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BRL CALIBRATION PROCEDURES FOR BALLISTIC PRESSURE TRANSDUCERS

CHARLES D. BULLOCK
ARPAD A. JUHASZ

JUNE 1988

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Current procedures used for the calibration of ballistic pressure transducers at BRL are described. Checks include evaluation of continuity, hysteresis, and zero return characteristics as well as calibration against a dead weight system. Static versus dynamic response behavior is evaluated with the aid of a high pressure dynamic positive step calibrator. For the most exacting measurements, adapters are used permitting calibration of transducers in the same mechanical environment as during measurement. Recommended recalibration intervals are indicated.

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I. INTRODUCTION

The mission of the Interior Ballistic Division of BRL includes research on novel ballistic concepts, charge design methodology and advancing the state of the art in interior ballistic computations. These efforts are supported by a variety of combustion, interior ballistic and ballistic simulator firings. Central to all these experiments is the measurement of pressure. Pressures may range from a few hundred pounds per square inch (Psi) (<1 MPa) to a hundred thousand Psi (690 MPa) full scale depending on the experiment. The quality of the measured pressures, in large scale, is dependent upon the methodology, care and accuracy of the calibration process. The present report is intended as a source of information and instruction for project engineers on ballistic pressure transducer calibrations and common problem areas in transducer use.

The primary function of the calibration procedures is to determine transducer response characteristics and to act as a screening tool to help weed out problem transducers before they are used. A secondary but vital function is to help solve measurement related problems and assure that the devices perform as required under the conditions of service. This paper is to discuss the procedures which have evolved over the past twenty five years at BRL for the calibration, selection and use of high pressure transducers for ballistic applications. It will include a discussion of the most important characteristics of high pressure transducers, BRL's calibration and evaluation procedures and a look at potential problem areas. Sources of additional information on pressure transducer calibration are provided in the bibliography.

II. DISCUSSION

Both SI and English units are currently in use at BRL. Although SI units are official, much of the equipment in use is labeled in English units and many project engineers prefer these in practice. In this report, therefore, pressure data are provided primarily in English units with SI equivalents appended.

1. TRANSDUCERS

Ballistic pressure transducers in routine use at BRL fall into two categories, piezoelectric element and single arm strain sensors. The commonly used piezoelectric transducers (gages) are obtained commercially. The strain sensor transducers are made privately for BRL. All of the above are used daily to measure pressures up to 100,000 Psi (690 MPa). The gages have a fast response (10-90 per-cent response times on the order of 10 microseconds). The events measured range from the sub-millisecond to several hundred millisecond time frames.

High pressure transducers can, with adequate care in calibration and use, be successfully employed to make measurements under 1000 Psi (6.9 MPa). This requires special calibration procedures, however, which will be discussed later. In addition to high pressure transducers, good low pressure, fast response transducers are also commercially available and find applications in ignition simulators and the like. At the other end of the spectrum, a current development effort is aimed at providing a ballistic pressure transducer capable of measuring pressures to 200,000 Psi (1380 MPa).

2. CALIBRATION PROCEDURES

The purpose of pressure calibration is to determine the response of the transducers to known pressures, to verify the response specified by the manufacturer, and to show repeatability. During the calibration procedure for a given transducer the following questions are considered:

- is the response continuous
- does it suffer from hysteresis
- does it return to zero
- is response linear or at least well-behaved
- is there a difference between first and subsequent cycles
- are static and dynamic characteristics the same
- have response characteristics changed with use

3. INITIAL SCREENING

Although pressure calibration values are derived using a primary deadweight standard, calibration work on a gage typically begins with an examination of continuity, hysteresis and zero return properties over the intended range of use. A schematic of the main calibration system in use at BRL is given in Figure 1. The system includes a deadweight primary standard as well as a secondary, NBS traceable, reference gage along with the required pneumatic and hydraulic pressure sources, accumulator and valving to support the operation. Pressurization is accomplished using the air pump/intensifier portions of the system.

The output of the test transducer is plotted (Y-axis) against the output of a stable reference strain gage transducer of known characteristics (X-axis) while the system is pressurized and depressurized over the desired pressure range. The response curve of the transducer is used as an indicator of its overall quality.

a. Continuity Examples of "good" and "bad" continuity response are given in Figure 2. In this case, both plots were obtained from the same transducer but at different times, indicating degradation in performance as a function of use. Normally, when discontinuities of this type are encountered, the transducer is retired.

b. Hysteresis Examples of "good" and "bad" hysteresis characteristics are shown in Figure 3. In the plot on the left the ascending and descending portions of the curve coincide. In the plot on the right the transducer appears to take a "set" on depressurization. Normally, a maximum hysteresis level of 1-2 per-cent of full scale is considered acceptable. Excessive hysteresis would make interpretation of the up and down slope portions of ballistic data difficult to interpret.

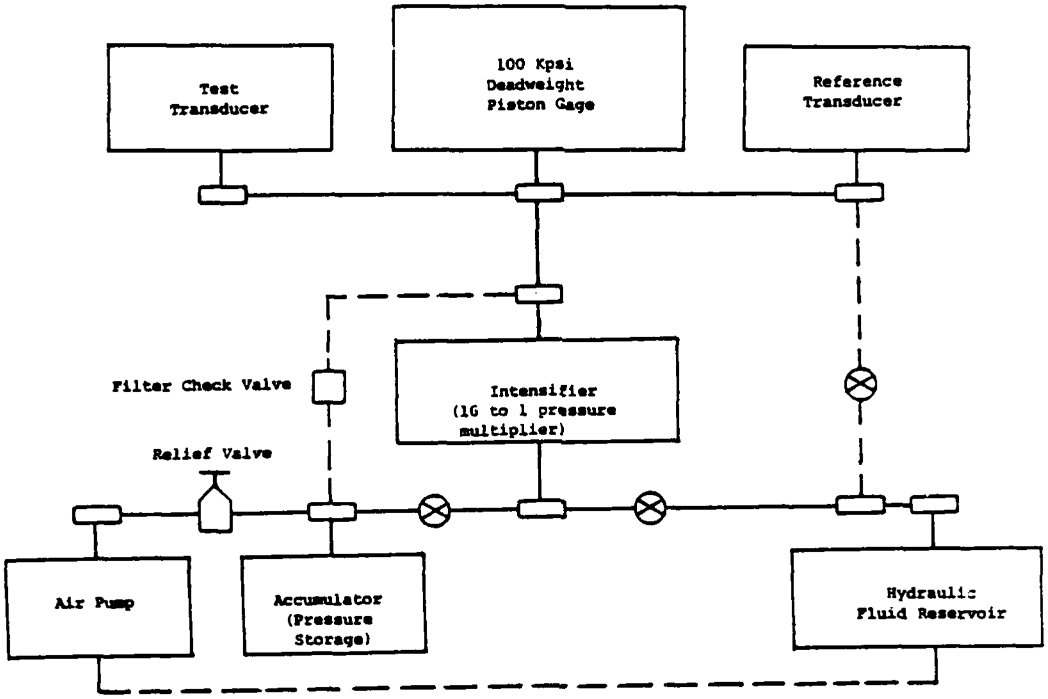
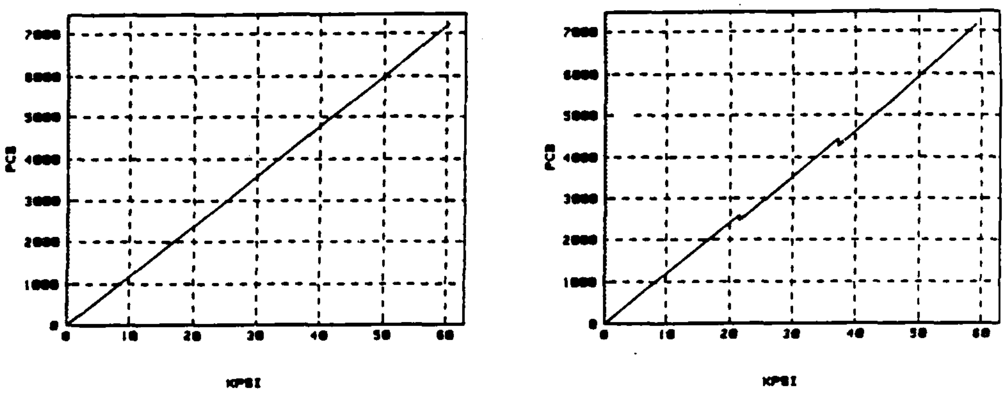


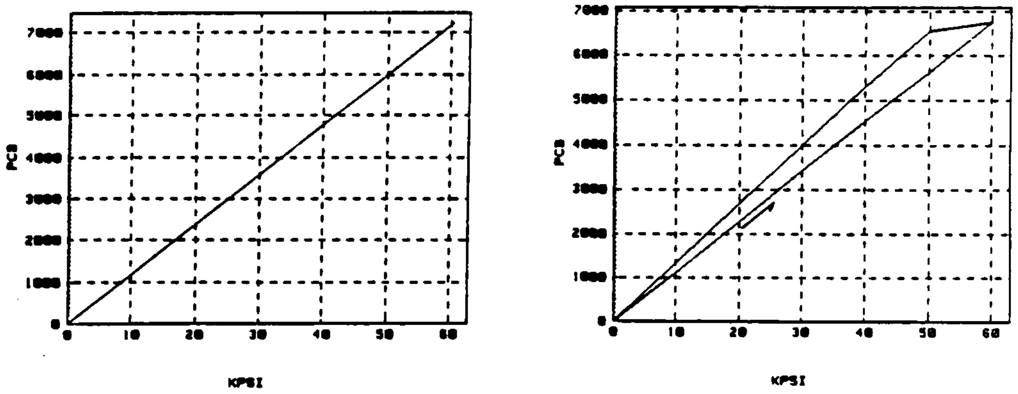
Figure 1. Schematic of the Main Deadweight Calibration System in Use at BRL



GOOD

BAD

Figure 2. Examples of Good and Bad Continuity of Response, 0-60 kpsi (0-414 MPa) (In this Case Response for the Bad Gage Deteriorates with Use.)

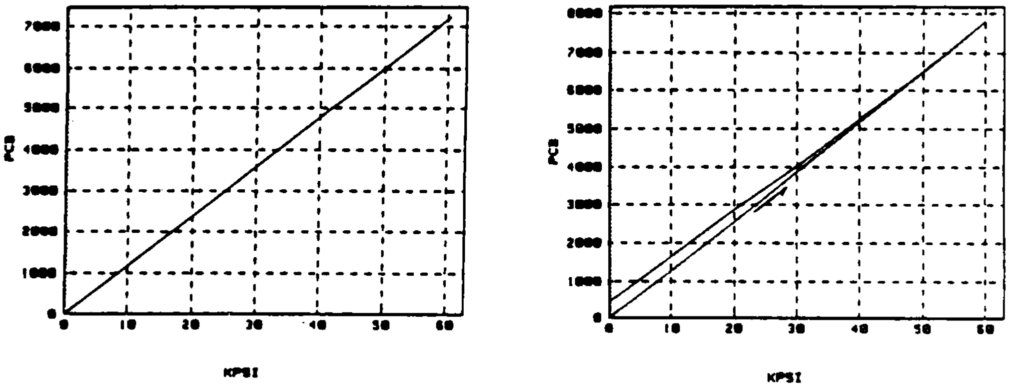


GOOD

BAD

Figure 3. Examples of Good and Bad Hysteresis Behavior 0-60 kpsi (0-414 MPa)

c. Zero return Examples of "good" and "bad" zero return properties of a transducer are given in Figure 4. In this case, the transducer exhibits a residual output after the pressure loading is removed. Normally, the maximum error in zero return deemed acceptable is one per-cent of full scale.

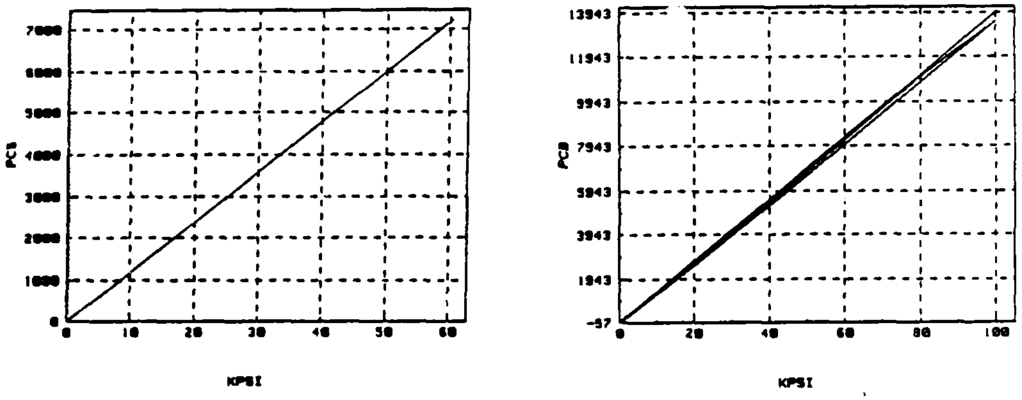


GOOD

BAD

Figure 4. Examples of Good and Bad Zero Return Characteristics, 0-60 kpsi (0-414 MPa)

d. First vs. subsequent cycle output A final characterization made at this point involves a comparison of the first and subsequent cycles of transducer output. With certain transducers, response characteristics change between the first and subsequent pressurizations for a given installation. This could lead to serious problems in measurements, especially in cases involving cyclic events such as multi-shot bursts. Examples of "good and "bad" first vs. second cycle output are given in Figure 5. Normally, a difference of less than one per-cent full scale variation of cyclic output is found to be acceptable.



GOOD

BAD

Figure 5. Examples of Good and Bad First vs. Subsequent Cycle Response, 0-60 kpsi (0-414 MPa) on left; 0-100 kpsi (0-690 MPa) on right

4. QUANTITATIVE PROCEDURES

Quantitative transducer response characteristics are obtained using a deadweight system. A simplified schematic is given in Figure 6. It consists of a calibration mass/piston combination which is floated by hydrostatic pressure at the base of the piston. At the point of equilibrium, that is, where the mass/piston combination is exactly balanced by pressure in the fluid, the hydrostatic pressure may be calculated by dividing the total mass ("weight" plus piston) by the piston area.[1] The output of the test transducer is measured at a series of float points corresponding to various mass loadings.

The static deadweight calibration method has both advantages and disadvantages; it is the most accurate and repeatable source of calibration pressures. Its principal disadvantage for ballistic applications is that it needs dynamic verification.

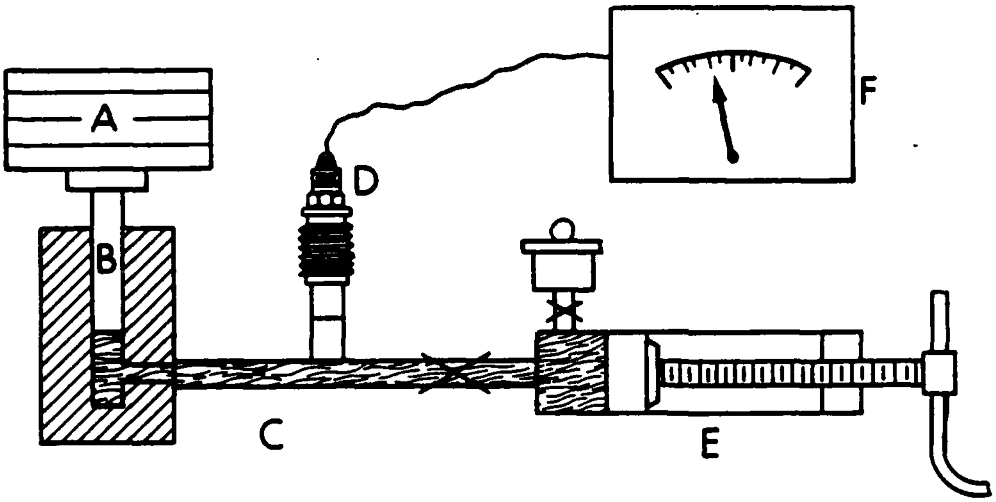


Figure 6. Simplified Schematic of a Deadweight System

A - Calibration Mass
B - Piston
C - Hydraulic Fluid
D - Test Transducer
E - Pressure Source
F - Readout Device

The deadweight calibrator used at BRL is a 100 Kpsi (0-690 MPa) Astra model D-100KS.[2] In this device the pressurizing fluid balances the force of a series of calibrated masses transmitted through a piston of precisely known area. A thin film of hydraulic fluid separates the piston from the cylinder wall and the piston is oscillated about its axis to reduce the effects of static friction. Various combinations of masses permit the generation of pressures at intervals as small as 100 Psi (.69 MPa) up to a maximum pressure of 100,000 Psi (690 MPa). In the "at-rest" position, all the masses are loaded onto the yoke. A series of air operated lifters is used to download respective masses to yield the desired pressures. The tare pressure (due to the weight of the yoke alone) is three thousand Psi (21 MPa), representing the minimum pressure attainable with this system. Common calibration intervals are 5 kpsi (34 MPa) and above.

The maximum error from all these sources for our facility is less than 0.25 per-cent, as measured by cross-floating our device against a Harwood controlled clearance deadweight calibrator.[3] The precision of the Astra gage as used is 0.15 per-cent.

The deadweight device as used in our main calibration station is given in Figure 1. The pressure generating source is an hydraulic intensifier (pressure multiplier) of 16:1 ratio, capable of producing over 100 kpsi (690 MPa). The low pressure side is driven by a 10 kpsi (69 MPa) air pump. The normal high pressure medium is Plexol 201 (now Monoplex), a synthetic lubricant. A check valve, relief valve, additional valving and hydraulic reservoir complete the system.

Transducers are calibrated over the range at which they will be used. Typically, if the expected maximum pressure for an experiment is 100 kpsi (690 MPa), a series of points at 20 kpsi (138 MPa) intervals is chosen for calibration. For a test series with an expected maximum pressure of 25 kpsi (173 MPa), 5 kpsi (34 MPa) intervals are used. Output values from both the upward and downward portions of the calibration cycle are included, giving typically 11 points for curve fitting purposes, see Table 1. The voltages from the readout device (column Y, Table 1) are converted to gage output units, in this case picocoulombs (column PCB), Table 1).

TABLE 1. Gage Calibration Record

GAGE: PIEZO

PT	KPSI	MPa	Y	PCB
1	0		0.0000	0.0
2	20	138	.2673	2673.0
3	40	276	.5399	5399.0
4	60	444	.8183	8183.0
5	80	552	1.1069	11069.0
6	100	690	1.4010	14010.0
7	80	552	1.1090	11090.0
8	60	414	.8219	8219.0
9	40	276	.5435	5435.0
10	30	138	.2700	2700.0
11	0		.0006	0006.0

```
FIRST DEGREE FITS

PCB =  8.6081E+01  1.3946E-01  *  PSI
PSI = -6.3059E+02  7.1683E+00  *  PCB
MPA = -4.3489E+00  4.9436E-02  *  PCB

CORRELATION COEFFICIENT =  .99985

SECOND DEGREE FIT

PSI = -4.6285E+02  7.5573E+00  *  PCB  -2.9739E-05  *  PCB  ^2
MPA = -3.1921E-01  5.2119E-02  *  PCB  -2.0510E-07  *  PCB  ^2

CORRELATION COEFFICIENT =  .99999
```

The data are fitted via a least squares method to a first degree equation (with intercept) and a second degree equation. Curve fitting is done both in terms of transducer response vs. pressure and pressure vs. transducer response (which is used in the computerized data reduction programs of ballistic data). Due to the slight curvature in even "good" pressure transducers, users generally prefer the second order fit for computerized data analysis purposes. For the sake of simplicity, however, they prefer the first order fits to make amplifier settings.

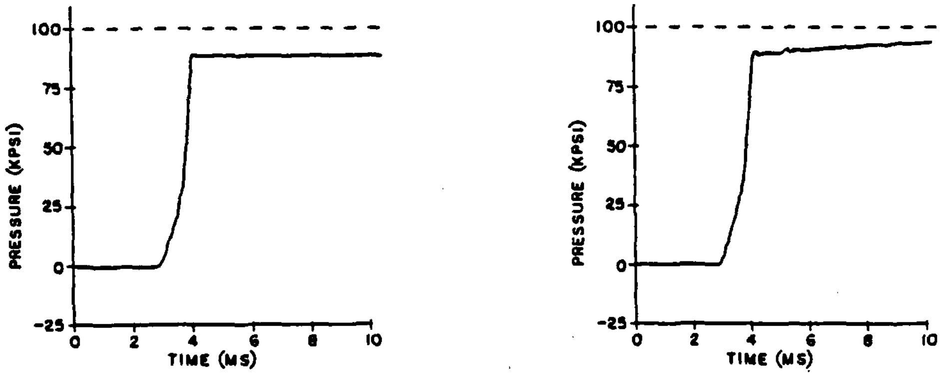
When high pressure transducers are to be used in low pressure measurements, special precautions are needed. Certain makes and models of high pressure transducers appear to have superior low pressure linearity and mounting torque sensitivity properties. These transducers are first pre-screened using the conventional technique. The best of the high pressure units are then calibrated to the desired low pressures against a 10 kpsi (69 MPa) deadweight system using the negative going pressure step method. That is, the deadweight system is floated at a given pressure against the gage and the pressure is released to zero. (The signal generated is equal to but opposite in sign to the output during actual pressure measurement). The amplifier is zeroed just prior to the pressure step, the whole process taking approximately one second. This fast procedure helps to reduce the effect of drift which can be a significant problem in using high pressure transducers at their low end. For calibrations under 0.15 kpsi (1.03 MPa) a commercial air operated dynamic calibrator is used.

5. PROBLEM AREAS AND SOLUTIONS

Among the practical transducer problems of interest to ballisticians are changes in response characteristics as a function of use, poor dynamic performance, response changes with calibration range, difficulties involving concentricity and depth tolerances in gage ports, and differential pressure measurements. The purpose of this section is to highlight some of these areas and to point out procedures which may help to prevent difficulties before they occur.

a. Change of response characteristics with use. It is normal for transducer sensitivity to change with use. Typically, gage response decreases with age, and linearity and hysteresis properties may be adversely affected. Presumably this is due to a gradual degradation of the sensing element. This need not be a problem, however. Regularly scheduled recalibration is used to keep track of these changes, users changing calibration constants as appropriate. For high pressure firings (90-100 kpsi) (621-690 MPa) recalibrations are recommended at 5-10 round intervals. At lower pressures, say 60 kpsi (414 MPa), recalibration after 25 - 50 rounds is recommended. In extreme cases, degradation can be sufficient to affect the continuity of response of the transducer (see Figure 2). In such cases the device is immediately retired. In other cases gages are retained until they fall outside of acceptable hysteresis or zero return characteristics.

b. Dynamic performance. Questions of the dynamic vs. static response behavior of ballistic pressure transducers have concerned ballisticians for some time. In an effort to address this problem, BRL in conjunction with the Harwood Engineering Company has developed a 150 kpsi (1035 MPa) positive step calibrator.[4] The device has been used to assess transducer dynamic performance properties. In most cases static and dynamic properties have agreed quite well. Occasionally, however, problems have occurred. Figure 7 illustrates examples of "good" and "bad" dynamic response behavior. In the bad response case the signal from the transducer is showing an upward creep over many milliseconds. Similar, but shorter term, instances have also been observed where the 10-90 per-cent response appears to be normal but the last 10 per cent of the response curve takes several milliseconds. It is thought that seal movement and air bubbles under the strain patch may have caused some of these problems. Other cases where dynamic response problems have occurred have involved eccentric loading of gages due to mismatch between transducer and mounting cavity, see Figure 8. Gage manufacturers' manuals often provide useful information about such problems.[5]



GOOD

BAD

Figure 7. Examples of Good and Bad Dynamic Response

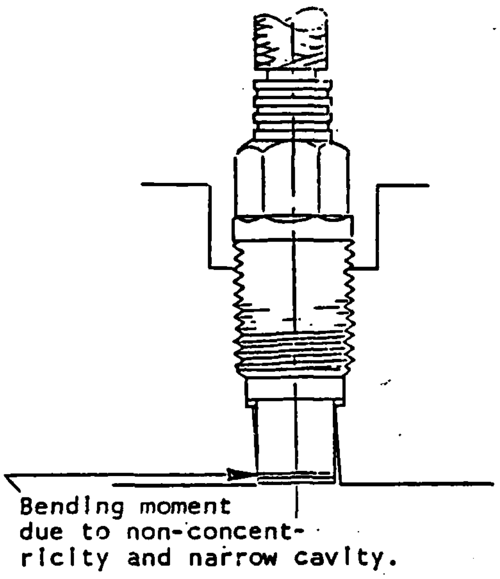


Figure 8. Concentricity Problems in Gage/Mount Installations

c. Calibration over the wrong range. A common error among project engineers is to use calibration data obtained over one range in analyzing the results of experiments over a significantly different pressure range. Table 2 illustrates this point. The gage in question was calibrated to 100 kpsi (690 MPa) and the calibration data fitted to a first and a second order equation. The error columns indicate the difference between the fitted equation and the measured calibration points. The greatest deviation from the curves comes at the low pressure end. For instance, the deviation between the experimental gage response and the fitted first degree curve at 20 kpsi (138 MPa) is 3.9 percent. The difference between the experimental data and the second degree fit is 3.1 percent. Recalibration of the gage over a lower pressure range, however, see Table 3, decreases the level of error at 20 kpsi (138 MPa) to less than a tenth of a percent for both the first and second degree fits.

TABLE 2. First and Second Degree Least Squares Fits to Static Gage Calibration Data - 0-100 kpsi (0-690 MPa)

PT	KPSI	PCB	1st PCB Degree Fit	Err%	2nd PCB Degree Fit	Err%
1	0	0.00	--	--	--	--
2	20*	2616.00	2715.51	3.90*	2697.53	3.12*
3	40	5384.00	5486.10	1.90	5434.87	0.94
4	60	8193.00	8256.70	0.78	8212.01	0.23
5	80	11021.00	11027.30	0.06	11028.96	0.07
6	100	13847.00	13797.90	0.36	13885.71	0.28
7	80	11090.00	11027.30	0.57	11028.96	0.55
8	60	8286.00	8256.70	0.36	8212.01	0.89
9	40	5470.00	5486.10	0.29	5434.87	0.64
10	20	2694.00	2715.51	0.79	2697.53	0.13
11	0	61.00	--	--	--	--

* PCB

First Degree Fit
PCB = a + b*PSI

a = -5.5096E+001
b = 1.3853E-001

r = 9.9988E-001

Second Degree Fit
$PCB = a + b*PSI + c*PSI^2$

a = 2.6818E+000
b = 1.3388E-001
c = 4.9753E-008

r = 9.9994E-001

TABLE 3. First and Second Degree Least Squares Fits to Static Gage Calibration Data - 0-25 kpsi (0-173 MPa)

PT	KPSI	PCB	1st PCB Degree Fit	Err%	2nd PCB Degree Fit	Err%
1	0	0.00	--	--	--	--
2	5	625.00	640.26	2.44	634.97	1.60
3	10	1272.00	1298.77	2.10	1282.03	0.79
4	15	1941.00	1957.27	0.84	1942.74	0.09
5	20*	2616.00	2615.78	0.01*	2617.10	0.04*
6	25	3300.00	3274.29	0.78	3305.12	0.16
7	20	2624.00	2615.78	0.31	2617.10	0.26
8	15	1952.00	1957.27	0.27	1942.74	0.47
9	10	1286.00	1298.77	0.99	1282.03	0.31
10	5	637.00	640.26	0.51	634.97	0.32
11	0	9.0	--	--	--	--

First Degree Fit
PCB = a + b*PSI

a = -1.8241E+001
b = 1.3170E-001

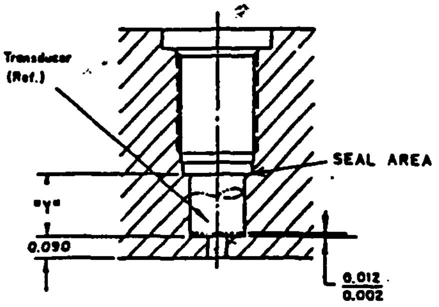
r = 9.9986E-001

Second Degree Fit
$PCB = a + b*PSI + c*PSI^2$

a = 1.5779E+000
b = 1.2531E-001
c = 2.7307E-007

r = 9.9998E-001

d. Mounting problems. Figures 8 and 9 present two common problems in transducer/mounting cavity interactions. A lack of concentricity in either the transducer or the mounting hole can result in eccentric loading. The curves may look "normal" but the response may be far out of line. Similar results can be noted if the sensing element touches the bottom of the mounting cavity. In the case of one popular commercial transducer, for instance, seal rings of two thicknesses, steel [.010 in (.254 mm)] or copper [.020 in (.508 mm)], are available. The cavities are dimensioned according to the intended seal thickness. Substitution of the thinner steel seal for the originally intended copper, for instance, can cause the transducer to "bottom" giving false, often high, readings.[5] While this may seem, on the surface, trivial, such problems are often hard to track down in practice due to the depth and inaccessibility of gage cavities. A related problem where tolerances are close is the flexing of the fixture in such a way as to introduce transient mechanical loading on the transducer. Some mounting problems may indicate their presence during installation. If the "feel" of the transducer being screwed into the cavity is "too tight" chances are that there is a concentricity problem. Evidence for this may be obtained by putting bluing compound on the front of the gage and examining the surface after installation/removal from the gage hole. Where interference occurs, the bluing compound is rubbed off. Alternately, recording electronics may be connected to the gage prior to installation to see if excessive signals are generated during the mounting procedure.



"Y" = .235 ± .002 when used with 600E42 seal
"Y" = .245 ± .002 when used with 600A10 seal

Figure 9. Example of Potential Gage "Bottoming" Due to Use of Seal Ring of Improper Thickness

e. Differential pressure measurements. One of the most exacting pressure measurement problems in gun ballistics involves so called differential pressure measurements. Typically, the objective is to measure pressure differences between the fore and aft ends of the breech section in the early portion of the ballistic cycle to detect the formation of pressure waves which may have undesirable effects on gun performance.[6] The problem is that whereas the event may have a maximum pressure of 80-90 kpsi (552-621 MPa), the region critical to pressure wave formation is often below 10 kpsi (69 MPa). The pressure differencing needs to be accurate at the low end of the range, where gage errors are greatest. For these measurements, transducers are preselected for the best linearity and hysteresis characteristics. In addition, two and sometimes three sets of calibration data are used for the same transducer depending on the pressure range being probed. For instance, calibration data for 10 kpsi (69 MPa) maximum may be used to interpret the low pressure end of the data while calibration data for 100 kpsi (690 MPa) maximum are used to interpret the overall character of the full pressure-time curve. An additional technique used to obtain quality pressure difference data involves the use of mounting adapters, see below.

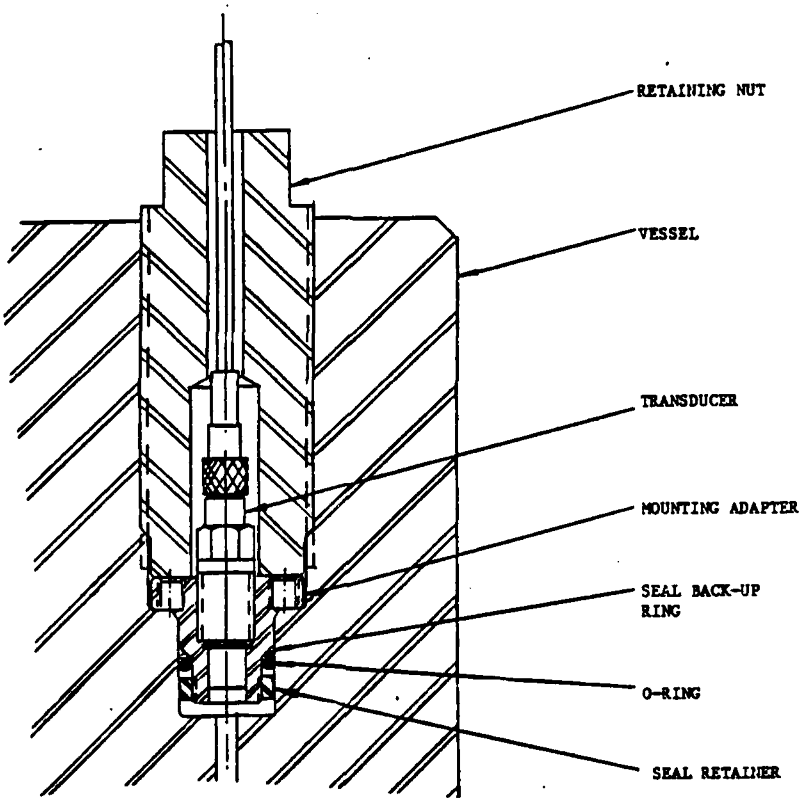


Figure 10. Schematic of a Gage Mounting Adapter

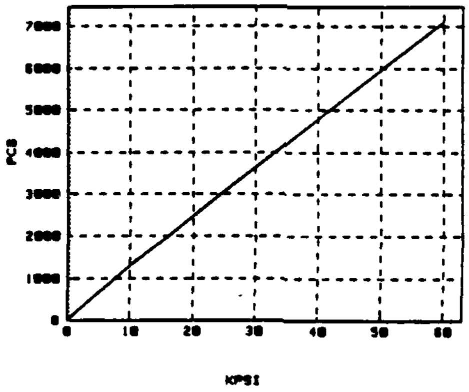


Figure 11. Three Superimposed Calibration Cycles for a Gage in a Mounting Adapter

f. Mounting adapters. One effective way of minimizing mounting problems is by use of an adapter. A typical example appears in Figure 10. The small size of the adapter permits easier machining and quality checks of the cavity dimensions. A further advantage is that calibration can be done in the adapter, making transducer remounting unnecessary. The adapter, in effect, protects the transducer from mounting strains in the fixture. If necessary, the measurement system, gage and amplifier, can be calibrated together, further refining the data. This can result in excellent performance and repeatability. Figure 11 shows the response behavior of a transducer in its adapter over three calibration cycles. The lines are indistinguishable. The impressive fact about this data is that the transducer had been used to make measurements between the calibration cycles.

III. SUMMARY AND CONCLUSIONS

The procedures in use at BRL are aimed at preventing problem transducers from entering the system and weeding out those whose useful life is past. Continuity, linearity, hysteresis and repeatability characteristics are evaluated for new transducers and for transducers submitted for recalibration. Numerical data are derived using a deadweight calibration system. Static vs. dynamic performance differences, when suspected, are evaluated using a high pressure, dynamic positive step calibration system. Calibrations are recommended at 5-10 round intervals when pressures in the range of 90-100 kpsi (621-690 MPa) are to be measured. For pressures in the 60 kpsi (414 MPa) regime recalibration is recommended at 25-50 round intervals. Calibration of transducers for the expected pressure range is strongly recommended, since needless large errors may be introduced at the low pressure end by the fitted curve. Gage adapters not only help to eliminate undesirable mounting effects on the measurements but permit calibration of the transducer in the mechanical environment of the actual measurement. This procedure has been especially useful in exacting measurement applications such as differential pressure measurements.

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6. Evans, J., "Instrumentation for Measuring Pressure Waves in Guns, Ballistic Research Laboratory Memorandum Report, ARBRL-MR-03218,

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The following selected sources provide needed insight and guidance regarding gages, calibration and measurement processes of interest to the interior ballistician. They are offered an an introduction to rather than an in-depth coverage of the field.

1. Handbook of Transducers for Electronic Measuring Systems, Harry N. Norton, Jet Propulsion Laboratory, California Institute of Technology, 1969, Prentice Hall Inc.

See especially the sections on electronic measuring systems, transducers, transducer performance determination, pressure and the glossary of terms in the appendix.

2. Performance Evaluation of Sensors, Paul S. Lederer, 12th Transducer Workshop, Range Commanders Council, White Sands Missile Range, New Mexico 88002.

This is a fine discussion of performance evaluation of sensors in general.

3. A Guide for the Static Calibration of Pressure Transducers, Draft ANCl Standard, Steven Rogero, Jet Propulsion Laboratory, PO Box 458, Edwards, CA 93523.

This is a thorough and readable source of information on all aspects of pressure gage calibration.

4. Standardized Weapon Chamber Pressure Measurement, W. Scott Walton, Material Testing Directorate, US Army, Aberdeen Proving Ground, MD 21005.

This is a comprehensive report on weapon pressure measurements in the 5-110 kpsi (34-758 MPa) range evaluating 15 different types of transducers. Both static and dynamic evaluation of gage performance are covered. The treatment is thorough, providing details of gages, mounting adapters, static and dynamic calibration techniques, gun firing records and field measurement problems.

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