# "STATE-OF-THE-ART" INSTRUMENTATION FOR PACKAGE DESIGN RESEARCH

Gregory D. Hoshal, President
Instrumented Sensor Technology, Inc.
Lansing, Michigan

**Gregory D. Hoshal** is founder of Instrumented Sensor Technology, a firm specializing in computerized sensing and recording instrumentation for shock and vibration. He holds B.S. and M.S. degrees in electrical engineering from Michigan State University, and is currently a Ph.D. candidate. Having published several papers in the field of electrical engineering, Mr. Hoshal is a member of the Institute of Electrical & Electronic Engineers, Eta Kappa Nu, SPHE, and NSTA.

*ABSTRACT*- Fundamental to optimum package design is a good statistical characterization of the environment to which the packaged product is exposed during shipment. In this paper the measurement of shock and its relation to package drop heights in the distribution environment is discussed. Modern microelectronics has now made possible extremely small, self-contained, computerized instruments for efficiently measuring induced shock in package distribution environments. A new instrument which has the capability of accurately recording complete tri-axial shock time histories of packages during shipment is discussed. The instrument is used in conjunction with the desk-top personal computer to efficiently analyze recorded information and provide valuable reports on date and time of impact occurrences, peak shock levels, velocity changes, and equivalent package drop heights.

## Introduction

Packaged products must have the ability to survive the hazards of the distribution environment if they are to meet consumer needs and arrive undamaged and functional. In designing to survive the environment, as well as provide the most optimal and cost efficient design, the packaging engineer is challenged to balance the following well-known equation[1].

$$\text{PRODUCT} + \text{PACKAGE} = \text{PHYSICAL DISTRIBUTION ENVIRONMENT} \qquad (1)$$

Among the measurable characteristics which present hazards in the physical distribution environment are: Shock, Vibration, Compression, Temperature, Humidity, Sunlight, and Contamination. Historically, the packaging engineer has lacked accurate, reliable, and reproducible information on these parameters within the distribution environment. As a result, package designs were more protective and costly than what were actually needed, or in other cases less protective than required. In many instances repeated product damage lead to costly package design iterations based only upon damage feedback information.

One of the environmental hazards which is frequently of primary concern, particularly within the small parcel environment is shock. Over the last twenty years the availability of laboratory instrumentation and test fixtures for simulating a wide variety of shock and vibration inputs to packaged products has advanced tremendously. As a result, damage boundary theory and product fragility characterizations have become well known. Today, within a well equipped package testing laboratory the *product + package* side of equation (1) can be accurately established. What has been lacking in many cases, however, is instrumentation for accurately and reliably collecting field data on the physical distribution environment.

Shock and impact events are often a major cause of product damage in shipment. Consequently, packaging professionals have evolved a protocol for designing and testing against environmental shock inputs. The first step in this design protocol is the determination of what is referred to as a "design drop height"[2-3]. In fact, however, many environmental shock inputs to packaged products may actually be caused by dynamics *other* than an ideal free-fall drop(e.g. horizontal collisions, mechanical handling system collisions, etc.). Because the free-fall drop test is easily understood and reproduced, it has become a leading standard from which to design against environmental shock inputs.

In order that the design drop height be useful and accurate in the package design process, it should closely reflect the dynamics of the actual physical distribution environment. Therefore, a method for collecting environmental data on shock(and drop heights) is necessary. Historically, one has often had to rely on published data compiled from a variety of testing projects, such as the FPL 22 report[4]. Aside from being "old" in the sense that the package handling methods have changed and become more automated since its collection, the fundamental accuracy of such data is in serious question as a result of the data measurement techniques used. Consequently, the packaging engineering community has since been calling out for "the ideal measurement device" from which to accurately define the dynamic shipping environment[5].

The technology for measuring impact acceleration waveforms on packages and products has existed for years. However, the miniaturization required to place such a measurement device within a small package for a long time duration, self-contained shipment has until recently not been feasible. Devices which have been available have been plagued by problems associated with accuracy, reliability, and measurement data reduction and interpretation. Analysis and reduction of recorded and collected impact acceleration data has previously been a time consuming and burdensome task. Today, however, the power available within the desk-top personal computer can be used to make such data analysis completely automated, time efficient, and extraordinarily accurate.

## Measurement of Impact Acceleration and Equivalent Drop Heights

Since the packaging engineering community has become accustomed to testing at "design drop heights" a method is required to derive package drop heights from measured acceleration waveforms. Because impact accelerations may occur from horizontal as well as more ideal vertical impacts, a standard technique is required to perform direct comparison between all measured environmental impacts which have the potential of causing product damage. The term which has evolved in this regard is the *equivalent drop height*. The equivalent drop height may be used to directly compare generic impact acceleration events resulting from any package orientation to the ideal free-fall acceleration impact.

**Deriving Equivalent Drop Heights from Impact Acceleration.** An important relationship exists between measured impact acceleration and equivalent drop heights. In order to derive valuable drop height design data from measured environmental acceleration waveforms this relationship should be understood.

Shown in figure 1 is a typical measured impact acceleration waveform. Note that for a typical impact measured in the distribution environment, the acceleration is usually distributed among three independent measurement axes, denoted $A_X$, $A_Y$, and $A_Z$. Therefore, a *tri-axial* accelerometer measurement capability is required to accurately capture all real environmental impact accelerations.

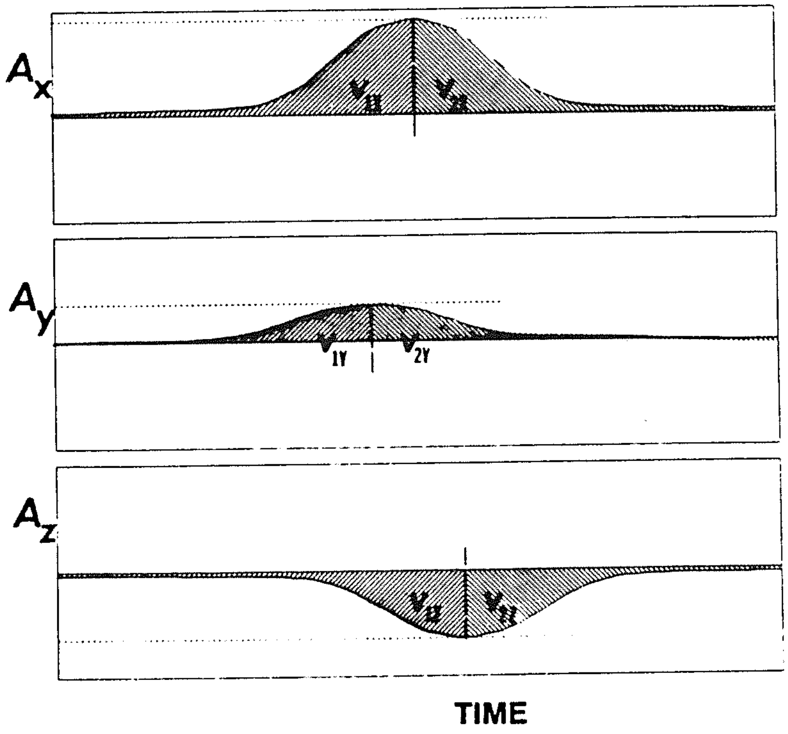


Fig. 1 Tri-axial acceleration waveforms illustrating a typical impact event in the distribution environment

From the measured tri-axial accelerations, one can determine a *resultant* acceleration waveform. The resultant acceleration is the magnitude of the combination of accelerations on each of the three independent axes. The resultant acceleration waveform is determined by combining each of the individual waveforms as given by (2).

$$(2) \quad A_r = \sqrt{A_x^2 + A_y^2 + A_z^2}$$

A resultant acceleration waveform is depicted in figure 2. The resultant acceleration waveform is used to derive an equivalent drop height from the impact event.

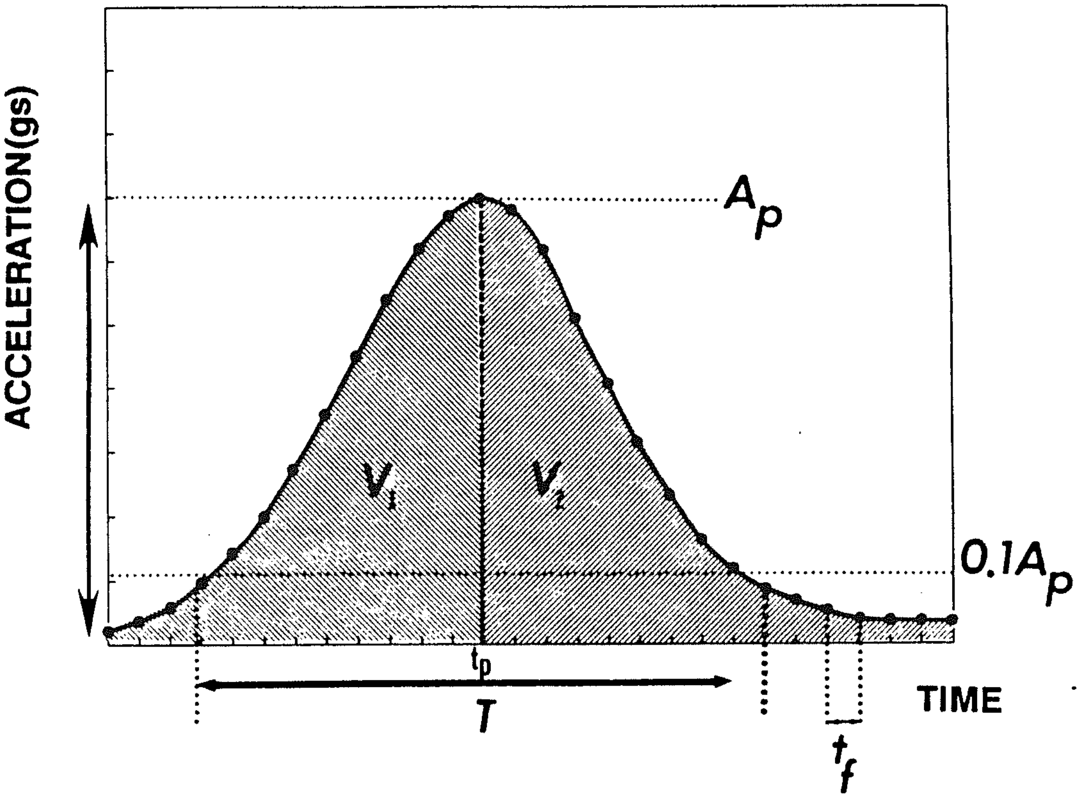


Fig. 2 Example of a resultant acceleration waveform from a tri-axial impact event

**Velocity Change.** The total area under the resultant acceleration waveform is often referred to as the *total velocity change*, $V_t$, experienced during the impact event. The total velocity change is made up of the *impact velocity*, $V_1$, and the *rebound velocity*, $V_2$, as given by (3).

$$(3) \quad V_t = V_1 + V_2$$

The peak level of the resultant acceleration is denoted as $A_p$. The *duration* of the impact event is usually measured as the time between the 10% amplitude points on the resultant acceleration waveform as shown in figure 2.

The equivalent drop height corresponding to a given resultant acceleration waveform is easily determined if one can accurately estimate the *impact velocity*. The equivalent drop height is related to the impact velocity as given by (4).

(4) $\mathbf{h = V_1^2/(2g).}$
( where g=acceleration of gravity= 386 inches/sec$^2$)

The problem typically encountered in this approach is in determining the impact velocity component of the total velocity change. The impact and rebound velocity are commonly related by what is referred to as the *coefficient of restitution*, denoted by e. The coefficient of restitution is defined as the ratio of the *rebound* velocity to the *impact* velocity of a typical impact.

(5) $\mathbf{e = V_2/V_1.}$

Theoretically e is limited to values between 0 and 1. However, typical values of e for real packages within the distribution environment range from about 0.3 to 0.7. Incorporating the coefficient of restitution into the formula for equivalent drop heights given from (3), (4) and (5) results in equation (6).

(6) $\mathbf{h = [V_t/(1+e)]^2 \; 1/(2g).}$

The problem which has historically been associated with this technique for equivalent drop height determination from acceleration waveforms is that e itself may change within the environment. Since e depends upon the type of surface on which the package is dropped as well as the package's orientation at impact, it has been difficult to "calibrate" a package with a pre-determined e value. Therefore, it is desirable to be able to *estimate* a value for e for each individual impact event recorded.

An algorithmic technique has been developed by the author which can be used to estimate a value for e *directly from the resultant impact acceleration waveform*. This technique provides acceptable estimates for e values ranging from approximately 0.3 to 0.7, which is the range typically encountered within the distribution environment. The algorithm, however, does assume certain conditions with respect to the resultant acceleration waveform. These conditions may generally be met by appropriate packaging considerations of the measurement instrument itself. If the algorithm estimates an e value *outside* of the expected range of e values(0.3 - 0.7), then a default value of 0.5 is used. Using this technique, the worst case drop height error possible in any single impact event is limited to be less than +/- 30% of the actual drop height. In actual tests, this approach has shown the *average drop height error to be less than 10%* over ten independent test drops, ranging from 6 inches to 60 inches.

## The Environmental Data Recorder

A new electronic device satisfying the requirements of the packaging engineer for acquiring environmental data on shock and drop heights has been developed. This new instrument, available from Instrumented Sensor Technology, is known commercially as the Environmental Data Recorder, or EDR-1. This new instrument, shown in figures 3 and 4, is a completely self-contained, portable, battery operated, transient shock recorder with a *built-in tri-axial accelerometer*. The instrument is designed with 100% solid state electronics, offering a high degree of reliability in field use. Weighing under 8 lbs, the instrument is user programmable by connecting it to the user's personal computer serial communications port for initial configuration prior to test. Once programmed, the EDR-1 may be packaged and shipped independently for several weeks, unattended, to monitor environmental shocks and drops. The recording instrument is *event-triggered*, and depending upon the programming configuration can selectively record complete tri-axial shock waveforms of up to *several thousand* impact events, if necessary.

For field testing requiring a smaller, lighter instrument, the model EDR-2 is also available. The EDR-2 is functionally identical to the EDR-1, however weighs only 4.3lbs and is roughly 2/3 the size of the EDR-1. The EDR-2 uses smaller batteries for its power supply and may operate for up to 10 days, before re-charging is required.

Recorded waveforms from the EDR are analyzed by the user's desk-top computer. Once the test shipment is complete, recorded shock waveform data is transferred from the EDR up to the desk-top computer to perform analysis and provide drop height reports from recorded acceleration waveforms, as well as statistical data reduction for large amounts of recorded data.

Both EDR instruments are accompanied by the EDR1S software package which facilitates initial instrument programming as well as recorded data analysis and report generation. The EDR-1 or EDR-2 along with EDR1S and the user's personal computer combine to provide a powerful data collection, analysis, and report generation system for collected environmental data.

A typical "Impact Report" format available from EDR1S on data collected with the EDR1 is shown in figure 5. Among the information available in a user-friendly spread-sheet format is date and time of impact event occurrence, duration of the event(in milliseconds), individual axis total velocity changes(in inches-per-second), resultant waveform velocity change, peak resultant acceleration(gs), and calculated equivalent drop height(inches).

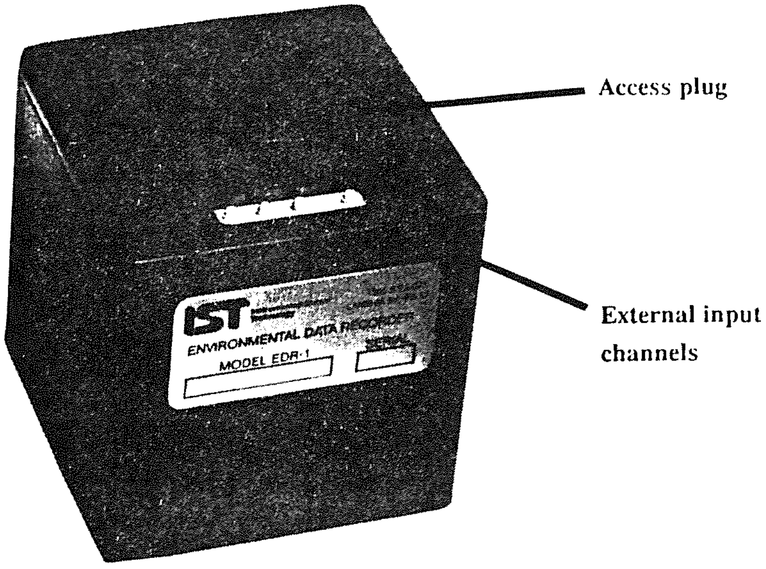


Fig. 3 Environmental Data Recorder

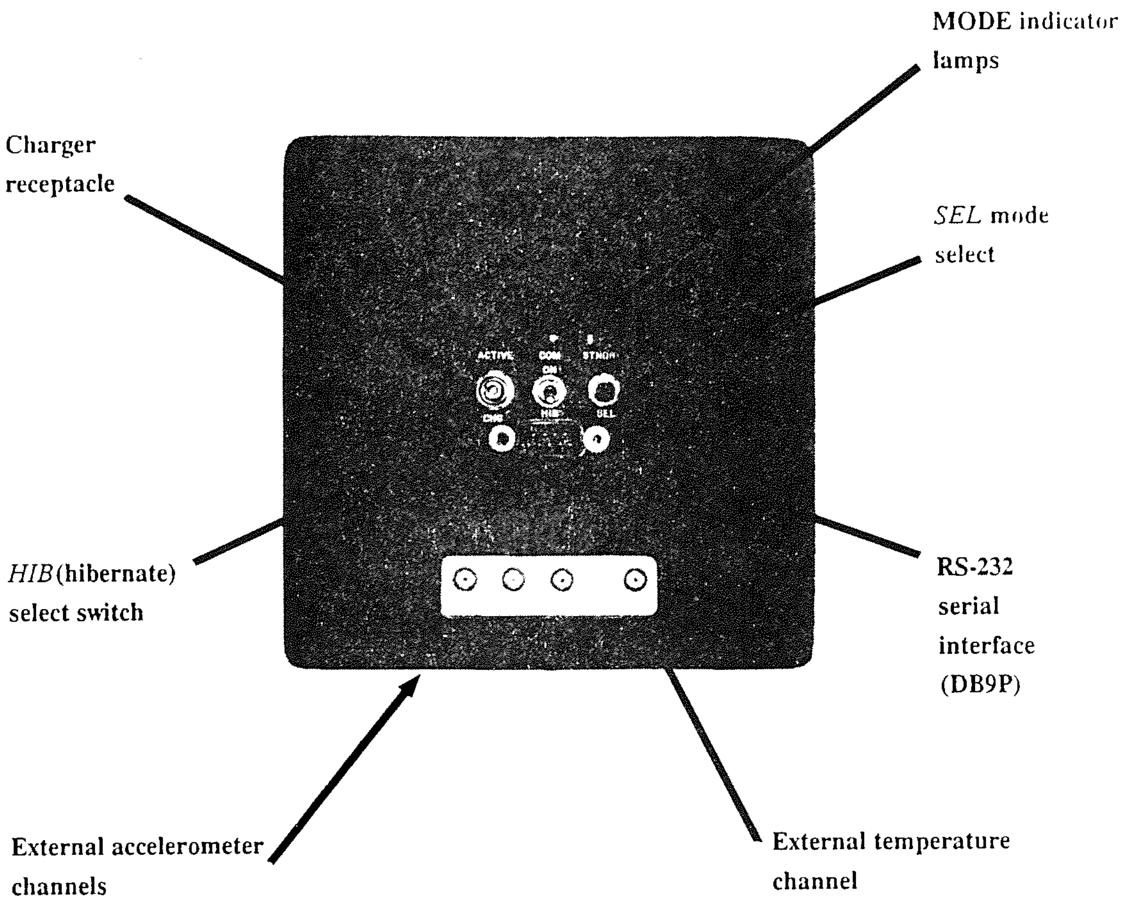
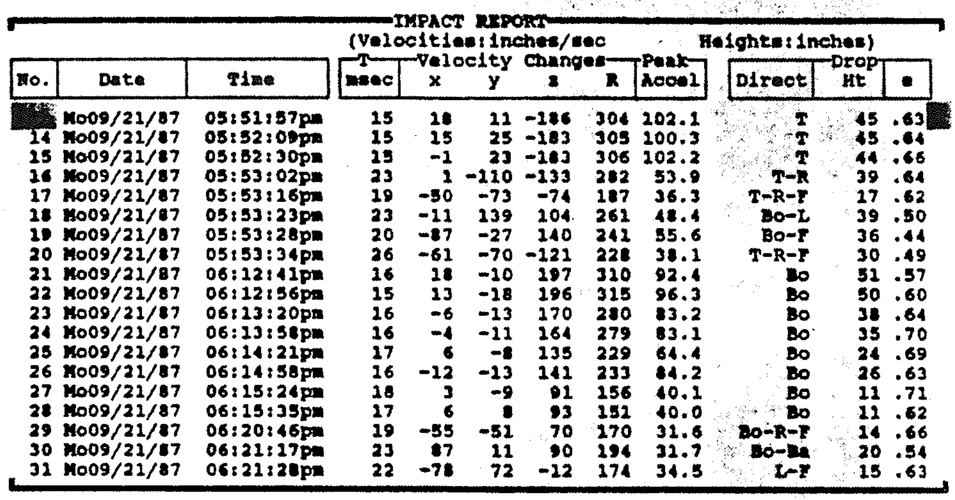


Fig. 4 Top View of EDR-1 With Control Panel Access



```
                            IMPACT REPORT
                  (Velocities:inches/sec        Heights:inches)
                   T     Velocity Changes     Peak            Drop
No.   Date        Time     msec  x    y    z    R  Accel   Direct  Ht    e

   Mo09/21/87  05:51:57pm   15   18   11 -186  304 102.1        T  45 .63
14 Mo09/21/87  05:52:09pm   15   15   25 -183  305 100.3        T  45 .64
15 Mo09/21/87  05:52:30pm   15   -1   23 -183  306 102.2        T  44 .66
16 Mo09/21/87  05:53:02pm   23    1 -110 -133  282  53.9      T-R  39 .64
17 Mo09/21/87  05:53:16pm   19  -50  -73  -74  187  36.3    T-R-F  17 .62
18 Mo09/21/87  05:53:23pm   23  -11  139  104  261  48.4     Bo-L  39 .50
19 Mo09/21/87  05:53:28pm   20  -87  -27  140  241  55.6     Bo-F  36 .44
20 Mo09/21/87  05:53:34pm   26  -61  -70 -121  228  38.1    T-R-F  30 .49
21 Mo09/21/87  06:12:41pm   16   18  -10  197  310  92.4       Bo  51 .57
22 Mo09/21/87  06:12:56pm   15   13  -18  196  315  96.3       Bo  50 .60
23 Mo09/21/87  06:13:20pm   16   -6  -13  170  280  83.2       Bo  38 .64
24 Mo09/21/87  06:13:58pm   16   -4  -11  164  279  83.1       Bo  35 .70
25 Mo09/21/87  06:14:21pm   17    6   -8  135  229  64.4       Bo  24 .69
26 Mo09/21/87  06:14:58pm   16  -12  -13  141  233  84.2       Bo  26 .63
27 Mo09/21/87  06:15:24pm   18    3   -9   91  156  40.1       Bo  11 .71
28 Mo09/21/87  06:15:35pm   17    6    8   93  151  40.0       Bo  11 .62
29 Mo09/21/87  06:20:46pm   19  -55  -51   70  170  31.6   Bo-R-F  14 .66
30 Mo09/21/87  06:21:17pm   23   87   11   90  194  31.7    Bo-Ba  20 .54
31 Mo09/21/87  06:21:28pm   22  -78   72  -12  174  34.5      L-F  15 .63
```

Fig. 5 Typical Impact Report Available from EDR1S

For large numbers of recorded impacts, the EDR1S program provides *automatic histogram generation* from calculated equivalent drop heights, as well as measured peak accelerations. Using this statistical data reduction feature, the user may view the results of large amounts of collected impact data in a single screen graph. A typical histogram screen plot available from EDR1S is illustrated in figure 6.

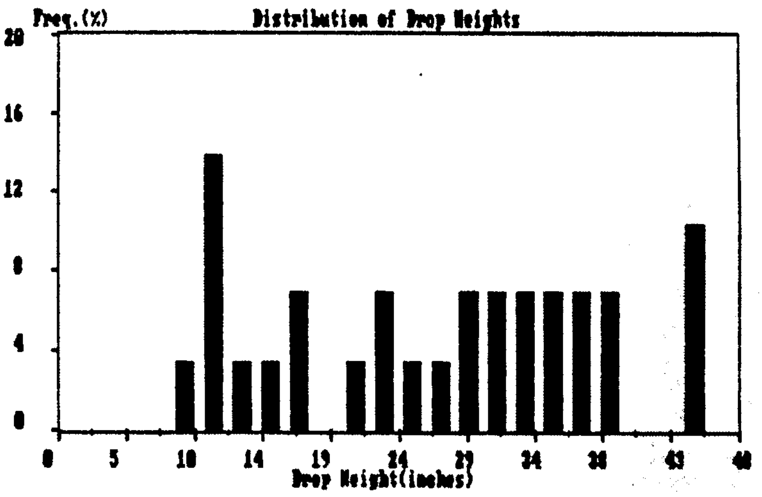


Fig. 6 Example of Histogram Graphics Feature of EDR1S

Individual impact acceleration waveforms may also be graphically displayed using the interactive waveform graphics feature within EDR1S. Individual or multiple events may be conveniently selected from the Impact Report for graphical display, as shown in figure 7.

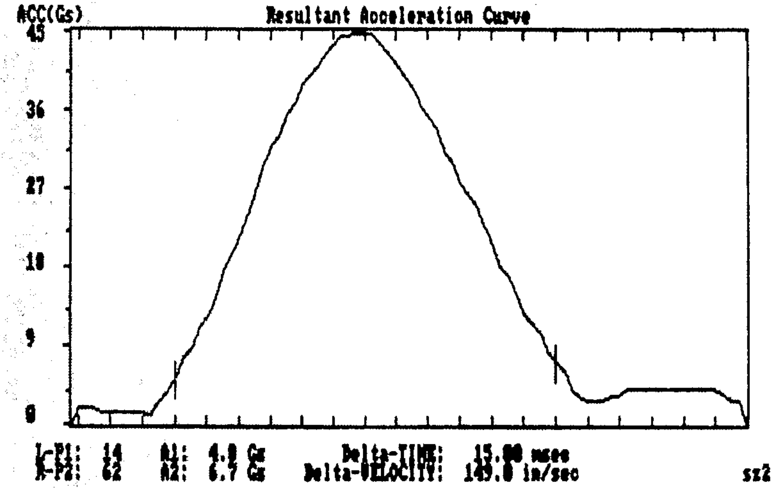


Fig. 7 Example of Graphical Waveform Analysis
Available in EDR1S

In addition to event-triggered recording from the built-in tri-axial accelerometer, the EDR instruments also offer three accelerometer input channels for programmable external shock recording. Using up to three external accelerometers, the instrument can serve as a laboratory-based transient shock recorder/drop test data recorder. In the distribution environment external accelerometers may also be used to simultaneously monitor different physical locations within a particular shipment.

## Summary

The packaging engineer has for years lacked reliable design data from which to formulate optimal package designs against environmental shock. A design methodology involving a "design drop height" has evolved, which along with product fragility data may be used to identify optimal package designs against environmental shock. Until recently, however, a void has existed in the area of instrumentation for reliably and accurately collecting environmental drop height data for packaged products. Today, micro-miniature computer technology and acceleration sensing devices has made possible new, miniature, instrumentation which can be used to accurately acquire this data. One leading commercially available instrument for shock and drop height recording is the Environmental Data Recorder from Instrumented Sensor Technology.

With the help of the ever-common desk top personal computer as a data analysis and reduction tool, the packaging engineer is today able to conduct accurate and sophisticated analysis of his product's distribution environment. Using his collected environmental data, the engineer will be better equipped to provide the most cost efficient package designs for his company while minimizing product damage for his end consumer.

---

**References**

1. Robert M. Fiedler, "Testing for Package Distribution Hazards", SPHE Technical Journal, Fall 1985.
2. William I. Kipp, "Measuring Drop Height in the Distribution Environment: Why and How", Proceedings 5th Annual Educational Conference on Distribution Packaging & Handling, Orlando FL, Feb. 1988.
3. 5 Step Packaging Development, MTS Systems Corporation, P.O. Box 24012, Minneapolis, MN, 1985
4. Fred E. Ostrem and W.D. Godshall,"An Assessment of the Common Carrier Shipping Environment," General Technical Report FPL 22, Forest Products Laboratory, U.S. Department of Agriculture, Madison, WI 53705, 1979.
5. J.N. Daniels and R.T. Sanders,"New Approaches to Defining the Distribution Environment", SPHE Technical Journal, Fall 1986.