Development and Evaluation of Measurement Devices Used to Support Testing of Radioactive Material Transportation Packages*

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INTRODUCTION

Radioactive material package designers use structural testing to verify and demonstrate package performance. A major part of evaluating structural response is the collection of instrumentation measurement data. Sandia National Laboratories (SNL) has an ongoing program to develop and evaluate measurement devices to support testing of radioactive material packages. Measurement devices developed in support of this activity include evaluation channels, ruggedly constructed linear variable differential transformers, and piezoresistive accelerometers with enhanced measurement capabilities. In addition to developing measurement devices, a method has been derived to evaluate accelerometers and strain gages for measurement repeatability, ruggedness, and manufacturers' calibration data under both laboratory and field conditions. The developed measurement devices and evaluation technique will be discussed and the results of the evaluation will be presented.

EVALUATION CHANNELS

Foil-type resistance strain gages and piezoresistive accelerometers are common measurement devices used in radioactive material package testing. Strain gages are used to measure surface strain at the mounted location and accelerometers are used to measure deceleration of the package or specific components. In most cases, the measurement device and associated data acquisition equipment are characterized by either the manufacturer or the organization performing the testing. The measurement system includes the measurement device, data collection system, and any interconnecting cables. The effects of the interconnecting cables, as well as other external influences and their contribution to the measurement, are not generally well defined. Evaluation channels are measurement devices that can be mounted on the package and subjected to the same environments as active measurement devices. The purpose of the evaluation channels is to determine the magnitude of signal contributors caused by factors other than strain or acceleration. A fixed resistance simulating either an accelerometer or strain gage is desirable. This fixed resistance should indicate only nonstrain or acceleration-induced resistance changes from external effects. Since strain gages are usually used in conjunction with accelerometers, the evaluation channels were sized for mounting similar to a commonly used accelerometer. Evaluation channels representing both piezoresistive accelerometers and 350 ohm strain gages have been developed by SNL and are commercially available. The evaluation device (Figure 1) is located in a case (body) made from 17-4 PH stainless steel. The body is 15 mm (0.6 in.) by 7 mm (0.3 in.) by 2 mm (0.1 in.) thick. A cavity

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is machined in the body to accept thick-film chip resistors matching the characteristics of an accelerometer or a strain gage. Cables are attached and routed through the case, and the body cavity is encapsulated to fix the position of the resistors. Two holes that accept 2.8 mm (0.11 in.) diameter screws are provided for mounting. Shock calibration performed on these devices indicated no apparent resistance change to shock levels as high as 15,000 g.

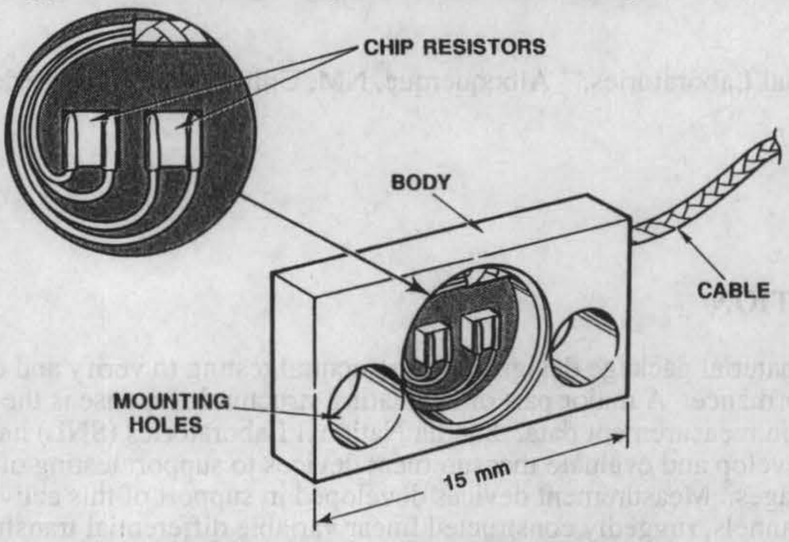

Figure 1. Diagram of an Evaluation Device

These accelerometer and strain gage evaluation channels provide a means of estimating the contribution of external factors in resistive-type measurement data. A comparison of these data to active measuring accelerometers or strain gages will determine the magnitude of possible unwanted contributors. Estimates of strain gage uncertainty based on test severity and gage installer expertise can range from 7% to 30% (Window and Holister 1982). By characterizing the contribution of nonstrain- or acceleration-induced effects, confidence in the data can be increased by demonstrating, using evaluation channels, that the external contribution levels are not a significant part of the measurement data. The evaluation channels provide a meaningful way of determining the magnitude of nonmeasurement-induced effects in dynamic data obtained during radioactive material package testing.

LINEAR VARIABLE DIFFERENTIAL TRANSFORMERS

A linear variable differential transformer (LVDT) is another measurement device used to collect data from radioactive material package testing. The device is used to measure small, single axis displacements, such as the distance change between a closure seal area and cask body, during dynamic testing. Conventional LVDTs are available from several manufacturers for low-shock and slow-displacement rate applications. In order to meet the need for a rugged measurement device suitable for high-shock dynamic displacement measurements, SNL, in conjunction with private industry, has developed a ruggedly constructed LVDT. The LVDT (Figure 2) consists of three major components. The 12.7 mm (0.5 in.) diameter threaded body-tube assembly contains electrical coils. A 2.5 mm (0.10 in.) diameter core is attached to a 1.5 mm (0.06 in.) diameter threaded rod that is allowed to move axially inside the body. As the core assembly is moved within the body, the voltage output changes in proportion to the position of the core. Displacements as small as 0.02 mm (0.001 in.) can be easily resolved. The nominal sensitivity of the LVDT is approximately 0.1 V/0.02 mm (0.001 in.). The device is designed to have a measurement range of ±1.27 mm (0.05 in.) and produces ±5 V at maximum range with linearity of approximately 0.5%. The input and output circuits are electrically isolated from each other and from the body, allowing either electrical floating or grounding of the device. The operating temperature for the LVDT ranges from -45°C (-50°F) to 122°C (250°F). The 25 mm (1.0 in.) long threaded housing was designed for easy installation and positive contact with the mounting surface. Conventional machining techniques are employed to mount these devices using American standard threads. This type of LVDT has been shock tested at amplitudes exceeding 1000 g (Madsen et al. 1987). The ruggedly constructed LVDTs can be used to characterize displacement changes at sealing surface to cask body interfaces during dynamic testing. These LVDTs provide a useful measurement tool in a small, rugged, and inexpensive package.

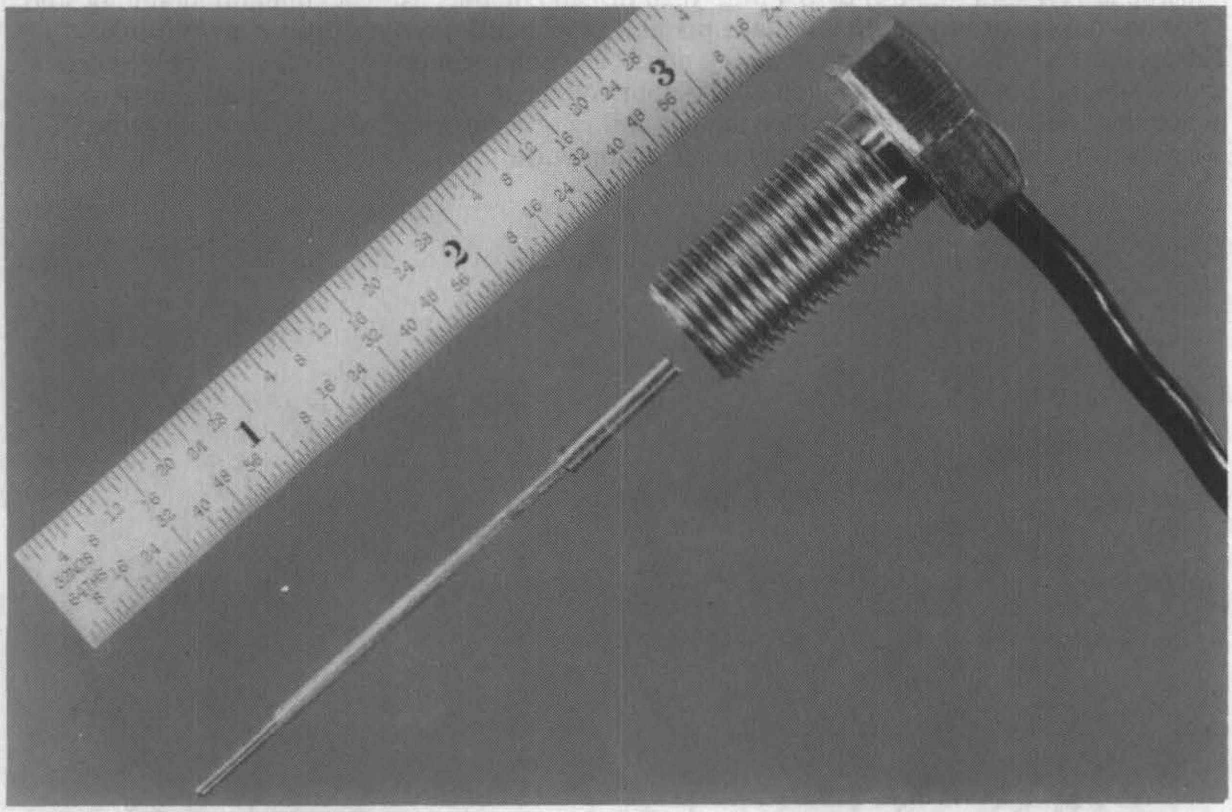

Figure 2. Ruggedly Constructed LVDT

PIEZORESISTIVE ACCELEROMETER

Piezoresistive accelerometers are commonly used in determining the structural response of radioactive material packages. In a piezoresistive accelerometer, the interrogating input is voltage. The output is a voltage which is proportional to acceleration. Piezoresistive accelerometers are essentially single-degree-of-freedom devices and are usually developed based on a cantilever beam principal. Impact testing of radioactive material packages may produce rapid acceleration rise-time response. This response can excite resonant frequencies in the accelerometer and possibly cause loss of data or permanent damage. To overcome the possibility of damage to the accelerometer, viscous damping may be used to reduce the frequency response of the accelerometer. The usable temperature range of viscous-damped accelerometers may not meet the requirements of the experiment. In most cases, the accelerometer selected should optimize the measurement output for the specific application. A compromise has been made in the past of selecting a measurement device with the proper range, frequency response, and output. In response to the need for an optimal piezoresistive accelerometer, SNL, in conjunction with private industry, has developed a pair of rugged, undamped piezoresistive accelerometers with integral hybrid microelectronics applicable for high-shock measurements. The accelerometers are available in either 2000 g or 20,000 g acceleration ranges. A monolithic sensing element is sculpted from a single chip of silicon which provides high-resonant frequency response. The nominal resonant frequency is 120 kHz for the 2000 g units and 400 kHz for the 20,000 g units. The accelerometers require a standard 10-volt excitation and produce ±2 volts output at full scale. The package (Figure 3) is also epoxy sealed for moisture protection. The accelerometers have an operating temperature range from -34°C (-30°F) to 66°C (150°F). The accelerometer linear frequency response extends to 30 kHz with an internally mounted 2-pole butterworth low pass filter. The accelerometer housing is 12.7 mm (0.5 in.) by 6.4 mm (0.25 in.) and mounts using an integral mounting stud. The nominal sensitivity (output voltage per unit acceleration) ranges from 1 mv/g for the 2000 g units to 0.1 mv/g for the 20,000 g units. Development testing on these accelerometers shows advantages in using the increased output voltage to provide better signal to noise ratios in acquired data, as well as to reduce the possibility of resonating, which may damage the accelerometers due to a rapidly rising acceleration pulse.

Figure 3. Rugged, Undamped Piezoresistive Accelerometer

ACCELEROMETER AND STRAIN GAGE EVALUATION METHOD

In conjunction with instrumentation measurement device development, a method has been derived to compare results from selected accelerometers and strain gages in both laboratory and field environments (Ammerman et al. 1991). Two types of accelerometers and strain gages were selected and evaluated. The evaluation is based on the results of tests conducted to measure ruggedness, failure frequency, repeatability, and manufacturer's calibration data. The accelerometers selected for this evaluation were Endevco 7270 series piezoresistive and Bruel and Kjaer (B&K) 8309 piezoelectric devices. The strain gages selected were manufactured by Micro-Measurement and BLH. The accelerometers were evaluated using calibration, shock, and end-impact testing. The strain gages were evaluated using static loading and impact testing. The range of evaluations provided well-characterized laboratory tests for both the accelerometers and the strain gages. The end-impact tests were used since they closely model the environment measurement devices encounter during testing of radioactive material packages. Multiple tests of each type were performed to determine the repeatability of the results.

The sensitivity, amplitude linearity, and frequency response of the accelerometers were determined using factory and SNL calibration. Three types of calibration were performed on the Endevco 7270 accelerometers at SNL: shock, centrifuge, and frequency response. The B&K accelerometers were calibrated using shock and frequency response methods. The nature of piezoelectric accelerometers precludes the use of centrifuge calibration techniques. The frequency response calibration was performed at room temperature and -29°C (-20°F). Three separate sets of accelerometers of each type were calibrated and compared to manufacturers' supplied data. The results of the calibration tests showed good agreement between the calibration techniques. The standard deviation of the sensitivities determined from all calibrations performed on any specific accelerometer was less than 3% of the average sensitivity.

Shock testing was performed on the accelerometers at levels representing package impact conditions. The evaluation consisted of a series of shocks applied to each of the three sets of accelerometers. Accelerometers were mounted to a fixture (Figure 4) which was attached to a vertical shock frame. The fixture was shocked at each of three levels: 1000, 5000, and 10,000 g. These acceleration levels were chosen to characterize the accelerometers in a range that envelops the response experienced in typical package tests. Each level was repeated three times for a total of nine shocks per accelerometer set. The data from the three sets of accelerometers were normalized with respect to a reference accelerometer mounted on the fixture. Figure 5 shows the distribution of the normalized peak accelerations for all shock tests. The standard deviation of the peak accelerations for the normalized shock testing was 3.4% of the average value.

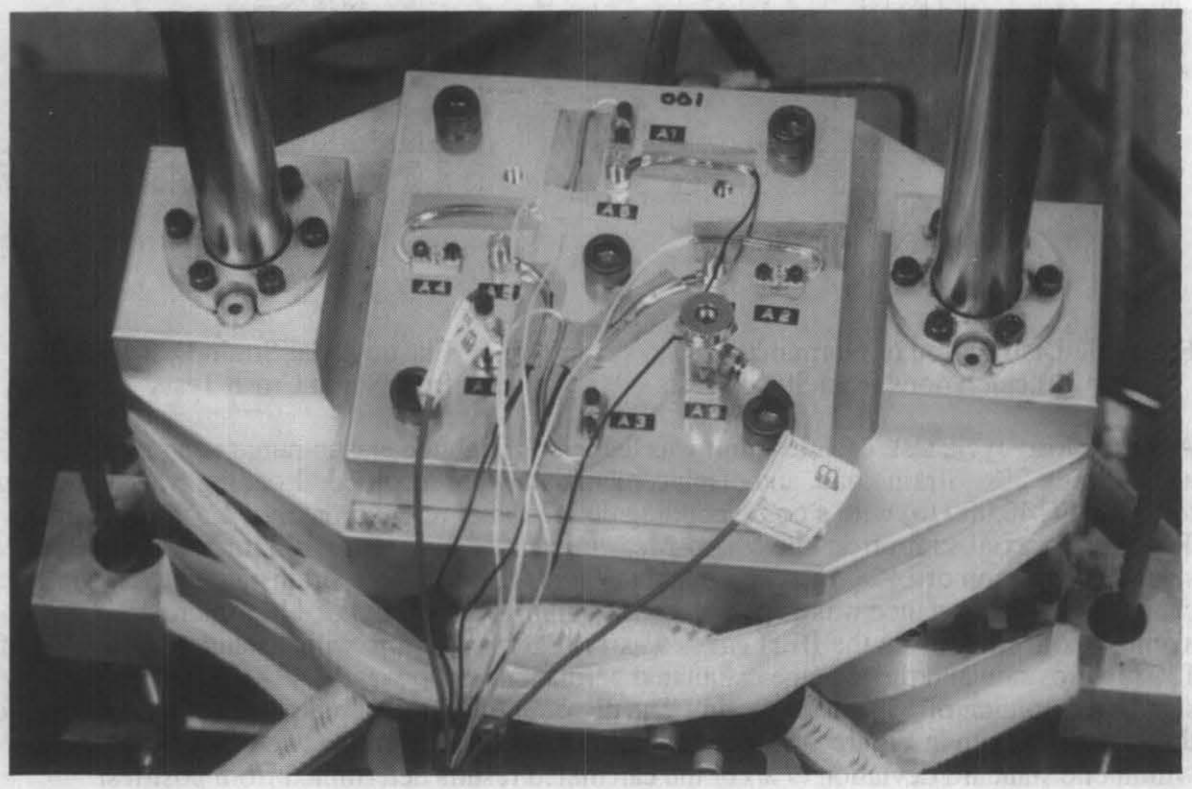

Figure 4. Mounting Fixture and Accelerometers for Shock Tests

Strain gages were initially evaluated by a series of static crush tests. Ten tests were performed on individual aluminum cylinder test units. Twelve biaxial strain gages from the two manufacturers were installed to measure strains in the axial and hoop directions. The instrumented test units were placed in a compression test machine and loaded. The load was cycled four times to 188 kN (40,000 lb), which is at approximately 70% of the elastic limit of the material. Data were collected on the response of the strain gages. For these tests, the strain gages exhibited similar behavior. Figures 6 and 7 show the distributions of maximum axial strain and maximum hoop strain from the first and fourth cycles of the elastic test. The average peak strain for the axial gages in the first cycle was 310 x 10^{-6} m/m (microstrain), with a standard deviation of 33 microstrain, and the average peak strain on the fourth cycle was 302 microstrain with a standard deviation of 29 microstrain. These values compare well with the theoretically calculated strain value of 308 microstrain. In the hoop direction, the average peak strain for the first cycle was 102 microstrain, with a standard deviation of 13 microstrain, and the average for the fourth cycle was 99 microstrain, with a standard deviation of 8 microstrain. The test results show that even in a well-characterized test, there was some scatter in the data. The standard deviation of the strain gage measurements was approximately 10% of the average value. The strain gages exhibited little hysteresis during the four load cycles.

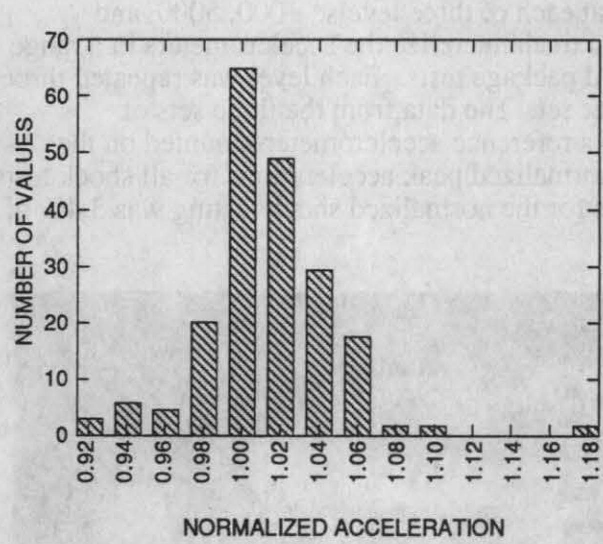

Figure 5. Distribution of Normalized Accelerations from Shock Tests

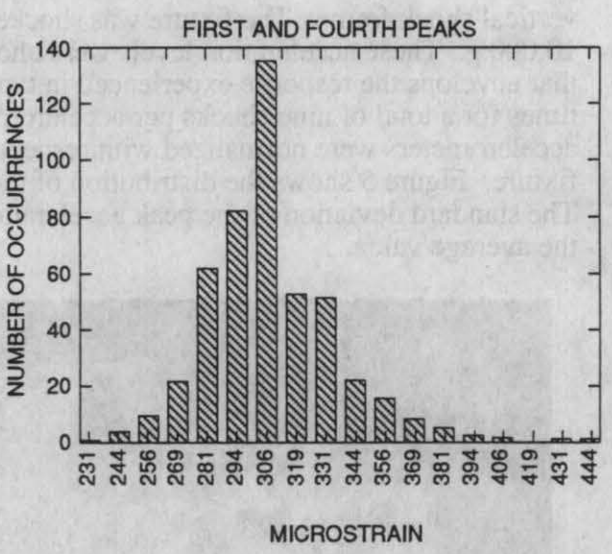

Figure 6. Elastic Axial Strain Distribution from Static Crush Tests

After the load cycle test, each test unit was loaded through the elastic range to a strain approaching 2%. Strain, load, and displacement data were recorded. Loading was applied up to 623 kN (140,000 lb) with a corresponding deflection of approximately 12.7 mm (0.5 in.). The average axial strain from the Micro-Measurement gages was 17,103 microstrain with a standard deviation of 1198 microstrain and the average permanent strain calculated from the change in gage resistance was 17,186 microstrain with a deviation of 1147 microstrain. The average axial strain from the BLH gages was 17,613 microstrain, with a standard deviation of 1500 microstrain and the average calculated permanent strain was 17,494 microstrain with a standard deviation of 1537 microstrain. The distribution of measured plastic strains from all of the gages is shown in Figure 8. Measured permanent strain from the two types of gages was within one standard deviation (7%) of the calculated results determined from post-test dimensional inspection.

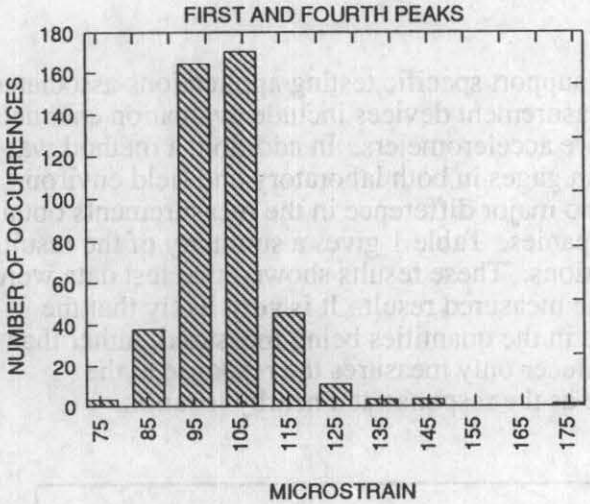

Figure 7. Elastic Hoop Strain Distribution from Static Crush Tests

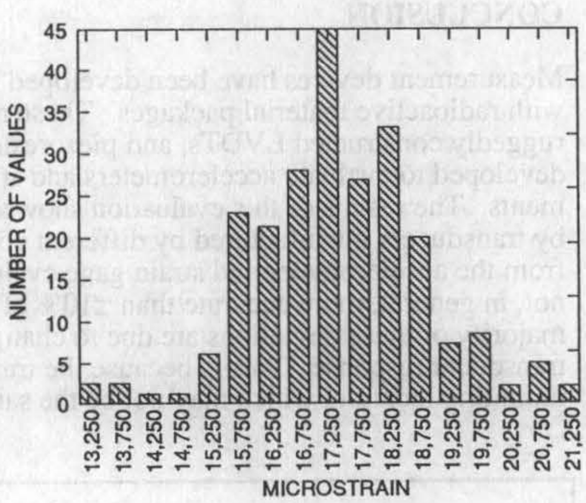

Figure 8. Plastic Axial Strain Distribution from Static Crush Tests

To evaluate the accelerometers and strain gages in an environment similar to package testing, a series of ten impact tests was performed. The structural code benchmark test unit (Glass 1989), shown in Figure 9, was selected to provide an economical vehicle that produces varying strain levels and accelerations with rapid amplitude changes. The test units were instrumented with four Micro-Measurements biaxial strain gages and two uniaxial strain gages. Four BLH biaxial strain gages and two uniaxial strain gages were also installed. The test cylinder was also instrumented with four Endevco accelerometers and three B&K accelerometers. The instrumented test units (Figure 9) were impacted at velocities of 13.4 m/s (44 ft/s) onto an unyielding steel target. The accelerometer data were filtered at 1000 Hz to best represent the rigid body response of the test unit. The filtered peak acceleration data had a standard deviation of 15% from their average value.

Figure 9. Structural Code Benchmark Test Unit Used for Impact Tests

CONCLUSION

Measurement devices have been developed to support specific testing applications associated with radioactive material packages. These measurement devices include evaluation channels, ruggedly constructed LVDTs, and piezoresistive accelerometers. In addition, a method was developed to evaluate accelerometers and strain gages in both laboratory and field environments. The results of this evaluation showed no major difference in the measurements obtained by transducers manufactured by different companies. Table 1 gives a summary of the results from the accelerometer and strain gage evaluations. These results showed that test data were not, in general, more accurate than ±10% of the measured result. It is very likely that the majority of these deviations are due to changes in the quantities being measured, rather than transducer response. This is because the transducer only measures the response at the mounting location, which may not be the same as the response at a nearby location.

Table 1. Results of the Accelerometer and Strain Gage Evaluations

Test Sequence	Measure	Mean	σ	%
Shock	Normalized Acceleration	1.01	0.034	3.40
Static Crush	Permanent Axial Strain	17,354 με	1,379 με	7.95
End Impact	Peak 1,000 Hz Filtered Acceleration	2,454 g	360 g	14.7

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