, by equating the maximum potential energy to the initial kinetic energy. The maximum force on the item is then known. But rather than use this approach, an equivalent formulation will be used, which will give the time history of the motion as well as the peak values.

Considering the package just after impact, the outer container is at rest, but the item is moving relative to the container with a speed equal to the impact velocity. Since there has not yet been any relative displacement between the item and the container, it is just as though the entire package had been at rest on the floor and the packaged item given a sudden velocity toward the floor. Thus, the motion is represented by the following differential equation:

$$M \frac{d^2y}{dt^2} + ky = Mg$$

where

M = mass of packaged item

y = displacement of mass relative to container (positive down)

t = time (measured from time of impact)

g = acceleration of gravity

V_o = impact velocity (equal to $\sqrt{(2 \times g \times \text{height of drop})}$)

Mg is the weight of the item, Ky is the force exerted on it by the cushioning. (It is assumed that the cushioning acts only in compression, thus the force is not 2ky.) The initial conditions are

$$y(0) = 0 \qquad \left.\frac{dy}{dt}\right|_{t=0} = V_o$$

The solution of this equation is

$$y(t) = V_o\sqrt{\frac{M}{k}} \sin\sqrt{\frac{k}{M}}\, t + \frac{Mg}{k}\left[1 - \cos\sqrt{\frac{k}{M}}\, t\right]$$

The velocity is

$$\frac{dy}{dt} = V_o \cos\sqrt{\frac{k}{M}}\, t + g\sqrt{\frac{M}{k}} \sin\sqrt{\frac{k}{M}}\, t$$

The assumption is now made that

$$V_o^2 >> \frac{g^2 M}{k}$$

In terms of the height of drop, h,

$$V_o^2 = 2gh$$

so that the above is equivalent to assuming that

$$2gh >> \frac{g^2 M}{k}$$

or

$$h >> \frac{Mg}{2k}$$

Since Mg/k is the static deflection of the mass on the spring, the assumption $V_o^2 >> g^2M/k$ is equivalent to the assumption that the height of drop is several orders of magnitude greater than half the static deflection. If this is so, y(t) may be approximated by

$$y(t) \approx V_o\sqrt{\frac{M}{k}}\sin\sqrt{\frac{k}{M}}\,t$$

The maximum displacement of the item within the container is, therefore, approximately

$$y_m \approx V_o\sqrt{\frac{M}{k}}$$

and its maximum acceleration is

$$a_m \approx V_o\sqrt{\frac{k}{M}}$$

Inspection of the expressions for the maximum acceleration and displacement, shows that the former varies directly as $\sqrt{k}$ while the latter varies inversely as $\sqrt{k}$. The spring constant is the only variable of the problem (V_o and M are given), and the selection of a value must be a compromise between minimizing the acceleration of the item and minimizing its displacement (i.e. required volume of the package).

The parameters given earlier will now be used

$$M = \frac{20}{g}\text{ slugs} \qquad h = 3\text{ ft.}$$

The fragility rating was given as 50 g's. Assuming that this has a suitable factor of safety included, it is best to choose k so that $a_m = 50$ g. This will minimize y_m. Inserting these values,

$$k = \frac{a_m^2M}{V_o^2} = \frac{a_m^2M}{2gh} = \frac{(50g)^2\,\frac{20}{g}}{2g \times 3} = 8333\,\frac{\text{lb.}}{\text{ft.}} = 694\,\frac{\text{lb.}}{\text{in.}}$$

$$y_m = V_o\sqrt{\frac{M}{k}} = \sqrt{2gh}\sqrt{\frac{M}{k}} = \sqrt{2g \times 3 \times \frac{20}{8333g}} = \sqrt{\frac{120}{8333}}$$

$$= .12 \text{ ft.} = 1.44 \text{ inches}$$

The assumption that $h >> \frac{Mg}{2k}$ should be checked. Since k is 8333 lb./ft.

$$\frac{Mg}{2k} = \frac{20}{2 \times 8333} = \frac{10}{8333} << h = 3$$

Thus the approximation is justified.

The maximum displacement of 1-1/2 inches represents the downward excursion of the packaged item. Since the cushioning is assumed to be undamped, the item will also travel 1-1/2 inches on the up stroke. Therefore, the height of the container must be at least three inches greater than the height of the item. (Of course, more than three inches is needed since the cushioning cannot be compressed to zero thickness.)

The cushioning system must now be examined to see if the displacement of the critical element exceeds the safe value. The critical element is assumed to be represented by a vertical mass-undamped spring and the dynamic system is idealized as shown in Figure 25.

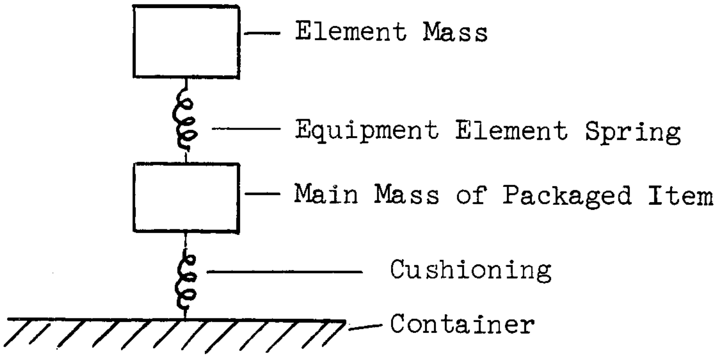


Figure 25

The motion of the element is excited by the motion of the main part of the packaged item (hereafter referred to as the primary mass). It will be assumed that the motion of the primary mass is not affected by the motion of the element, that is, there is no loading of the primary mass by the element. Thus, the dynamic system can be reduced to the system in Figure 26.

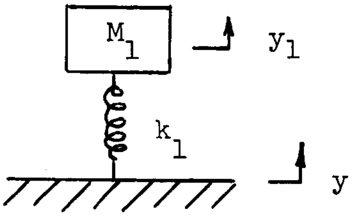


Figure 26

The equation of motion of the element mass is

$$M_1 \frac{d^2 y_1}{dt^2} + k_1 (y_1 - y) = 0$$

where

M_1 is the mass of the element

k_1 is the equivalent spring constant

y_1 is the absolute displacement of the element

y is the displacement of the primary mass

Since the extension of the element is of interest, write $y_1 = y + \delta$ where δ is the relative displacement of the element. The equation of motion then becomes

$$M_1 \frac{d^2 \delta}{dt^2} + k_1 \delta = - M_1 \frac{d^2 y}{dt^2}$$

or

$$\frac{d^2 \delta}{dt^2} + \frac{k_1}{M_1} \delta = 50 \text{ g} \sin \sqrt{\frac{k}{M}} t$$

where the value of the acceleration of the primary mass has been inserted. Since the cushioning is undamped, the primary motion is of long duration. Thus, the steady state solution of the equation is more important than the transient part. The steady state contribution is

$$\delta = \frac{50\ g}{-\frac{k}{M} + \frac{k_1}{M_1}} \sin\sqrt{\frac{k}{M}}\, t$$

and the maximum extension of the element is

$$\delta = \frac{50\ g}{\left|\frac{k}{M} - \frac{k_1}{M_1}\right|}$$

The given and computed values of the parameters are

$k = 8333$ lb/ft $\qquad$ $k_1 = 10^5$ lb/ft

$M = 20/g$ slug $\qquad$ $M_1 = 1/(2\ g)$ slug

Inserting these values, gives

$$\delta = \frac{50\ g}{\left|\frac{8333}{20/g} - \frac{10^5}{1/2g}\right|} = \frac{50}{\left|416 - 2 \times 10^5\right|} = 2.5 \times 10^{-4} \text{ ft.} = .003 \text{ inches}$$

Since the maximum allowable extension was given as .005 inches, the cushioning is adequate.

There is one aspect of the dynamics of this problem which has been ignored and that is the possibility of the package rebounding from the floor. This potential rebound is not due to the outer container-floor interaction, which has been assumed to be completely plastic, but to the forces set up in the cushioning.

Consider Figure 25 in which the primary mass has completed its first descent and is now nearing the end of the upstroke.

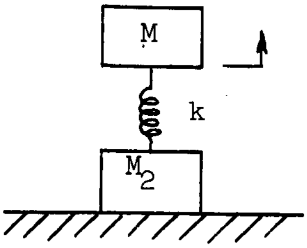


Figure 27

Here M_2 is the mass of the outer container. The forces acting on M_2 are its weight, the floor reaction, and the spring force. While the container is in contact with the floor, the following relation is satisfied

$$M_2 g + ky = R$$

where R is the floor reaction, positive up, and y is the displacement of M, positive down, as before. Since R cannot be negative, the container will rebound when

$$M_2 g + ky < 0$$

ky is the force in the spring and is due to the acceleration of the primary mass and its weight

$$ky = Mg - M \frac{d^2y}{dt^2}$$

In this instance, the contribution of the weight cannot be ignored. Substituting into the last inequality, the condition for rebound becomes

$$M_2 g + Mg - M \frac{d^2y}{dt^2} < 0$$

or

$$M \frac{d^2y}{dt^2} > g (M + M_2)$$

Now the maximum acceleration on the upstroke is equal to the maximum on the downstroke. Writing

$$a_m = G_m g$$

gives finally

$$G_m > \frac{M + M_2}{M}$$

If this inequality is satisfied, rebound occurs.

In this example, $G_m = 50$. M_2 was not given but is usually less than M. Thus, the package will rebound.

Package rebound does not affect the maximum acceleration of the primary mass because the total energy of the system is bounded by the initial potential (or kinetic) energy, thus limiting the extension of the spring. That is, the acceleration can never exceed the value at the end of the first downstroke. Rebound will, however, affect the motion of the primary mass, and therefore the response of the critical element, because the governing equations of motion are different.

4.2 Analytical Design of Cushioning

In this section, the approach to the design of package cushioning presented by Raymond Mindlin(16) will be discussed. His technique is to represent the load-deflection characteristics of a given cushioning material by a relatively simple analytical expression and to find closed form expressions for the maximum acceleration and displacement due to a given height of drop (or equivalent velocity step) as was done in the preceding illustrative example.

The task of determining the mechanical adequacy of a cushioning material must begin with experimental determination of the mechanical properties, that is, the stress-displacement characteristics. The stress is required, rather than the force, because all other parameters being constant, the force required for a given displacement of the material will be proportional to the cross-sectional area. Displacement must be specified rather than nominal strain (i. e. displacement divided by original thickness), because although the displacement for a given stress will increase with increasing thickness, the changes will not usually be proportional. Thus, the original thickness of the cushioning will be a parameter affecting the mechanical properties of the cushioning.

Another factor affecting the observed stress-displacement curve is the rate of loading used in the test. This is because many materials have internal velocity-dependent damping, and the total force resisting displacement is the sum of the elastic (displacement-dependent) force and the damping force. If the rate of load increase (or equivalently, the rate of displacement) is low enough, the effect of damping will be negligible and the observed force is due to the elastic part only. If, however, this stress-displacement curve is used in a cushioning problem, the results may be in error because the actual displacement rate is not small; it is initially equal to the impact velocity. Thus, it is necessary to artificially introduce a damping force into the equation of motion, as Mindlin does in the examples he gives.

An alternate approach (if time and money permit) might be to include the displacement rate as a parameter and, using a displacement-controlled instrument, to obtain stress-displacement curves for various values of the parameter (of the order of impact velocities). The measured stress, P(y), is then

$P_E(y) + P_D(\dot{y})$ where P_E is the elastic stress and P_D is the additional stress due to damping, which is constant for a given curve (because the displacement rate is constant).

Consider now a package which is dropped. If the damping is not too large the maximum force exerted by the cushioning will occur near the end of the first downstroke. That is, to a first approximation, the maximum displacement and maximum acceleration occur simultaneously. Therefore, denoting the initial kinetic energy of the packaged item by T_o, the principle of the conservation of work and energy gives, within the approximations introduced earlier,

$$T_o = A \int_o^{y_m} P_E(y)\, dy + A \int_o^{y_m} P_D(\dot{y})\, dy$$

where A is the bearing area of the packaged item on the cushioning. Defining the average damping stress, P_D, by the relation

$$\bar{P}_D = \frac{1}{y_m} \int_o^{y_m} P_D\,(\dot{y})\, dy$$

the above equation may be written

$$T_o = A \int_o^{y_m} [P_E(y) + \bar{P}_D\,]\, dy$$

Assuming that $P_D(\dot{y})$ is a monotonically increasing function of the velocity $\dot{y}$, an average velocity, $\bar{\dot{y}}$, may be defined by the following relation:

$$\bar{P}_D = P_D\,(\bar{\dot{y}})$$

The problem is then to relate $\bar{\dot{y}}$ to the impact velocity. If this can be done, then the stress-strain curve with the appropriate controlled displacement rate can be chosen for a particular problem. The maximum displacement can then be found from the relation

$$T_o = A \int_o^{y_m} [P_E(y) + \bar{P}_D]\,dy = A \int_o^{y_m} P(y)\,dy$$

where P(y) is the apparent cushioning stress measured at the appropriate displacement rate. When y_m is known, the maximum acceleration, which is approximated by the acceleration at the end of the first downstroke, can be found from the relation

$$a_m \approx \frac{A}{M} P_E\,(y_m)$$

where M is the mass of the packaged item. $P_E(y)$ can be found by finding the stress-displacement curve for a very low displacement rate so that the damping force is negligible.

Unfortunately, in order to find the relation between $\bar{\dot{y}}$ and the impact velocity, $P_D(\dot{y})$ must be known and the motion of the stress must be found. This is precisely the difficulty which the approximation is intended to eliminate. By considering a linear system, however, an order of magnitude of the ratio $\bar{\dot{y}}/V_o$, where V_o is the impact velocity, can be found.

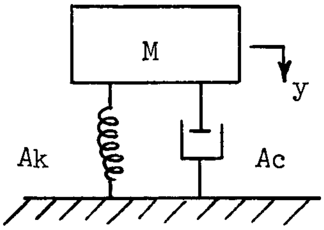


Figure 28

In the mass-spring system shown in Figure 28, Ak is a linear spring and Ac is a linear dashpot. Measuring y as shown, the equation of motion is

$$M\ddot{y} + Ac\dot{y} + Aky = 0$$

with initial conditions $y(0) = 0$, $\dot{y}(0) = V_o$.

Rewriting the differential equation as

$$\ddot{y} + 2\xi\,\omega_n\dot{y} + \omega_n^2\,y = 0$$

where $\omega_n = \sqrt{Ak/M}$ is the undamped natural frequency and $\xi = C/2\sqrt{A/kM}$ is the fraction of critical damping, the solution is, for $\xi << 1$

$$y(t) = \frac{V_o}{\omega_n}\,e^{-\xi\omega_n t}\,\sin\omega_n t$$

$$\dot{y}(t) = V_o\,e^{-\xi\omega_n t}\,[-\xi\sin\omega_n t + \cos\omega_n t]$$

The maximum displacement occurs when the velocity first becomes zero. Setting

$$-\xi\sin\omega_n t + \cos\omega_n t = 0$$

the appropriate time satisfies

$$\tan\omega_n t_m = \frac{1}{\xi}$$

and for $\xi << 1$,

$$t_m = \frac{\pi}{2\omega_n}$$

Therefore,

$$y_m \approx \frac{V_o}{\omega_n}\,e^{-\frac{\pi\xi}{2}}$$

Now

$$P(y) = P_E(y) + P_D(\dot{y}) = ky + C\dot{y}$$

Therefore,

$$\bar{P}_D = \frac{1}{y_m}\int_0^{y_m} P_D(\dot{y})\, dy = \frac{1}{y_m}\int_0^{t_m} P_D(\dot{y})\dot{y}\, dt$$

Substituting the expressions for y_m, $\dot{y}$, $P_D(\dot{y})$ and t_m

$$\bar{P}_D = C\, V_o\, \omega_n\, e^{\frac{\pi\xi}{2}} \int_0^{\frac{\pi}{2\omega_n}} e^{-2\xi\omega_n t}\, [\xi^2 \sin^2\omega_n t - 2\xi \sin\omega_n t \cos\omega_n t + \cos^2\omega_n t]\, dt$$

Using the approximation, $\xi^2 << 1$ the result is (to zero order in ξ)

$$\bar{P}_D \approx \frac{\pi}{4}\, C\, V_o$$

Since

$$P_D(\dot{y}) = C\,\dot{y}$$

$$\bar{\dot{y}} = \frac{\pi}{4}\, V_o$$

Thus, the average velocity $\bar{\dot{y}}$ is about three quarters the impact velocity V_o. It is not unreasonable to expect that for nonlinear cushioning, the factor is also of this order of magnitude, and that this value can be used without too much error.

To illustrate the use of these results, suppose that a given cushioning material is to be used to protect an item from an impact velocity of magnitude V_o. From the catalog of stress-displacement curves, the designer selects those corresponding to test displacement rate of $3/4\ V_o$. The stress-displacement function is then a function of the depth of cushioning, d, and will be denoted by P(y; d). y_m is then found from the relation

$$1/2 \quad MV_o^2 = A \int_0^{y_m} P(y ; d)$$

Then for a given d, the quasistatic loading curve is used to find the elastic part of the stress, which is the only part acting at the end of the downstroke. Finally, the maximum acceleration is found from Newton's law.

$$a_m = \frac{1}{M} P_E (y_m; d)$$

The optimum thickness of cushioning is that for which the following criteria are met.

1. $a_m \leq$ fragility rating
2. $y_m < d$
3. d minimized

It should be noted that because this technique does not give the time history of the motion it cannot be used to predict the response of a critical element.

In order to determine the limitations on this method, sample calculations were performed for cubic cushioning with cubic damping. The equation of motion is

$$M\ddot{y} + C(\dot{y} + \bar{a}\,\dot{y}^3) + k(y + \bar{b}\,y^3) = 0$$

The initial kinetic energy of the mass is $1/2\ M\ V_o^2$. V_o was taken to be 15 and $\bar{b}$ was set at 0.2. The equation can be rewritten

$$\ddot{y} + 2\xi\,\omega_n (\dot{y} + \bar{a}\,\dot{y}^3) + \omega_n^2 (y + \bar{b}\,y^3) = 0$$

ξ, $\bar{a}$, and ω_n were varied and the following cases were examined

case	ω_n	ξ	$\bar{a}$
1	5	.01	.00
2	5	.01	.01
3	5	.01	.05
4	5	.01	.10
5	5	.10	.00
6	5	.10	.01
7	15	.01	.00
8	15	.01	.01
9	15	.01	.05
10	15	.01	.10
11	15	.10	.00
12	15	.10	.01

The maximum displacements and accelerations were obtained by integrating the equation of motion and the approximate values were found by the procedure described. The results are shown in Table 15, where the starred quantities refer to the approximate values.

The maximum percentage difference between the exact and approximate accelerations is 2%, which is negligible in view of the other inaccuracies present in the analysis.

When $\bar{a} = 0.1$, the initial damping force is $V_o + \bar{a} V_o^3 = 15 + 0.1 (15)^3 = 15 + 377 = 352$. Thus, although the nonlinear part of the force is significant,

TABLE 15

Case	y_m	y_m*	a_m	a_m*
1	2.37	2.37	126	126
2	2.33	2.34	122	121
3	2.20	2.23	108	108
4	2.07	2.10	95.8	96.1
5	2.18	2.18	106	105
6	1.92	1.92	83.7	83.5
7	.943	.942	250	250
8	.922	.928	243	242
9	.852	.867	220	220
10	.787	.796	199	197
11	.837	.836	218	214
12	.714	.704	179	177

it does not affect the results. The limitation on the procedure seems to be that

$$\frac{V_o + \bar{a} V_o^3}{V_o} \times \xi = \xi \ (1 + \bar{a} V_o^2) = \xi^* < 0.5$$

where ξ^* is an equivalent damping factor. This is reasonable, for, even in a linear system, a damping factor of 1/2 or greater means that the maximum acceleration is experienced immediately after impact and not at the end of the first downstroke as required for this analysis.

In view of the preceding discussion, stress-displacement curves for a particular material should be classified according to initial thickness of cushioning and loading displacement-rate. If these curves are to be used in analytical work, the stress-displacement relations should be expressed in mathematical form. Mindlin has pointed out that the quasistatic curves (negligible displacement rate) for many cushioning materials may be characterized by one of the following forms:

1. linear
2. cubic
3. tangent
4. hyperbolic tangent .

Typical graphs corresponding to these types are shown in Figures 29, 30, 31 and 32 along with the functional relation. The dynamic curves for constant displacement-rate may be obtained by adding a constant damping stress to the static stress. The k's, b's, r's and P_o are constants which must be determined from the experimental curves. Mindlin's suggestions for doing this are given later.

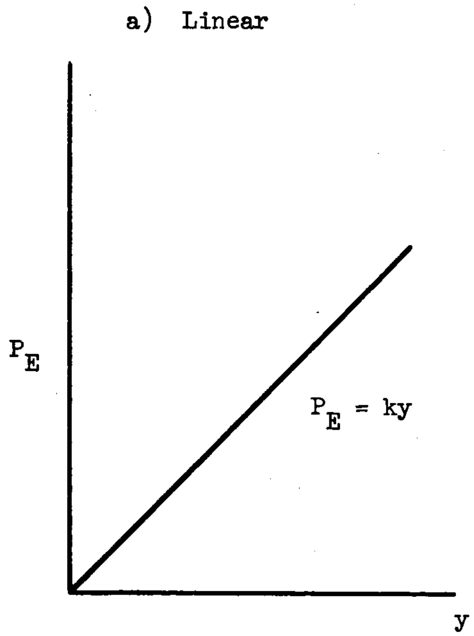


Figure 29

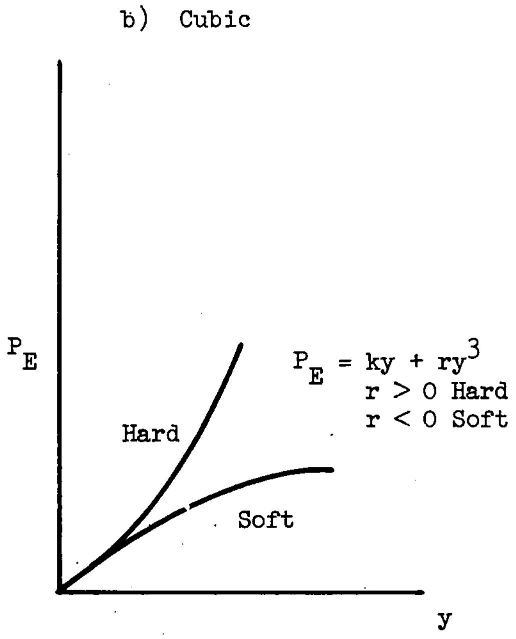


Figure 30

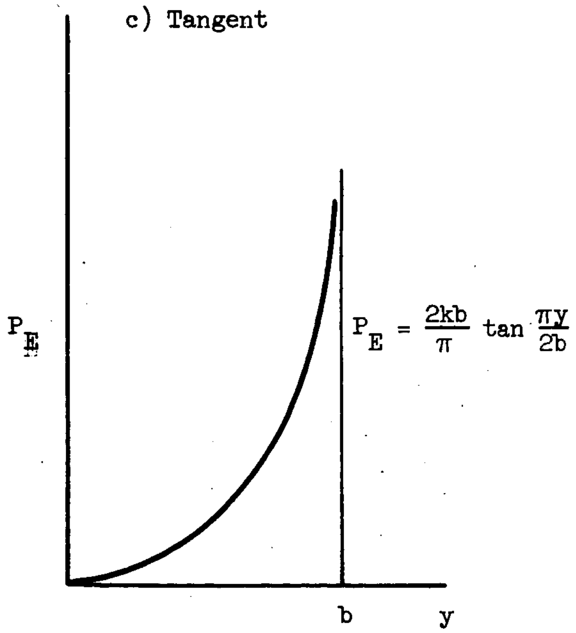


Figure 31

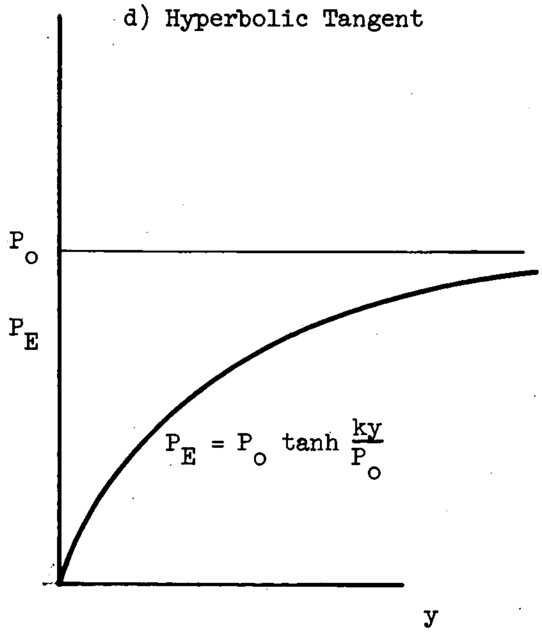


Figure 32

A linear relationship is rarely found for distributed cushioning, although it may be an adequate representation when a metallic spring is to be used. Cubic elasticity represents a deviation from linearity. This is the type of relationship found in a tension spring package. Although the individual spring characteristics are linear, the geometrical arrangement introduces nonlinearities which may be approximated by a cubic deviation. The deviation may be "hard" or "soft" depending on whether the stress for a given displacement is greater or less than the linear value.

Tangent elasticity is typical of many distributed materials and it provides a good model when gradual bottoming is to be expected. A hyperbolic tangent relationship can be used as a model for a material which limits the maximum stress which can be transmitted.

Once the stress-displacement relationship has been expressed in one of the above forms, the maximum displacement of the packaged item during the first quarter cycle of vibration can be found. This will also be the absolute maximum for, if the package remains in contact with the floor, damping will reduce the amplitude on subsequent quarter-cycles and, if the package rebounds, the increased gravitational potential energy will reduce the maximum elastic potential energy and hence the maximum displacement.

The following methods can be used to determine the values of the constants in the force-displacement relations:

Cubic

1. Multiply the weight of the packaged item by the maximum acceleration in g's. For this force, find the corresponding displacement from the experimental curve.

2. Choose another point on the curve halfway to the origin from the first point and read off the force and displacement.
3. Substitute these two pairs of values in the force-displacement relation to obtain two equations which can be solved for k and r.

Tangent

1. Measure the initial slope of the experimental curve. This is the value of k.
2. Read off the asymptotic value of displacement. This is d.

Hyperbolic tangent

1. Measure the initial slope of the experimental curve. This is the value of k.
2. Read off the asymptotic value of force. This is d.

Once these parameters are found, some additional pairs of force-displacement values should be computed and checked with the curve. If the agreement is not too good, it may be necessary to adjust the values of the constants.

To summarize, the following method is used to find the maximum displacement and acceleration of the packaged item:

1. The initial potential Mgh is found (or equivalently the initial kinetic energy, $1/2\ M\ V_o^2$).
2. The energy is set equal to the potential energy of the cushioning at the end of the first downstroke, $A \int_0^{y_m} P_E(y)\ dy$ plus the energy dissipated by damping, $A \int_0^{y_m} P_D(y)\ dy$ The change in gravitational potential energy after impact is neglected.

3. The energy dissipated by damping is represented as $A \overline{P}_D y_m$ where $\overline{P}_D$ is the average damping stress, and $\overline{P}_D$ is approximated as $P_D(3/4\ V_o)$. Thus the work-energy equation is

$$Mgh = A \int_0^{y_m} P_E(y)\, dy + A\, P_D(3/4\ V_o)\, y_m$$

4. The equation in (3) is replaced by

$$Mgh = A \int_0^{y_m} P(y)\, dy$$

where $P(y)$ is the cushioning stress-displacement curve measured at a constant displacement rate of $3/4\ V_o$.

5. This last equation is solved for y_m.
6. The maximum force in the cushioning is assumed to act at the end of the downstroke. Thus

$$a_m \approx \frac{A}{M} P_E\,(y_m)$$

Tables 16 and 17 give the maximum displacements and accelerations for the four types of cushioning shown above. When there is damping, the values cannot be given explicitly and are presented as solutions to algebraic or transcendental equations. When $\overline{P}_D = 0$, explicit expressions can be given.

The discussion until now has dealt with the determination of the maximum values of acceleration and displacement of the primary mass during the first quarter-cycle of vibration after impact. Since these are the maxima for all times, no further analysis is required unless the packaged item contains a critical element.

TABLE 16

$\bar{P}_D \neq 0$

	Linear	Cubic	Tangent	Hyperbolic Tangent
$P(y)$	$ky + \bar{P}_D$	$ky + ry^3 + \bar{P}_D$	$\frac{2kb}{\pi} \tan \frac{\pi y}{2b} + \bar{P}_D$	$P_o \tanh \frac{ky}{P_o} + \bar{P}_D$
y_m	$y_m^2 + \frac{2\bar{P}_D}{k} y_m - \frac{2Mgh}{Ak} = 0$ $(y_m = - \frac{\bar{P}_D}{k} + \sqrt{\frac{\bar{P}_D^2}{k^2} + \frac{2Mgh}{Ak}})$	$y_m^4 + \frac{2k}{r} y_m^2$ $+ \frac{4\bar{P}_D}{r} y_m - \frac{4Mgh}{Ar} = 0$	$\exp (\frac{\pi^2 \bar{P}_D}{4b^2 k} y_m) \cos \frac{\pi y_m}{2b}$ $= \exp (- \frac{\pi^2 Mgh}{4b^2 ka})$	$\exp (\frac{k\bar{P}_D}{P_o^2} y_m) \cosh \frac{ky_m}{P_o}$ $= \exp (\frac{kMgh}{P_o^2 A})$
a_m	$\frac{Ak}{M} y_m$	$\frac{A}{M} (ky_m + ry_m^3)$	$\frac{A}{M} \cdot \frac{2bk}{\pi} \tan \frac{\pi y_m}{2b}$	$\frac{A}{M} P_o \tanh \frac{ky_m}{P_o}$

TABLE 17

$\bar{P}_D = 0$

	Linear	Cubic	Tangent	Hyperbolic Tangent
$P(y)$	ky	$ky + ry^3$	$\frac{2kb}{\pi} \tan \frac{\pi y}{2b}$	$P_o \tanh \frac{by}{P_o}$
y_m	$\sqrt{\frac{2Mgh}{Ak}}$	$\left[- \frac{k}{r} + \sqrt{\frac{k^2}{r^2} + \frac{4Mgh}{AR}} \right]^{\frac{1}{2}}$	$\frac{2b}{\pi} \tan^{-1} (x)$ $x = \sqrt{\exp (\frac{\pi^2 Mgh}{2b^2 kA}) - 1}$	$\frac{P_o}{k} \tanh^{-1} (z)$ $z = \sqrt{1 - \exp (- \frac{2kMgh}{P_o^2 A})}$
a_m	$\sqrt{\frac{2kghA}{M}}$	$\frac{A}{M} y_m \sqrt{k^2 + \frac{4Mghr}{A}}$	$\frac{2kb}{\pi M} x$	$\frac{A}{M} P_o z$

If the maximum acceleration of the primary mass is reached in a time which is large compared to the natural period of vibration of the critical element, then the element may be assumed to be loaded statically and its displacement, at the time at which the acceleration of the primary mass reaches its peak, is found by taking the equation of motion of the element, setting the acceleration and velocity of the element relative to the primary mass equal to zero, the primary acceleration equal equal to the maximum and solving for the maximum relative displacement. This will be a good approximation whether or not the package rebounds.

If the variation of the acceleration of the primary mass is more rapid, the relative displacement of the element will differ from its static value and the amplification factor (the ratio of the actual maximum to static maximum) may be greater or less than one, depending upon the relationship between the natural frequency of the cushioning and that of the element. The effect of the acceleration of the primary mass upon the element (under non-static conditions) depends upon whether the package rebounds or remains in contact with the floor. Thus, when the variation of the acceleration of the primary mass is rapid enough to excite transients in the element response, the motion of the primary mass must be investigated both before and after rebound.

The analysis of the motion for the various types of cushioning considered earlier, both damped and undamped, is fairly complicated. It involves finding the motion of the primary mass before and after rebound and using it as the input to the element. Mindlin has considered several cases and the results are presented in his report to which the reader is referred.

4.3 Additional Considerations

The major part of the discussion up to this point has involved generalizations and idealizations. Assumptions concerning the dynamics of container impacts were introduced, stress-displacement laws given in analytical form, and formulas derived for maximum displacement and acceleration in terms of initial conditions, which were expressed as suddenly applied velocities and related to heights of drop.

However, from a practical point of view, cushioning materials are not closed form mathematical expressions, but are real materials which have weight, take up space, react to atmospheric conditions, and cost money. Thus, the task of specifying the proper cushioning is not just a matter of finding a material which restricts the acceleration of the packaged item to an allowable value, but one which also yields the lowest costs, and will, if necessary, withstand a harsh environment. Furthermore, although an estimated height of drop may have some rational basis, it is only a guess, because the drops which a package experiences are obviously random.

In this section, some practical aspects of package design will be introduced. Packaging geometries will be discussed and cost estimates outlined along with other points. Since these areas will not be explored in depth, the reader is referred to the Military Standardization Handbook - Packaging Cushioning Design(17) prepared by the U. S. Forest Products Laboratory from which most of the material in this section was adapted. (Hereafter referred to as F.P.L. Report.)

4.3.1 Nonmechanical Cushioning Requirements

The facets of the problem to which the package designer should first give his attention are the characteristics of the item to be shipped and the hazards to which it may be subjected. The former will be assumed given to him (by the designer of the item, for example). The latter can be estimated by the package designer by charting the route which the package will follow from point of origin to point of destination, listing the handling procedures which will probably be used and either forming quantitative estimates of the shock magnitudes or referring to the statistics of handling shocks, if the appropriate sets are available.

In addition to the mechanical loadings which the item must endure, the entire package must be able to withstand the atmospheric environment. In particular some cushioning materials are susceptible to extreme heat or cold, or extreme humidity or dryness, and, as a result, lose their effectiveness. Therefore, as part of the hazards to which the package may be subjected, the designer should note these conditions and use this information to immediately eliminate certain cushioning materials from consideration.

After eliminating inappropriate materials, the next task is to choose one of the remaining possibilities, and to decide upon the amount of material needed and the method of application (i. e. whether to completely surround the item with cushioning or to use pads on the sides, etc.). If only a few units are to be shipped, cost will not be a factor and the designer can rather arbitrarily select a material and a convenient method of application. If, however, large quantities are involved, a cost analysis will be necessary before a rational decision can be made.

4.3.2 Alternate Approach to Cushioning Design

Regardless of whether or not the designer has access to statistical height of drop data, he must first choose a material and determine the amount and application method for a single drop height. Because of the simplicity and general applicability, the F.P.L. report recommends that this be accomplished through the maximum acceleration-static bearing stress curves. As mentioned previously, these curves give, for a specific material and a specific height of drop, the maximum acceleration which an item will experience as a function of the static bearing stress which it exerts on the cushioning (i.e. weight/bearing area) and the thickness of the cushioning. These curves are derived experimentally and a flat drop is assumed. A typical set is shown in Figure 33 for urethane foam (polyester) and a drop height of thirty inches. These curves were obtained at a temperature of 75°F and a relative humidity of fifty percent. It has been found that the dynamic properties of most materials are virtually unaffected by a reduction in temperature until a critical temperature is reached, at which time the maximum accelerations greatly increase. For polyester urethane foam this temperature is 14°F.

4.3.3 Methods of Cushioning Application

For a given material the amount needed and the method of application must be determined concurrently because the latter affects the bearing area and thus the static stress. The three most common methods are complete encapsulation, side pads, and corner pads. These are illustrated in Figure 34 below showing the side view of cubical item in its outer container. Side pads may allow the designer to use a smaller volume of material than would be necessary for complete

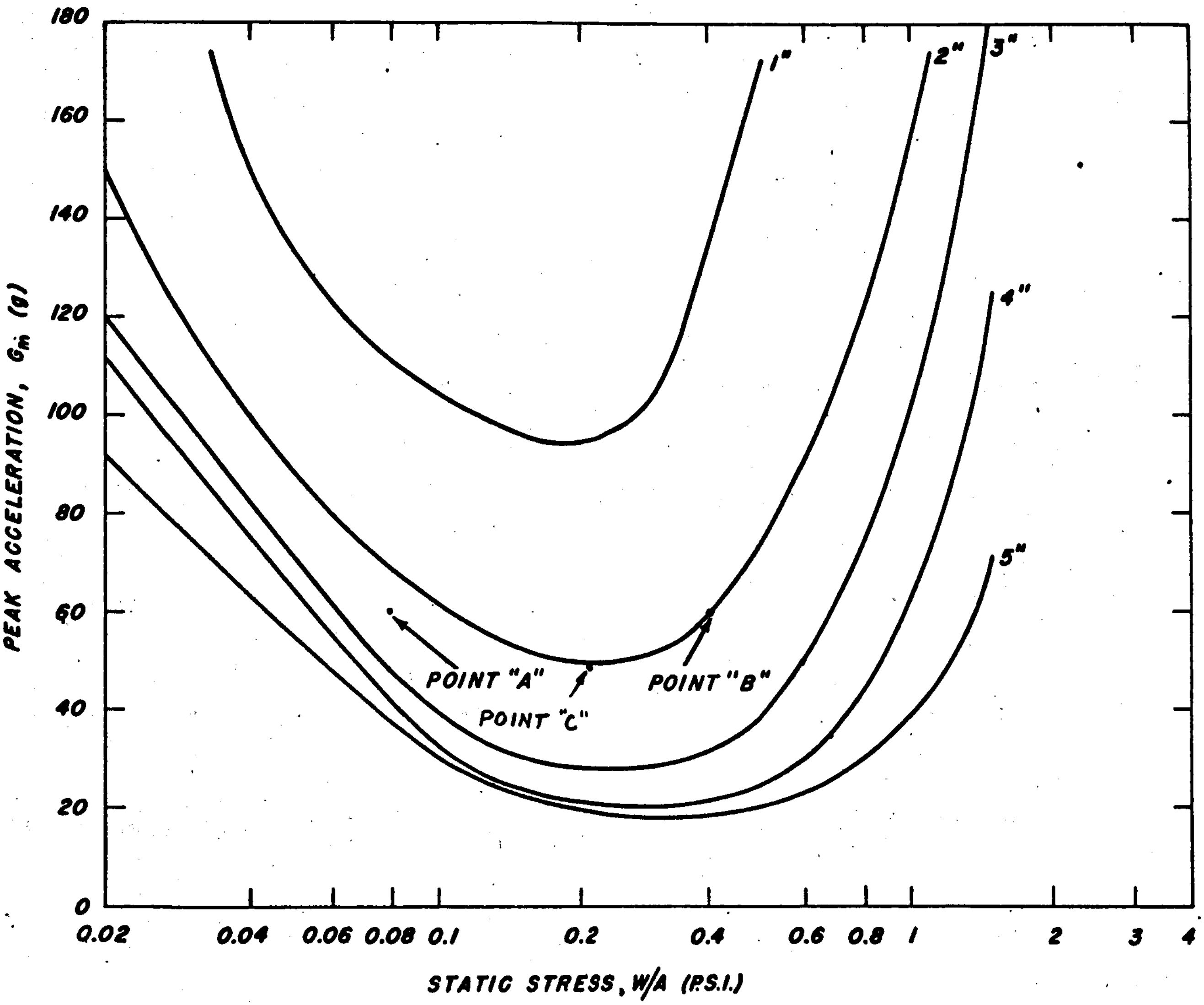
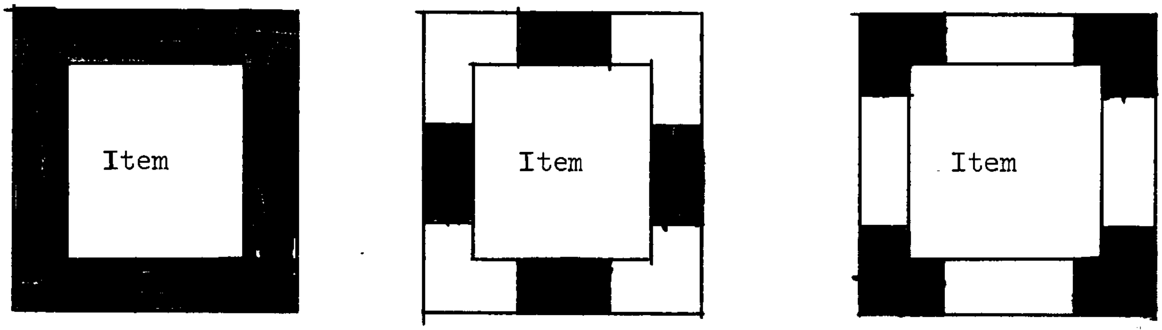


Figure 33 URETHANE FOAM POLYESTER-THIRTY INCH DROP HEIGHT

encapsulation. However, care should be taken to ensure that the pads do not become so slender as to act as columns and buckle. If this should happen, the item might rotate within the outer container and bump sharply against the interior walls. It has been shown that buckling will not occur if $A > 16\ d^2/3$, where A is the cross-sectional area of the side pad and d is its initial thickness.



Complete Encapsulation

Side Pads

Corner Pads

Figure 34

As an illustration, consider the following example taken from the F.P.L. Handbook:

An 8 pound, 10 inch cubical item with a fragility rating of 60 g, is to be protected from a 30 inch drop using urethane foam (polyester). Specify the cushioning needed for the three methods of application, using Figure 33.

a. For complete encapsulation, the bearing area is the area of the side of the item, in this case $10 \times 10 = 100\ in^2$. The static stress is, therefore, $8/100 = .08$ psi. Referring to the curves it is seen that point A lies at 60 g and .08 psi and indicates that the necessary thickness is between 2 and 3 inches. Since it is difficult to interpolate, the cushioning will be taken 3 inches thick. The necessary volume is 6 x 100 x 3 = 1800 in^3. (The factor of 6 occurs because there are six sides.)

b. If the bearing stress for encapsulation falls to the left of point "C", as it does in this case, material can be saved by using side pads. If the area of the side pad is chosen so as to make the bearing stress 0.4 psi (corresponding to point "B") then only 2 inch thicknesses are needed. Since the item weighs 8 pounds, the cross-sectional area will be 20 in^2 (4.5 in x 4.5 in) and the total volume is 6 x 20 x 2 = 240 in^3. Thus, a considerable amount of material is saved using side pads.

c. Corner pads can be used but the total bearing area and thickness can be equal to that for the side pads. The pads can be designed in this case, by cutting each side pad into four equal squares and moving one of each set to each corner of that face. Thus, no material would be saved over side pads.

After calculating the thicknesses of cushioning required, the interior dimensions of the outer container must be found. In doing this, it should be noted that the cushioning will be displaced because of the weight of the item. This static displacement must be compensated for so that the item will fit snugly within the container-cushioning system. Assuming, for this example that the static displacement is 1/2 inch for all three methods of application, the required dimensions are

a. complete encapsulation = 3 + 10 + 3 = 16 inches for two sides;
3 + 10 + 3 - 1/2 = 15 1/2 inches for the third side.

b. side and corner pads = 2 + 10 + 2 = 14 inches for two sides;

2 + 10 + 2 - 1/2 = 13 1/2 inches for the third side.

4.3.4 Economic Considerations

If there are a number of cushioning materials available, the package engineer has several alternative methods of obtaining the required protection. When a large number of items are to be packaged, a cost analysis should be performed so that the total cost per unit for each combination of cushioning material and method of application can be estimated and the most economical chosen. The following factors are involved in the cost estimates:

1. Cost of cushioning materials
2. Cost of platens or other devices which may be necessary to distribute the weight of the packaged item evenly
3. Cost of the container
4. Cost of labor
5. Cost of shipping

The following example adapted from the F.P.L. Handbook is an illustration of a typical cost analysis.

One thousand items are to be packaged individually to withstand a drop of thirty inches. Each item is a parallelopiped of dimensions 12 x 6 x 6 (inches) and weighs 7 1/2 pounds. The fragility rating is 40 g. Three cushioning materials are chosen for consideration - urethane foam polyester (2.0 lb/ft^3), urethane foam polyether (1.5 lb/ft^3), and rubberized hair (2.0 lb/ft^3). The methods of application which will be examined are complete encapsulation and corner pads.

For complete encapsulation, the bearing areas are taken to be the surface areas of the faces. These are 72 in^2 for the top, bottom, and sides, and 36 in^2 for the ends. The corresponding static bearing stresses are obtained by dividing the weight by the area. These are .10 psi (top, bottom and side) and .21 psi (ends).

The following thicknesses of material were obtained by referring to the acceleration curves.

Material	Top, Bottom, Sides	Ends
Urethane polyester	3 in.	3 in.
Urethane polyether	3 in.	3 in.
Rubberized hair	4 in.	5 in.

Following are the dimensions of the pieces required for the various materials. It should be noted that the pieces will overlap. This will afford better protection for the edges of the item.

Material	Top, Bottom (2)	Sides (2)	End (2)	Total Volume
Urethane polyester	12 x 6 x 3	12 x 12 x 3	12 x 12 x 3	15.0 bd ft
Urethane polyether	12 x 6 x 3	12 x 12 x 3	12 x 12 x 3	15.0 bd ft
Rubberized hair	12 x 6 x 4	12 x 14 x 4	14 x 14 x 5	27.0 bd ft

One bd ft is the volume of a slab 1 ft^2 and 1 inch thick

With this information, the cost of the cushioning material can be found, the container size and its cost can be computed, and the labor and shipping costs can be estimated. The results are given in Table 18.

TABLE 18

Material	Material Cost	Cushioning Cost	Container Dimension	Container Cost
Urethane Polyester	$.25 bd/ft	$3.75	18 x 12 x 11 3/4	$.72
Urethane Polyether	.15	2.25	18 x 12 x 11 3/4	.72
Rubberized hair	.14	3.78	22 x 14 x 13 3/4	.89

Material	Labor Cost	Shipping Cost	Total cost/unit
Urethane Polyester	$.59	$.39	$5.45
Urethane Polyether	.59	.38	3.94
Rubberized hair	.70	.49	5.86

The height of the outer container contains an allowance of 1/4 inch for static deflection. The labor cost was found by estimating the time required and multiplying by an hourly wage of $2.40. The shipping cost was based on $3.16 per hundred weight.

These calculations show that, for complete encapsulation, urethane foam polyether yields the lowest total cost per package. It is now necessary to repeat the computation of corner pads. The results are given in Table 19.

TABLE 19

Material	Dimensions of Pads (8)	Cost per Piece	Cushioning Cost
Urethane Polyester	2 x 2 x 2 (3 in. thick)	$.38	$3.04
Urethane Polyether	3 x 3 x 3 (3 in. thick)	.55	4.40
Rubberized hair	3 x 3 x 3 (5 in. thick)	.69	5.52

Material	Container Dimension	Container Cost	Labor Cost	Shipping Cost	Total Cost
Urethane Polyester	18 x 12 x 11 3/4	$ .72	$.37	$.35	$4.48
Urethane Polyether	18 x 12 x 11 3/4	.72	.37	.34	5.83
Rubberized hair	22 x 16 x 15 3/4	1.01	.50	.51	7.54

These costs are all above $3.94. Thus, complete encapsulation by urethane polyether is the most economical method of cushioning (of those considered).

4.3.5 Calculation of Optimum Design Drop Height

As discussed earlier, when the package designer has access to an appropriate statistical distribution of drop heights, his analysis should include a search for the optimum design drop height. The design drop height is the maximum height from which the package may be dropped without damaging the item. The optimum value is that for which the total real cost of the shipment is minimized. This total real cost may be given by the following formula:

$$C_T = N \times C_s + N \times f \times C_E = N \times (C_s + f \times C_E)$$

where

N is the number of units in the shipment

C_s is the original cost of shipment per unit

f is the probability that a package will be dropped from a height greater than the design drop height h.

C_E is the total additional cost per unit incurred when an item is dropped from a height greater than the design height

C_T, C_S and f are functions of h. C_E is equal to the cost of the item if it cannot be repaired. If it can be repaired, C_E is equal to the cost of parts and labor plus additional shipping charges. It may also reflect the estimated dollar value of intangibles (such as good will).

Thus, to find the optimum design drop height, C_T must be minimized. However, since N is independent of h, the optimum drop height is independent of the number of units in the shipment and it is only necessary to minimize $(C_s + f \times C_E)$.

To illustrate this analysis, the preceding example will be extended. The F.P.L. Handbook gives maximum acceleration curves for drop heights of 18, 24, 30 and 36 inches. From the results of the preceding calculations, it can be assumed that complete encapsulation by urethane foam polyether is the most economical combination of method and material for any height of drop. Therefore, the design and shipping cost estimate was performed for the three additional design drop heights given above. The results are given in Table 20.

The handling statistics will now be introduced. These will be taken from Figure 6. This curve was obtained by shipping a large number of packages along various rail routes and determining the drop heights which each package experienced. The figure shows the fraction of packages which were dropped from a height greater than h as a function of h. Since the number of units was fairly large, the fraction is equal to the probability that a single package will be dropped from a height greater than h when shipped along a similar rail route. Because this curve combines the results of all handling operations performed along the route, the probabilities are dependent upon the number of such operations. Therefore, in using this curve for the problem at hand, it will be assumed that the shipping route is similar to the one used in the survey.

The dimensions of the packages used in the survey were 17-1/2" x 12" x 11-1/2" and the weight was 22 pounds. Thus, they are almost identical in size to the packages in this problem but are about twice the weight. This latter factor should not be too important.

The following probabilities were taken from the curve:

h	f
18	.075
24	.032
30	.013
36	.005

TABLE 20

h	Top(2) Dimensions	Side (2) Dimensions	End (2) Dimensions	Volume Bd. Ft.	Cushioning Cost	Container Dimensions	Container Cost	Labor Cost	Shipping Cost	C_s
18	12 x 6 x 3	12 x 12 x 3	12 x 12 x 2	13.0	$1.95	16 x 12 x 11-3/4	$ .64	$.59	$.36	$3.54
24	12 x 6 x 3	12 x 12 x 3	12 x 12 x 3	15.0	2.25	18 x 12 x 11-3/4	.72	.59	.38	3.94
30	12 x 6 x 3	12 x 12 x 3	12 x 12 x 3	15.0	2.25	18 x 12 x 11-3/4	.72	.59	.38	3.94
36	12 x 6 x 4	12 x 14 x 4	14 x 14 x 4	24.2	3.63	20 x 14 x 13-3/4	1.09	.59	.46	5.77

Assuming that the additional cost associated with damage per unit, C_E, is \$20, the following table shows the total real cost per unit, C_T, as a function of design drop height, h.

h	C_s	$f \times C_E$	$C_s + f \times C_E$
18	\$3.54	\$1.50	\$5.04
24	3.94	.64	4.58
30	3.94	.26	4.20
36	5.77	.10	5.87

Thus, for the four drop heights considered the optimum is 30 inches. If C_E is \$10, the following table applies:

h	C_s	$f \times C_E$	$C_s + f \times C_E$
18	\$3.54	\$.75	\$4.29
24	3.94	.32	4.26
30	3.94	.13	4.07
36	5.77	.05	5.82

The optimum design drop height is still 30 inches. When C_E is \$5, the costs are:

h	C_s	$f \times C_E$	$C_s + f \times C_E$
18	\$3.54	\$.38	\$3.92
24	3.94	.16	4.10
30	3.94	.07	4.01
36	5.77	.03	5.80

In this case, the optimum design height is 18 inches. This trend is expected since the lower the cost of damage, the less reason there is to protect the item.

In this analysis it has been assumed that damage occurs the first time that a package is dropped from a height greater than the design height and that the item is not weakened by lower drops. If this assumption is not valid then the strength of the item (i.e. its fragility rating) is a function of the handling history of the item, that is, the number and magnitudes of previous drops. More detailed statistical information than used here is needed, and the analysis is more complicated, requiring reliability theory.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The severest shock environment encountered by cargo being shipped occurs during handling operations.

Very sparse data is available concerning the shock environment incident to the handling operations.

Data are available to show the number and height of drops for particular packages, distribution systems and handling operations. The effect of package characteristics such as size and weight, the effect of distribution system, the effect of labels and handholds, and the distribution of drops over the faces edges and corners has been determined from limited studies.

Data are insufficient at the present time to accurately describe the environment for any given package and distribution system.

Information on the handling environment can be obtained by systematic observation of all handling operations or by instrumented packages.

The number of drops received by a package is highly variable. Very misleading information can be obtained from measurements recorded on a few packages.

The maximum shocks incident to the handling environment occur so infrequently that it is uneconomical to design a package to protect it against there accidents unless very costly items are involved.

The drops received by a package show a large number of small drops with relatively few higher drops. Most packages receive only one drop at the higher levels with a very few having more than two. Thus, it would be very easy to overtest when applying the higher drop heights to the various corners, edges and faces of a package.

A package can be dropped everytime it is handled. Thus the most direct method for improving cargo handling is to reduce the number of handling operations. This is apparent in the marked difference in full container handling as opposed to packages handled individually, i.e., mixed goods.

A continued effort should be directed toward securing and incorporating results of recent field measurement programs of the transportation and handling environment. A number of programs are in progress which should produce very useful information. One program in particular is concerned with fork truck operations for which very little data could be found.

Packaging engineers designing cushioning or shock isolation systems require information concerning the fragility ratings of equipment. Information of this type should be compiled and included in the design criteria.

The performance characteristics of shock isolation systems would also be useful to packaging engineers. The transfer functions of various shock isolation systems should be compiled and incorporated in the manual.

APPENDIX A

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APPENDIX B

LISTING OF AGENCIES AND ORGANIZATIONS CONTACTED FOR INFORMATION APPLICABLE TO THE HANDLING ENVIRONMENT

Tektronix, Inc.
P. O. Box 500
Beaverton, Oregon

Eastman Kodak Company
Industrial Engineering Division
Rochester, New York

National Safe Transit Committee
45 East 22nd Street
New York, New York 10010

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Department of the Navy
David Taylor Model Basin
Washington, D. C. 20007

J. Algot Johnson
9 Sheridan Drive
Short Hills, New Jersey

Clark Equipment Company
Industrial Truck Division
Battle Creek, Michigan

Corps of Engineers
ERDL
Fort Belvoir, Va.

United Technology Center
Division of United Aircraft Corp.
Sunnyvale, California

U. S. Naval Bureau of Ordnance
Special Project Office SP-2
Washington, D. C.

Matson Navigation Company
215 Market St.
San Francisco, Calif. 94105

Swedish Packaging Research Institute
Elektravagen 53
Box 420 54
Stockholm 42, Sweden

Westinghouse Electric Corp.
246 East Fourth Street
Mansfield, Ohio

Northrup Corporation
Norair Division
Hawthorne, California

The Gerstenslager Company
Wooster, Ohio

Yale Materials Handling Division
Yale & Towne, Inc.
11000 Roosevelt Boulevard
Philadelphia, Pa. 19115

North American Aviation, Inc.
Space and Information Systems Division
12214 Lakewood Boulevard
Downey, Calif. 90241

Packaging and Material Handling Lab.
U. S. Naval Station
Bayonne, New Jersey

Sandia Corporation
Sandia Base
Albuquerque, N. M.

U. S. Army Natick Laboratories
Natick, Massachusetts 01762

United States Department of Agriculture
Forest Service
Forest Products Laboratory
Madison, Wisconsin 53705

Wirebound Box Manufacturesr Assoc.
222 West Adams Street
Chicago, Illinois 60606

Fibreboard Paper Products Corp.
475 Brannan Street
San Francisco, Calif.

General Electric Company
One River Road
Schenectady, New York 12305

Pace Engineering Company
13035 Saticoy Street
North Hollywood, Calif. 91605

The Impact Register Company
P. O. Box 445
Champaign, Illinois 61823

Gaynes Engineering Company
1652 W. Fulton
Chicago, Illinois 60612

Department of the Air Force
Headquarters Mobile Air Materiel Area
Brookley Air Force Base, Alabama 36615

Towmotor Corporation
16100 Euclid Avenue
Cleveland 12, Ohio

White Trucks
A Division of
White Motor Corporation
P. O. Box 5757
Cleveland, Ohio 44101

United Air Lines
P. O. Box 8800
O'Hare International Airport
Chicago, Illinois 60666

Society of Packaging & Handling Engineers
14 East Jackson Blvd.
Chicago, Illinois 60604

Package Research Laboratory
A Division of Stapling Machines Co.
Rockaway, New Jersey

REA Express
219 East 42nd Street
New York, New York 10017

U.S. Naval Supply Depot
5801 Tabor Avenue
Philadelphia, Pa. 19120

The Impact-O-Graph Corp.
1762 East 18th Street
Cleveland, Ohio 44114

Inertia Switch Incorporated
311 West 43rd Street
New York, New York 10036

L.A.B. Corporation
P. O. Box G
Skaneateles, New York 13152

General Testing Laboratories
of Alexandria, Inc.
1200 Duke Street
Alexandria, Virginia 22314

Container Corporation of America
900 North Ogden Avenue
Chicago, Illinois 60622

The Printing, Packaging & Allied
Trades Research Association
Patra House
Randalls Road
Leatherhead, Surrey, England

Ministry of Aviation
Royal Radar Establishment
St. Andrews Road
Great Malvern, Worcs., England

Bureau of Explosives
59 E. Van Buren Street
Chicago, Illinois 60605

IBM
1000 Westchester Avenue
White Plains, New York 10604

Picatinny Arsenal
P & B Lab. Bldg. 403
Dover, New Jersey

Department of the Air Force
Air Force Flight Dynamics Laboratory
Wright Patterson Air Force Base
Dayton, Ohio 45433

Toby Hanna Army Depot
Toby Hanna, Pennsylvania

Pacific Intermountain Express
P. O. Box 958
Oakland 4, Calif.

American Airlines
633 Third Avenue
New York, New York 10017

Harnischefger
4400 W. National Avenue
Milwaukee, Wisconsin, 53246

Glass Container Mfgs. Institute, Inc.
Packaging Research Laboratory
1405 South Harrison Road
East Lansing, Michigan 48823

Xerox Corporation
P. O. Box 1540
Rochester, New York 14603

National Wooden Pallet Mfgs. Assoc.
1619 Massachusetts Avenue, N. W.
Washington 36, D. C.