SHRP/LTPP FWD CALIBRATION PROTOCOL
March 1994

INTRODUCTION

This document describes the procedure for calibration of falling weight deflectometers (FWDs) which was originally developed by the Strategic Highway Research Program (SHRP). This protocol is now administered by the Long-Term Pavement Performance (LTPP) Division in the Federal Highway Administration.

The procedure is written primarily for use with the Dynatest falling weight deflectometer, however it can also be used with the KUAB FWD. Due to differences in the design of the KUAB certain details are not applicable. Special procedures for the calibration of KUAB FWDs are included in Appendix B. It may be possible to use the procedure for other types of FWDs with minor modifications of the hardware and of the data acquisition software. The procedure is not applicable to the calibration of cyclic loading and other types of pavement deflection testing equipment.

In this procedure, the deflection and load transducers from the FWD are first calibrated individually against independently-calibrated reference devices. This is called "reference calibration," and it is performed at a LTPP Regional Calibration Center, or any other properly equipped location. The calibration of the FWD deflection sensors is further refined by comparing them to each other in a process referred to as "relative calibration." Relative calibration is done as a final step that accompanies reference calibration, and it can also be carried out alone, at any suitable location. There is no corresponding relative calibration procedure for the load measurement system.

The procedure results in calibration factors which are entered into the FWD software as multipliers. When the FWD measurements are multiplied by the calibration factors the result is a measurement which has been corrected to agree with the calibration instrumentation. It is necessary that there be a place in the FWD software to enter the calibration factors. That is the responsibility of the FWD manufacturer.

To use this procedure Dynatest FWDs must have Edition 10 or higher software. Earlier Editions do not have the pause feature and do not allow programming the required number of drops in the test sequence. Furthermore, it is not possible to leave the load plate down, as is called for in this procedure. Thus, Dynatest FWDs must be upgraded to Edition 10 or higher software *before* calibration.

FREQUENCY OF CALIBRATION

Reference calibration should be performed at least once per year, or as soon as possible after a sensor has been replaced on the FWD. Relative calibration should be performed in conjunction with reference calibration.

Relative calibration should be performed on the deflection sensors at least once per month. It should also be performed immediately after a deflection sensor is replaced.

PERSONNEL

FWD System Operator
Calibration System Operator

REFERENCE CALIBRATION PROCEDURE

Equipment Preparation

The FWD should be in good operating condition prior to performing reference calibration. Particular attention should be paid to cleaning the magnetic deflection sensor bases to insure that they seat properly. Also verify that the FWD load plate is firmly attached to the load cell and that the load plate swivel operates freely. In the event that the load plate is loose, the lower bolts should be tightened to a torque of 10.2 N-m (7.5 lbf-ft) and set with Locktite before proceeding. (**Note:** This torque requirement is applicable to the Dynatest FWDs. For non-Dynatest FWDs consult the manufacturer.) All electrical connectors should be inspected and, if necessary, cleaned and firmly seated.

The FWD should be at room temperature. If the FWD has been outdoors at a very low or a very high temperature, sufficient time should be allowed for it to equilibrate to room temperature. It is recommended that a series of warm-up drops be performed immediately prior to beginning calibration, to assure that the rubber buffers have been thoroughly warmed up.

Set the FWD mass and drop heights to produce loads within ±10 percent of 27, 40, 53, and 71 kN (6, 9, 12, and 16 kips). For the Dynatest FWD, it is possible to be within this tolerance for the highest load, and yet to have the drop height set too high. *Before* placing the reference load cell under the load plate, and with the mass positioned at drop height four (the highest position), verify that there is at least a 102 cm (4 in) clearance between the highest point on the mass subassembly and the underside of the brace between the two columns that surround the cylinders that raise and lower the load plate. If the clearance is too small, reposition the target for the fourth drop height to achieve the required clearance. This should assure that there will be adequate clearance when the reference load cell is in position under the load plate.

Before beginning any calibration work, and throughout the entire calibration period, it is necessary that there be no data filters in operation in the FWD. Verify that the "peak smoothing" processor has been turned off. This feature is accessed from the Dynatest Main Menu by selecting "Road Options" (item #3, followed by item #12), where "Peak Readings" should show "direct" and not "smooth."

General Procedure

The FWD load cell should be calibrated at least twice. Multiple calibration tests are performed on the load cell, and the results are averaged. Acceptance criteria based upon the repeatability of the calibration factor are identified in the load cell calibration procedure. If the results persist in failing the acceptance criteria, then the cause of the erratic results should be identified and corrected.

Each deflection sensor shall be calibrated once. Spare deflection sensors do not have to be calibrated until they are in active use. After all load and deflection sensors have been calibrated, the interim calibration factors shall be entered into the FWD computer before proceeding with relative calibration.

A sample reference calibration setup screen for the Dynatest FWD with Edition 10 or Edition 20 software is given in Figure 1. The information in Figure 1 can also be used as the basis for setup of Dynatest FWDs running Edition 25 and higher software.

```
    Reference Calibration
1.  Test UNITS...:  lbf.mil.inch   (kPa.mu.mm)
2.  Temperature...: Fahrenheit     (Centigrade)
3.  Stn.Request...: OFF            (ON)
4.  Test Checks...: NONE           (Decreasing defls, Roll-Off, RollOFF+Decr)
5.  Reject prompt.: OFF            (ON)
6.  Stationing....: [Doesn't matter]
7.  Temp.Request..: OFF            (ON)
8.  Cond.Request..: OFF            (ON)
9.  Variation  : Load NOT Checked! Deflections NOT Checked!
10. Diameter of Plate: 11.8
11. Deflector distances: [Doesn't matter. Keep what you have.]
                               1                   2
12. Drop No.   : 123P4P5P6P7P8P9P0P1P2P3P4P5P6P7P8P9P0P1P2P3P4P5P6P7S...........
13. Heights    : CCCP1P1P1PIP1PIP2P2P2P2P2P2P3P3P3P3P3P3P4P4P4P4P4P4P11111111111
14. Test Plots : ...............................................................
15. Save Peaks : ...*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*...........
16. Load His   : ...............................................................
17. Whole His  : ...........*.........*.........*..........*....................

18. Load another TEST SETUP.
```

Figure 1. Reference Calibration Test Setup for the Dynatest FWD

A complete summary of the data to be recorded is given in Table 1. Before beginning to perform the calibrations, FWD-specific information should be recorded via printouts from the FWD data acquisition program screens (e.g., showing the deflection sensor serial numbers and calibration factors, load cell serial number, calibration factor, and sensitivity, and voltage screens from the Dynatest software), which have been annotated with the date and FWD identification information (i.e., FWD model and serial number).

Locate the calibration data acquisition system as close as possible to the FWD computer so that the two systems operators will be able to converse easily. Load the reference calibration software **FWDREFCL** into the reference system computer. Directions for performing reference calibration using this software are provided in the **FWDREFCL** User's Guide.

Before doing any calibrations, verify that the computers for the FWD and the reference data acquisition system are registering the correct date and time. If either is set incorrectly, correct it before proceeding.

Table 1-FWD Calibration Data Reporting Requirements

Data Item	**Mode of Entry**	**Source**[1]
FWD Operator Name	Manual	Operator
Calibration System Operator Name	Manual	Operator
Date and Time of Calibration	Automatic	Computer Clock
FWD Serial/ID Number	Manual	Operator
FWD Manufacturer	Manual	Operator
FWD Owner	Manual	Operator
FWD Load Cell Serial Number	Manual	Transducer Setup and Gain Printout
FWD Deflection Sensor Serial Numbers	Manual	Transducer Setup and Gain Printout
Reference Load Cell Serial Number	Automatic	Configuration File[2]
Reference LVDT Serial Number	Automatic	Configuration File[2]
FWD Calibration Center Location	Automatic	Configuration File[2]
Current Calibration Factor for FWD Load Cell	Manual	Transducer Setup and Gain Printout
Current Cal. Factors for FWD Deflection Sensors	Manual	Transducer Setup and Gain Printout
Ref. Load Cell Calibration Constants	Automatic	Configuration File[2]
Ref. Load Cell Calibration Date	Automatic	Configuration File[2]
Ref. LVDT Calibration Constants	Computed	**FWDREFCL** Software
Ref. LVDT Calibration Date	Automatic	**FWDREFCL** Software
FWD Load Cell Readings (20 total)	Manual	FWD Computer
Ref. Load Cell Readings (20 total)	Automatic	Calibration Data Acquisition System
FWD Deflection Readings (20 per sensor)	Manual	FWD Computer
Ref. LVDT Readings (20 per sensor)	Automatic	Calibration Data Acquisition System
Interim Cal. Factors from Reference Calibration	Computed	**FWDREFCL** Software
FWD Relative Calibration Data	Automatic	Relative Calibration Data Files
Calibration Factors from Relative Calibration	Computed	**FWDCAL2** Software
Final Calibration Factors	Manual	Final Gain Worksheet

[1] For SHRP FWDs. Source may be different for FWDs from other manufacturers.

[2] Reference calibration configuration file (**FWDREFCL.CNF**).

Equipment

As described in Appendix A.

FWD Load Cell Calibration Procedure

1. If the reference load cell has not been calibrated within the last 12 months, then it should be recalibrated in accordance with the procedure given in Appendix D.

2. Attach the cable from the signal conditioner to the reference load cell, turn on the signal conditioner, and allow the system to warm up for at least 60 minutes.

3. Initialize the computer data acquisition program. This will include entry of operator names, FWD serial number, FWD load cell serial number, and its current calibration factor.

4. Position the FWD so that the load plate is near the center of the calibration test pad, or on any other stiff, smooth surface. Verify that there is no sand or other loose debris under the reference load cell.

5. Position the reference load cell beneath the FWD load plate, making sure that the three guides are aligned around the plate. **Zero the signal conditioner with the load plate high**, so that there is no external load on the reference load cell.

   Note: For accurate results it is critically important that the reference load cell be zeroed with the FWD load plate in the raised position. Also, the signal conditioner excitation and gain must be set exactly to the levels at which the reference load cell was calibrated.

6. Complete the following sequence of drops, as shown in Figure 1, for a single test:

   3 seating drops at height 3 (data not recorded), followed by a pause

   5 drops at height 1, with a pause after each drop

   5 drops at height 2, with a pause after each drop

   5 drops at height 3, with a pause after each drop

   5 drops at height 4, with a pause after each drop except the last

   Stop after the last drop (plate remains down)

   As shown in Figure 1, it is useful to program six drops at each height, rather than five, so that one can be considered a "spare" in case a drop is missed by the reference system instrumentation. If the first five drops are successfully recorded, then the data for the sixth drop can be discarded.

The plate should not be raised at any time during the sequence. Data from both the FWD load cell and the reference system should be recorded for all drops except the three seating drops.

7. Perform the load cell reference calibration twice. If the two calibration factors agree within 0.003, then the results of the two tests shall be averaged. If they are outside this limit, then a third calibration of the load cell shall be performed. If the standard deviation of the three results is less than 0.0030 (based on n - 1 degrees of freedom), then the three results shall be averaged. If the standard deviation exceeds 0.0030, then all three calibration factors shall be discarded and the load cell calibration procedure should be repeated.

8. Upon completion of the calibration testing, raise the FWD load plate and remove the reference load cell.

Load Cell Calibration Acceptance Criteria

Process the data sets according to the procedure in the section on Reference Calibration Data Analysis. The presence of any of the following conditions invalidates the load cell calibration test results.

- Excessive noise messages for drop heights 2, 3, or 4. (For the low drop height (e.g., the 27 kN (6,000 lb) load level) there is seldom enough free-fall time for the vibration caused by the release of the mass to attenuate before the mass strikes the plate. Thus excess noise messages at the low drop height may, in general, be disregarded.) The noise, due either to electrical noise or mechanical vibrations, is of concern only if it results in an erroneous zero value or an erroneous peak reading. The time history graphs provided by the **FWDREFCL** software should be viewed to determine if the noise is of concern before rejecting the calibration.

- Standard deviations for the five readings at any drop height that differ by more than a factor of three between the reference system data set and the FWD data set.

- Standard error of the adjustment factor (see Reference Calibration Data Analysis) in excess of 0.0020.

- Failure to satisfy the repeatability criteria for multiple calibration tests.

Should any of these conditions occur, the load cell calibration test procedure must be repeated after identifying the source of the problem and correcting it.

FWD Deflection Sensor Calibration Procedure

1. Initialize the computer data acquisition program. This would include entry of the operator names, FWD serial number, FWD deflection sensor serial number, and its current calibration factor.

2. Clean the spring-loaded tip of the LVDT. Use a non-lubricating contact cleaner in a pressurized can to spray cleaner into the bearing sleeve until the tip goes in and out without noticeable friction. Check by working the tip in and out. The stroke should be smooth, without "bumps." If the LVDT cannot be made to operate smoothly do not continue with the calibration.

3. Use the micrometer calibrator to calibrate the LVDT. To do this, the LVDT should first be positioned in the calibrator and set to the null point (zero voltage output), with the micrometer set to 5 mm. The micrometer should then be advanced slightly beyond 7 mm, and returned to the 7 mm mark. Verify that the MetraByte board reads within ± 30 bits of -2000 bits. If necessary, adjust the Gain knob on the 2310 signal conditioner in increments of 0.1 (for instance, from a setting of 1.50 X1 to a setting of 1.40 X1) to achieve the required reading. The LVDT voltage output and the micrometer reading (7 mm) should be recorded.

   The micrometer should be moved in 0.5 mm increments to a final reading of 3.0 mm, with the micrometer reading and LVDT voltage output recorded at each 0.5 mm step. Turn the barrel of the micrometer in one direction only, to avoid errors due to backlash.

   Analyze the resulting data using a linear regression to determine the coefficient m in the equation $Y = m X + b$, where Y is the position of the LVDT tip in microns, as measured by the micrometer, and X is the corresponding voltage output in bits, as read by the computer data acquisition board. (The **FWDREFCL** software provides prompts for this entire process, reads and records the requisite data, and performs the computations.)

   The slope m will be close to -1.00 microns per bit. In general the slope should not change by more than ±0.5 percent from one calibration to the next. The standard error of the slope should be less than 0.0010. If a larger standard error is obtained, the LVDT calibration should be repeated.

4. Enter the LVDT calibration results into the computer data acquisition system. (This is handled automatically by the **FWDREFCL** software.) After the calibration results are entered, the signal conditioner gain must not be changed.

5. Secure the LVDT in its holder on the reference system aluminum beam, so that it is near the null point (e.g., zero voltage output). Verify with a spirit level that the LVDT is vertical in its holder. If it is not vertical, adjust the position of the aluminum beam to attain verticality. This may require shimming the beam where it is bolted to the concrete block.

6. Position the FWD trailer so that the load plate is as close as possible to the deflection sensor holder. It is important, however, that the FWD should not come in contact with the beam or any other part of the reference system during the testing.

7. Remove the deflection sensors from their holders on the FWD beam, and verify that they are free of dirt and grime which would adversely affect their seating in the reference system deflection sensor holder. Run the magnetic base over a piece of fine-grained emery paper that is placed on a firm, flat surface (such as the upper flange of the aluminum beam), to assure that it is clean.

8. Place one deflection sensor in the sensor holder, and position the LVDT holder so that the LVDT and the FWD sensor holder are aligned concentrically.

9. Place a second deflection sensor on top of the LVDT holder, so that it will measure the movement of the end of the beam (and hence, of the LVDT housing).

10. Zero the signal conditioner. Since the LVDT is a linear device, this can be done with the FWD plate either up or down, as is convenient.

11. Complete the following sequence of drops, as shown in Figure 1, for a single test:

    3 seating drops at height 3 (data not recorded), followed by a pause

    5 drops at height 1, with a pause after each drop

    5 drops at height 2, with a pause after each drop

    5 drops at height 3, with a pause after each drop

    5 drops at height 4, with a pause after each drop except the last

    Stop after the last drop (plate remains down)

    As shown in Figure 1, it is useful to program six drops at each height, rather than five, so that one can be considered a "spare " in case a drop is missed by the reference system instrumentation. If the first five drops are successfully recorded, then the data for the sixth drop can be discarded.

    The plate should not be raised at any time after the seating drops. One complete FWD time history plot should be studied for the fifth drop at each drop height, to verify that the calibration beam does not move prior to the recorded peak deflection.

Deflection Sensor Calibration Acceptance Criteria

Process the data sets according to the procedure in the section on Reference Calibration Data Analysis. The presence of any of the following conditions invalidates the deflection sensor test results.

- Movement of the calibration beam, as measured by the deflection sensor resting on the top of the beam, prior to, or simultaneous with, the peak deflection reading from the device under test. It is entirely possible that there will ultimately be some movement of the beam, as the deflection wave passes under the concrete inertial block. The important criterion is whether the beam moved prior to the time that the deflection sensor on the ground registered its peak reading. Beam movement can be determined by inspection of the FWD time history data files. At the moment when the sensor being calibrated shows its peak reading the sensor on the reference beam should show no more than ±2 microns (±0.08 mils) of displacement.

- Excessive noise messages for drop heights 2, 3, or 4. (For the low drop height (e.g., the 27 kN (6,000 lb) load level) there is seldom enough free-fall time for the vibration caused by the release of the mass to attenuate before the mass strikes the plate. Thus excess noise messages at the low drop height may, in general, be disregarded.) The noise, due either to electrical noise or mechanical vibrations, is of concern only if it results in an erroneous zero value or an erroneous peak reading. The time history graphs, provided by the **FWDREFCL** software, should be viewed to determine if the noise is of concern before rejecting the calibration.

- Standard deviations for the five readings at any drop height that differ by more than a factor of three between the reference system data set and the FWD data set.

- Standard error of the adjustment factor (see Reference Calibration Data Analysis) in excess of 0.0020.

- An average peak deflection for five drops from the high drop height (e.g., the 71 kN (16,000 lb) load level), as register by the reference LVDT, that is less than 400 microns (16 mils).

Should any of these conditions occur, the calibration test for the deflection sensor must be repeated after identifying the source of the problem and correcting it.

Reference Calibration Data Analysis

1. Analyze the data as follows (calculations are done automatically by the **FWDREFCL** software):

   A. Perform a least squares regression forced through zero for all of the data for each measurement device (i.e., 20 pairs of data per test --5 replicates at each of 4 load levels). The result of this regression will be the coefficient for an equation of the form Y = m X, where Y represents the response of the reference system, X represents the response of the FWD measurement device, and m is the slope of the regression line. Both X and Y should be measured in the same system of units.

B. The coefficient, m, determined in step A, represents the adjustment factor for the calibration factor in the FWD Field Program. The new calibration factor is computed by multiplying the former calibration factor by the coefficient m from step A. This is listed as the new calibration factor on the **FWDREFCL** report.

2. Evaluate each data set with respect to the acceptance criteria given in the preceding sections. Repeat the unacceptable tests.

3. Enter the acceptable calibration factors for all sensors (load and deflection transducers) in the FWD Field Program before continuing with the relative calibration. The new calibration factor for the FWD load cell is a "final" calibration factor, while the new calibration factors for the deflection sensors are "interim" factors, which will be further refined by doing relative calibration.

RELATIVE CALIBRATION PROCEDURE

General Background

Relative calibration of the FWD deflection sensors is used to ensure that all sensors on a given FWD are in calibration with respect to each other. As such, it serves as the final step in the overall FWD calibration process, and as a quick means to periodically verify that the sensors are functioning properly and consistently.

Relative calibration uses the relative calibration stand supplied by the FWD manufacturer. The sensors are stacked vertically in the stand, one above another, so that all sensors are subjected to the same pavement deflection. Relative calibration assumes that the overall mean deflection, as determined from simultaneous measurements by the full set of deflection sensors, yields an accurate estimate of the true deflection. This assumption requires that the deflection sensors must have first been subjected to the reference calibration procedure.

Some FWDs have fewer than or more than seven active deflection sensors. If they do, these procedures should be modified to calibrate the actual number of active sensors in use on the FWD.

Equipment

FWD relative calibration stand with as many positions as the number of active deflection sensors. For the purpose of illustration a seven-position stand is assumed herein.

FWD relative calibration software (**FWDCAL3**) and documentation.

General Procedure

The process involves rotation of each deflection sensor through every position in the calibration stand. Each combination of sensors and levels is considered a "set," and the number of sets of data will be equal to the number of sensors. The test point is "conditioned " before beginning the calibration procedure to reduce the possibility that set will be significant in the data analysis. The required order of movement of the sensors is shown in Table 2. In order for the data processing with **FWDCAL3** to be done correctly it is very important that the sensor rotation from set to set be done correctly. Spare deflection sensors do not have to be calibrated until they are in active use.

Table 2 -Relative Calibration Sensor Positions by Set

Level in Sensor Stand		Deflection Sensor Number in the Stand						
	Set:	1	2	3	4	5	6	7
(Top)								
A		1	2	3	4	5	6	7
B		2	3	4	5	6	7	1
C		3	4	5	6	7	1	2
D		4	5	6	7	1	2	3
E		5	6	7	1	2	3	4
F		6	7	1	2	3	4	5
G		7	1	2	3	4	5	6
(Bottom)								

Note: The rotation must be done as prescribed above in order for the software (FWDCAL2) to work properly. For instance, for Set 2, move Sensor 2 to the position formerly occupied by Sensor 1, etc.

When done in conjunction with reference calibration, the relative calibration procedure shall be repeated twice: Acceptance criteria based upon the repeatability of the calibration factor are identified in the relative calibration procedure. If the results persist in failing the acceptance criteria, then the cause of the erratic results should be identified and corrected.

After the relative calibration is completed, the final calibration factors shall be entered into the FWD computer.

A sample relative calibration setup screen for the Dynatest FWD with Edition 10 or Edition 20 software is given in Figure 2. The information in Figure 2 can also be used as the basis for setup of Dynatest FWDs running Edition 25 and higher software.

```
    Reference Calibration
1.  Test UNITS...:  lbf.mil.inch   (kPa.mu.mm)
2.  Temperature...: Fahrenheit     (Centigrade)
3.  Stn.Request...: OFF            (ON)
4.  Test Checks...: NONE           (Decreasing defls, Roll-Off, RollOFF+Decr)
5.  Reject prompt.: OFF            (ON)
6.  Stationing....: [Doesn't matter]
7.  Temp.Request..: OFF            (ON)
8.  Cond.Request..: OFF            (ON)
9.  Variation  : Load NOT Checked! Deflections NOT Checked!
10. Diameter of Plate: 11.8
11. Deflector distances: [doesn't matter - keep what you have]
                        1          2           3          4
12. Drop No.   : 1234567P8901234P5678901P2345678P9012345P6789012P3456789S.......
13. Heights*   : CC44444PCC44444PCC44444PCC44444PCC44444PCC44444PCC44444S1111111
14. Test Plots : ...............................................................
15. Save Peaks : ...*****.*****.*****.*****.*****.*****.*****.*****.............
16. Load His  : ................................................................
17. Whole His : ................................................................

18. Load another TEST SETUP.
19. Store the CURRENT TEST SETUP.

*Note:  Drop height should be adjusted to attain deflections within the specified
```

Figure 2. Relative Calibration Test Setup for the Dynatest FWD

Relative Calibration of the Deflection Sensors

1. Remove all of the deflection sensors from their holders on the FWD. Make sure that the sensors are labeled (e.g., from 1 to 7, or 0 to 6) with respect to their normal position on the FWD. The center sensor is position number "1" on the Dynatest FWD and is position number "0" on the KUAB FWD.

2. Label the seven levels on the sensor stand from "A" to "G." The top level is usually labeled "A."

3. Position the seven deflection sensors in the stand for the first of the seven sets according

to Table 2.

4. Support the sensor stand in a vertical position. Mark the location where the stand rests so that it can be relocated precisely on the same spot. This may be done by gluing a washer to the pavement, or by making a small divot in the pavement with a chisel.

5. Select the FWD drop height and the distance from the loading plate to the sensor stand to yield deflections on the order of 400 to 600 microns (16 to 24 mils). If deflections in this range cannot be achieved, then it may be necessary to relocate the FWD to a different pavement. In general, a concrete pavement on a relatively weak subgrade will yield the required deflection. In most cases the reference calibration test pad should be usable for relative calibration.

6. Warm up the FWD rubber buffers and condition the test point by repeating a sequence of ten drops until the loads and deflections that are registered are nearly uniform. The deflections in a sequence of ten drops should not be showing a steadily increasing or decreasing trend. If liquefaction or compaction is indicated by the warm-up data, relocate the FWD to another pavement.

7. Lower the FWD loading plate. DO NOT raise the loading plate or move the FWD during the relative calibration testing. This will assure a constant distance between the center of the load plate and the base of the sensor stand.

8. For each set make two seating drops (no data recorded) followed by five replicate drops (for which data is recorded) while holding the stand in a vertical position. With seven sets and 5 replicate drops, data for a total of 35 drops is required (see Figure 2).

Relative Calibration Data Analysis

A three-way analysis of variance should be used to evaluate the data. This will partition the variance into four sources: (1) that due to sensor number, (2) that due to position in the calibration stand, (3) that due to set, and (4) that due random error of measurement. This analysis is performed by the **FWDCAL3** software. In this analysis, deflection is the dependent variable, and sensor number, position and set are the three main factors. The three hypotheses that may be tested are:

H_0: Sensor number is a significant source of error

H_0: Data set number is a significant source of error

H_0: Position in the stand is a significant source of error

Through the use of hypothesis testing it is possible to determine whether random error due to sensor number, due to position in the calibration stand, and due to set number are statistically significant. The only factor that should result in a change in the deflection sensor calibration factors is sensor number.

If the random error due to sensor number is found to be statistically significant, then the calculated adjustments in the calibration factors for each sensor should be made. If a change is made in the calibration factor for one sensor, then the calibration factors for all sensors should be changed in accordance with the calculations.

If position in the stand is statistically significant, it is likely that the stand was not held vertical throughout all of the sets during the test. Or a connection in the stand may have been loose. The problem should be corrected, and the test should be repeated.

If set is statistically significant, there may have been a systematic change in the properties of the pavement materials, for instance due to compaction or liquefaction. The test should be repeated after the testing site has been further "conditioned" according to the procedure. If the deflection readings do not become relatively constant during the conditioning, then another site should be selected for the testing.

The mere fact that either position or set, or both, are significant does not necessarily invalidate the relative calibration. Judgement must be used to assess whether or not these factors may be of sufficient physical significance (as opposed to statistical significance) to require that the relative calibration should be repeated or that a new test site should be selected.

The standard error of measurement (e.g., the square root of the mean square error due to error) should be on the order of 2 microns (0.08 mils) or less if the system is working properly and the calibration test was conducted carefully.

The analysis of the data obtained from the relative calibration procedure and the method used to determine revised calibration factors is as follows (calculations are done automatically within the **FWDCAL3** software):

1. Compute the mean deflection measurement, x_i, for each sensor (average for the seven sets) and the overall mean, x_0, for all of the sensors averaged together.

2. Compute the adjustment ratio, R_i, of the overall mean to the sensor mean for each sensor. This is also called the "means ratio."

$$R_i = \frac{x_0}{x_i}$$

3. Compute the final calibration factor for each sensor by multiplying the adjustment ratio, R_i, times the current or interim calibration factor for the sensor.

Relative Calibration Acceptance Criteria

When relative calibration is conducted in conjunction with reference calibration, the procedure is repeated two times. If the two sets of calibration factors agree within 0.003 for each deflection sensor, then the results of the two tests shall be averaged. If they are outside the limit, then a third relative calibration shall be performed. If the standard deviation of the three results (based on n - 1 degrees of freedom) is less than 0.0030, then the three results shall be averaged. If the standard deviation exceeds 0.0030, the relative calibration procedure should be repeated.

An example of the calculations following this procedure is shown in Appendix C. The average final calibration factors should be computed, and the factor for each deflection sensor should be entered into the FWD computer software (e.g., the "FWD Field Program").

When relative calibration is done alone, typically on a monthly basis, then adjustment of the calibration factors in the FWD Field Program should be made only when those changes are both significant, and verified to be necessary .The following guidelines are to be used to evaluate the need for adjustment to the calibration factors.

1. Computed sensor adjustment ratios, R_i, between 0.997 and 1.003 inclusive are considered to be equivalent to a ratio of 1.000. In other words the required adjustments are trivial and need <u>not</u> be made.

2. Where the adjustment ratios for one or more sensors fall outside of the range 0.997 to 1.003, the relative calibration process should be repeated. If both sets of data agree within 0.003, the gains should be adjusted for <u>all</u> sensors.

3. According to the recommendations of the FWD manufacturers, a final calibration factor less than 0.98 or greater than 1.02 is possibly indicative of a damaged sensor, which should be repaired by the manufacturer, or replaced. Final calibration factors that are within this range should be entered into the FWD data collection software.

4. If any calibration factors are changed, the relative calibration process must be repeated to verify the accuracy of the final values. The resulting adjustment ratios should be within the range 0.997 to 1.003 for all sensors. If they are not, the test procedure should be repeated.

Reports

The full FWD calibration report shall consist of the following:

- Printouts of the following Dynatest FWD Field Program screens (or equivalent for non-Dynatest FWDs).

    - Transducer Setup and Calibration Factors
    - Voltages
    - Load Cell Calibration

    Each of the above printouts is to be annotated with the FWD unit identification (e.g., manufacturer's serial number or agency ID), and the calibration date.

- All printouts from the **FWDREFCL** software.

- The final printouts from the **FWDCAL3** software for all relative calibration trials.

- The Final Calibration Computation worksheet (see Appendix C).

Distribution of this report shall be as follows:

- Original retained by FWD operator for submission to his agency (LTPP Regional Engineer for LTPP FWDs).

- One copy transmitted to LTPP Division Office within one week of calibration.

- One copy retained on file by the Calibration Center for a period of at least three years.

The diskettes on which the reference and relative calibration data are stored should be kept in the FWD. It is recommended that labeled backup copies be kept on file with the calibration report at the office out of which the FWD is operated. For the LTPP FWDs, additional backup copies of the calibration diskettes are to be kept on file at the LTPP Regional Office.

When relative calibration is done alone (e.g., as a monthly calibration check), the relative calibration report will consist of all printouts from the **FWDCAL3** software, annotated as necessary to explain any problems which might have been encountered.

APPENDIX A: REFERENCE CALIBRATION EQUIPMENT AND FACILITIES

I. Facilities

Indoor space with:

- Easy access for FWD and towing vehicle.
- Level floor large enough so that both the FWD trailer and the towing vehicle can sit level during the test and be enclosed indoors.
- Reasonably constant temperature (between 50 and 100 F) and humidity (40-90 percent), heated, but not necessarily air conditioned.
- Good security for calibration equipment.

Test pad:

- 15 feet by 15 feet, with an 8-foot wide clear zone around perimeter (for maneuvering FWDs and the reference data acquisition system).
- Smooth, crack-free portland cement concrete surface. A modest amount of hairline cracking is permissible. Should the test pad develop cracks which are visibly open (1/16 inch or more), it should be replaced.
- Isolated (by impregnated felt bond breaker, or sawed and caulked joint) from the area where the concrete inertial block supporting the aluminum reference beam will rest.
- Slab deflection of at least 400 microns (16 mils) due to 71 kN (16,000 lb) load at the position of the deflection sensor holder when the FWD is in the specified position for calibration. The sensor holder should be located not closer than two feet from the edge of the test pad, but it is not required, nor is it possible, that the test pad should deflect uniformly across the entire area of the pad. Because the inertial block supporting the aluminum reference beam must be placed adjacent to, but not on the calibration test pad, the maximum possible distance from the sensor holder to the edge of the test pad will be about five feet.

Note: Calculations indicate that an acceptable fatigue life can be achieved with a 5-inch-thick portland cement concrete slab resting on an 8-inch open-graded crushed stone base. A layer of filter fabric should be placed below the base to protect it from intrusion of subgrade fines. To achieve adequate deflections, the subgrade modulus should be less than 12,000 psi (80 MPa) with bedrock deeper than 25-30 feet. Where bedrock exists at depths of 15 to 25 feet, a subgrade modulus of 7,500 psi (50 MPa) or less will be needed. Test pads located where bedrock is less than 15 feet deep are likely to be very sensitive to minor variations in subgrade moisture, and hence are not advisable.

II. Equipment

- Concrete inertial block (17.8 kN (4,000 lbs.)).
- 5-foot aluminum reference beam.
- Air-Cel low frequency (8 Hz) rubber isolation pads for support of the concrete block.
- LVDT mounting hardware.
- Deflection sensor holder assembly.
- Magnetic tip for LVDT.
- Schaevitz Model GCD-121-125, 0.125-inch stroke DC LVDT with Cannon connector.
- Schaevitz metric LVDT calibrator C-41M.
- Measurements Group, Inc. Vishay Model 2310 signal conditioner, with factory modification for + 15 VDC and -15 VDC excitation.
- Keithley-MetraByte Model DAS-16G A/D data acquisition board, with STA-16 screw terminal board and C-1800 ribbon cable. The G2 version of the data acquisition board is recommended for IBM PC-XT and PC-AT computers, and compatibles; the G1 version is acceptable. A Model µ DAS-16G board should be used with IBM PS/2 (microchannel bus) computers.
- Connecting cables, Vishay to LVDT and Vishay to MetraByte.
- FWD reference calibration software (**FWDREFCL**) and documentation.
- Custom built reference load cell (300 mm diameter, 180 kN (40,000 lb) capacity).
- Connecting cable, Vishay to load cell.

Note: Drawings of each of the special items of equipment, and cabling diagrams, are available from the Long-Term Pavement Performance (LTPP) Division at the Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, Virginia.

IBM PC-XT or PC-AT, or compatible, computer recommended; IBM PSI2 computer acceptable. Configuration:

- 80386 processor or higher.
- 33 MHz or faster processor speed.

- Co-processor, if applicable.
- 1 megabyte or more RAM.
- 100 megabyte or more hard drive.
- An 8-bit expansion slot for the MetraByte board.

Monitor:

- Color monitor; monochrome not recommended.
- VGA recommended; EGA acceptable.

Graphics Printer:

- Laser printer recommended; dot matrix acceptable, but very slow.

(Where both "recommended" and "acceptable" options are given in the above specifications, an effort has been made in the software development to accommodate both alternatives. However, since most of the testing has been done on computer hardware meeting the "recommended" specifications, installation of the calibration station will go more smoothly if those specifications are met. A demonstration version of the **FWDREFCL** software is available from the LTPP Division in the Federal Highway Administration (located at the Turner-Fairbank Highway Research Center, McLean, VA) which can be used to determine if the computer and peripherals will work satisfactorily with the program.)

APPENDIX B: SPECIAL PROCEDURES FOR TESTING THE KUAB FWD

Reference calibration of the KUAB FWD can be carried out in a manner very similar to the procedure outlined for the Dynatest FWD. However, because the KUAB has its load plate forward of the deflection sensor beam (i.e., toward the towing vehicle), it will be necessary to place the trailer on an angle with respect to the test pad, so that the load plate can be positioned as close as possible to the LVDT and the deflection sensor holder. The end of the aluminum beam holding the LVDT should be just behind the trailer wheels, near the place where the "foot" of the KUAB A-frame rests on the floor.

KUAB FWDs must have operational program SFWD version 4.0 or higher to perform reference calibrations. This version can be obtained from the manufacturer.

Before the reference calibration procedure is performed, the FWD Operator should first conduct a static calibration of the deflection sensors. The KUAB software will automatically file the static calibration factors. The manufacturer recommends that the dynamic calibration factors be entered as 1.05 for all sensors. These values should not be changed during or after the reference calibration.

Due to the larger distance between the center of the load plate and the seismometer holder it may not be possible to achieve the specified deflection of 400 microns (16 mils) at 16,000 pounds. The deflections should be as large as possible.

To achieve the specified load levels refer to the information provided by the manufacturer. The exact combination of weights and buffers will vary between the different KUABs. Adjust the drop height endswitches as necessary to be within the specified load tolerance.

In general the KUAB will be tested with the 17-millisecond rubber buffers installed. The reference data acquisition system and the **FWDREFCL** software allow for calibration using the 25-millisecond buffers, but the movement of the aluminum beam should be checked carefully to assure that there is no motion before the ground deflection peaked out.

The **FWDREFCL** software contains an number of special features to accommodate the KUAB, and thus in initializing the software, the FWD type should be set for "KUAB." The deflection sensor that is mounted through the load plate (i.e., the center sensor) is called sensor number zero on the KUAB, and it is in position number 0 as far as **FWDREFCL** is concerned.

KUAB FWDs with version 4.0 software are able to pause during the drop sequence, prior to releasing the mass. This is achieved by entering the letter "P" after the drop height position code during programming of the drop sequence. For example, the required reference calibration drop sequence would be entered as follows (drop height, number of drops):

333(1P,6)(2P,6)(3P,6)(4P,6)S

The pause occurs with the mass elevated, ready to drop. The mass will not be released until the FWD operator strikes a key.

The S programmed at the end of the drop sequence will stop the testing sequence with the load plate remaining on the test pad after the final drop. To repeat the drop sequence without raising the load plate initiate the drop sequence in the normal manner and override the ensuing error statements regarding transport position, etc., by choosing to ignore.

Because the top of the reference load cell is 300 millimeters in diameter, it will only be possible to calibrate the small (300 mm) load plate on the KUAB. If the KUAB is outfitted with the large (450 mm) load plate, it should be replaced with the 300 millimeter load plate in order to attain accurate results.

A special holder is provided for mounting the KUAB seismometer under the LVDT. The Dynatest geophone holder should be removed and the KUAB holder bolted down in its place. The LVDT mounting plate that attaches to the end of the aluminum beam should be removed from its position under the beam and reinstalled on top of the beam. The KUAB deflection sensors will be slid upward off the two rods that hold them in position on the sensor beam in the trailer. Remove the tripod foot by loosening its holding screw, and then slip the deflection sensor over the peg on the holder under the LVDT. Tighten the holding screw firmly.

Conducting load plate calibration is particularly difficult with the KUAB, because it is hard to detect when the FWD mass has been released. To make this easier, a double layer (or thicker) of "duct tape" should be wrapped around the guide post (down which the runners under the falling mass roll), located an inch or two above the bottom of the stroke. The proper position for the tape can be found when the mass is at its lowest drop height. Adjust the KUAB load sensitivity in the reference system computer to a value of 5 to 10 bits.

The presence of the tape during load plate calibration may generate warning messages about "excess noise in the average zero." The "bump" that is generated as the mass runs past the (tape triggers the start of load data acquisition, but the vibration that it causes may not yet be damped out when the mass strikes the plate. Check the time history traces carefully to be sure that the vibration had no effect on the accuracy of the peak load that was registered. If there is a problem, try moving the tape to a position higher on the guide post.

Remove the tape after completion of the load plate calibration.

Enter the new calibration factors for the deflection sensors as the "SHRP Calibration Factors" under the Calibrate menu in the KUAB operational program. The calibration factor for the 300 mm load plate is entered in the same manner. The calibration factor for the large (450 mm) load plate should remain unchanged.

Most KUAB FWDs do not have a calibration stand for performing relative calibration. Thus it may not be possible to perform the relative calibration procedure as described herein.

Limited experience in the calibration of KUAB FWDs has shown that the combination of static calibration and dynamic calibration may be adequate to yield a satisfactory calibration and accurate final calibration factors. However, relative calibration further refines the reference calibration factors, and it allows a monthly check of the accuracy of the deflection sensors. Thus it is highly recommended that a means of performing relative calibration with the KUAB FWD be obtained.

APPENDIX C: SAMPLE COMPUTATION OF FINAL CALIBRATION FACTORS

	Final Calibration Factors				
	From Relative Calibration			Average Final	Standard
Sensor	Trial 1	Trial 2	Trial 3	Calibration Factors	Deviation
1	1.014	1.011	1.015	1.013	0.0021
2	1.010	1.007	1.012	1.010	0.0025
3	1.012	1.010	1.013	1.011	0.0015
4	1.016	1.020*	1.017	1.018	0.0021
5	1.017	1.018	1.018	1.018	0.0006
6	1.008	1.013*	1.011	1.011	0.0025
7	1.012	1.012	1.009	1.011	0.0017

Notes:

1. If the results from the first two trials agree within 0.003 for each deflection sensor, then it is not necessary to perform a third test. Average the results of the first two trials, and enter the average final calibration factors in the FWD computer. In the example above, after Trial 2 the data marked (*) did not meet this criterion.

2. If three trials are performed, compute the mean and the standard deviation of the three results for each deflection sensor. If the standard deviations (based on n - 1 degrees of freedom) are all less than 0.0030, enter the average final calibration factors in the FWD computer. If any of the standard deviations exceed 0.0030, repeat the entire relative calibration test.

APPENDIX D: REFERENCE LOAD CELL CALIBRATION PROCEDURE

INTRODUCTION

The reference load cell is a precision instrument, capable of measuring loads within ±0.3 percent or better. Such a high degree of precision can be attained, however, only if this calibration procedure is followed exactly. It is essential that the reference load cell be calibrated using a universal testing machine that is properly maintained and accurately calibrated.

FREQUENCY OF CALIBRATION

Calibration of the reference load cell should be performed at least once per year. It should also be performed immediately after any of the six Allen head screws that attach the load measurement links to the upper or lower plates of the reference load cell are loosened. Calibration would also be necessary if the load cell fails to pass the unbalanced zero test (within ±5 percent) as detected by the **FWDREFCL** program.

EQUIPMENT

- Universal testing machine. A static testing machine, hydraulic or screw-powered, with a load capacity of 120,000 pounds or more should be used for the reference load cell calibration. Although the reference load cell will only be calibrated to a capacity of 20,000 pounds, the higher capacity of the testing machine assures that the test frame will be adequately rigid. The testing machine should have several load ranges, among them a 0 - 20,000 pound range (slightly higher ranges, such as 0 - 24,000 pounds, etc., would be acceptable). Care must be taken to avoid overloading the reference load cell during its calibration.

  Note: Do <u>not</u> use a servo-controlled, closed-loop testing system such as a MTS machine for this purpose. In general such equipment does not provide the high degree of accuracy that is required for this calibration.

- Bearing blocks: special wood/aluminum bearing blocks.

- Measurements Group, Inc. Model 2310 Signal Conditioner. This should be the <u>same</u> signal conditioner that will be used in the reference calibration procedure.

- Keithley-MetraByte DAS-16G data acquisition board, installed in the same computer that is used for reference calibration.

- Push-button trigger for activating the data acquisition system.

The reference load cell and its cable, and the associated signal conditioner, data acquisition board and computer should be considered a system of instruments, which should be calibrated together and used together.

CALIBRATION OF EQUIPMENT

The universal testing machine should be calibrated according to ASTM procedure E-74 within twelve months prior to conducting this procedure. The device(s) used to calibrate the universal testing machine should be certified to be traceable to the National Institute for Science and Technology (NIST - formerly the National Bureau of Standards) calibration(s). The certificate of calibration provided for the universal testing machine should be used to develop an adjustment algorithm which will correct the indicated load on the universal testing machine to the NIST load. It is highly recommended that the reference load cell be calibrated soon after the universal testing machine is calibrated.

The MetraByte board should be calibrated according to the procedure described in the manufacturer's instruction manual. Its accuracy should be verified using a reference voltage source such as a 1.350 volt mercury cell (e.g., camera battery in new condition).

The 2310 signal conditioner amplifier should be balanced according to the procedure described in the manufacturer's instruction manual. With the signal input terminals shorted together, at gain 100 the ac noise on the ±10 volt output terminals should be 1 millivolt or less.

EQUIPMENT PREPARATION

Inspect the reference load cell carefully before calibration. Verify that the cable and the Amphenol connectors are making proper contact in their sockets (e.g., fitting and locking tightly). Make a continuity check to verify that there are no breaks in the wires. Verify that the Allen screws on the load cell are tight.

Note: The six Allen screws on the top and the bottom of the load cell were torqued to 100 lb.-in. and set with Locktite during assembly. These screws should not be loosened unless it is absolutely necessary. If any of the screws are loosened, they should be removed one at a time and their threads cleaned. Locktite should be reapplied to their threads, and they should be torqued to precisely 100 lb.-in.

Verify that the three steel pads on the bottom of the reference load cell are in good condition. Verify that one of the wood/aluminum bearing blocks has a ribbed rubber pad cemented to it. If the edges of the rubber pad are loose, use rubber cement to reattach it.

Install a spherically-seated bearing block in the cross head of the universal testing machine.

Make the following settings on the front panel of the 2310 signal conditioner:

- Excitation Voltage set to 10 volts.
- Filter set to 1000 Hz.
- AC IN button fully extended (e.g., out).
- Gain set to 5.5 X100.
- Auto Balance switch OFF.

Verify that the Tape Playback switch on the rear panel of the signal conditioner is OFF. Position the signal conditioner and the computer several feet apart near the testing machine and attach them to ac line power.

COMPUTER PREPARATION

Use the same computer system for reference load cell calibration that is used for FWD calibration. A graphics printer must be available.

Load the software **LDCELCAL** into the reference system computer. This program should be located in the same subdirectory with **FWDREFCL.EXE** and **FWDREFCL.CNF**. A disk with the files **REFLCCAL.WK1** and **REFLCCAL.FMT** on it should be inserted in drive A. The computer must be running under **DOS** and not under **WINDOWS** during the calibration.

The computer program **LDCELCAL** is designed to interact with a Lotus 1-2-3, version 2.3, spreadsheet to accomplish the data analysis. The subdirectory containing the 1-2-3 program must be on the PATH in order for the two programs to work together successfully. The **WYSIWYG** add-in utility should be installed according to the Lotus directions. Defaults in Lotus 1-2-3 should be set as follows.

- Default directory: A:\
- Auto-execute macros: on
- Auto-attach add-in #1: C:\LOTUS\WYSIWYG

See the Lotus User's Manual for instructions regarding setting the defaults. If the program is correctly installed and set up, the data analysis will be run, a listing of the data will be produced, and graphical output will be printed automatically. A demonstration version of **LDCELCAL** is available to use with Lotus 1-2-3 to verify that your computer system can interact properly with the program.

CALIBRATION PROCEDURE

1. Attach the cable from the signal conditioner to the reference load cell, turn on the signal conditioner, and allow the system to warm up for at least 60 minutes. Attach the cables connecting the signal conditioner to the computer. Attach the push-button trigger in the blue terminal box of the MetraByte data acquisition system. Turn on the computer and the printer. If an hydraulic universal testing machine is used, turn the pump on and allow it to warm up for 15 minutes.

2. Place a wood/aluminum bearing block with no rubber pad in the center of the testing machine platen.

3. Place the reference load cell on top of the bearing block with the three steel pads down (i.e., in contact with the top surface of the lower bearing block).

4. Place the second bearing block on top of the load cell with the cemented rubber pad down (i.e., in contact with the top surface of the load cell).

5. Carefully align the edges of the load cell and the two bearing blocks, and center the system under the upper loading block of the universal testing machine.

6. Set the testing machine on a range equal to or slightly larger than 20,000 pounds. Apply a nominal load of 20,000 pounds to the reference load cell three times. Apply the load at a rate in the range of 5,000 to 20,000 pounds per minute.

7. Temporarily remove the upper wood/aluminum bearing block. Set the Auto Balance switch on the 2310 signal conditioner to OFF. Read and record the unbalanced zero voltage. If this voltage is in excess of ±5 volts the load cell has been damaged by yielding and it should be returned to the manufacturer for repair.

8. Push down the Auto Balance switch on the signal conditioner to the RESET position and release it to the ON position. Adjust the Trim knob until the MetraByte board reads 0 bits.

9. Replace and align the upper bearing block, rubber pad down. Verify that the three guide fingers do not come in contact with the upper bearing block.

10. Apply a load of 20,000 pounds, and while it is held relatively constant verify that the MetraByte board reads within ±30 bits of -2000 bits. If necessary, adjust the Gain knob on the 2310 signal conditioner in 0.1 increments (for example, from a setting of 5.50 X100 to 5.40 X100) to achieve the required reading. Release the load. Record the gain setting.

    Note: When the load is released the MetraByte board will not read exactly zero because it was zeroed without the upper bearing block in place. Do <u>not</u> rezero the signal conditioner at this point.

11. Apply load at a rate of 500 to 1,000 pounds per minute. Record the MetraByte board readings at 1,000 pound intervals up to a maximum load of 20,000 pounds. While releasing the load, record a reading at 10,000 pounds and at zero load.

12. Remove the upper bearing block and, if necessary, adjust the Trim knob on the signal conditioner until the MetraByte board reads 0 bits. Push and hold the Cal switch in the +B position and record the reading. Repeat for the -B position. Set the Auto Balance switch to OFF and again record the unbalanced zero voltage. This reading should be within three bits of the earlier reading. If it is not, repeat the calibration procedure from step 4 (be sure that the load cell is centered in the testing machine, and be sure to repeat the 20,000-pound preloading procedure in step 6).

DATA ANALYSIS

Using a spreadsheet utility program such as Lotus 1-2-3, enter the results of the calibration. In column A enter the nominal loads registered by the universal testing machine (i.e., 0, 1000, 2000, etc.). In column B correct these loads to the NIST traceable loads, based on the certificate of calibration for the testing machine. In column C subtract the tare weight of the upper bearing block from the loads in column B. In column D enter the MetraByte board readings in bits. Note that the readings are negative. In columns E, F, G and H calculate V^2, V^3, V^4, and V^5, respectively (where V represents the readings in column D).

Use the spreadsheet regression utility to calculate a linear regression of corrected load (as the Y-variable) versus bits (as the X-variable). The regression should be forced through zero, yielding an equation of the form $Y = mV$, where Y is the corrected load (column C), V is the voltage (column D), and m is the slope of the line of best fit. The coefficient m should be approximately -10 pounds per bit.

Use the regression utility to calculate a fifth degree polynomial regression of the form:

$$Y = A_1 V + A_2 V^2 + A_3 V^3 + A_4 V^4 + A_5 V^5$$

where the coefficients A_i are determined by the regression. Evaluate the polynomial solution according to the following criteria.

1. The standard error of the Y estimate should be less than ±50 pounds.

2. The standard error of each of the coefficients should be small with respect to the coefficient. Generally speaking the coefficient should be at least a factor of ten larger than its standard error. For instance, if the coefficient A_2 is -0.15, its standard error should be 0.015 or smaller. If this is not the case, the regression coefficient is not significant.

If the standard error of any of the coefficients is too large (e.g., not significant), repeat the, regression using a fourth degree polynomial of the form:

$$Y = A_1 V + A_2 V^2 + A_3 V^3 + A_4 V^4$$

Again evaluate the polynomial according to the criteria in 1 and 2 above. When the evaluation criteria are satisfied, and <u>all</u> of the coefficients are significant (usually this will happen with either a fourth degree, third degree, or second degree polynomial), record the regression coefficients.

Note: The LOTUS 1-2-3 spreadsheet template that accompanies **LDCELCAL** will perform the step-down egression automatically, and it will choose the correct polynomial.

ENTER THE REGRESSION COEFFICIENTS IN FWDREFCL

The regression coefficients should be entered in the data acquisition program **FWDREFCL**. Instructions for doing this can be found in the Load Cell Setup section of the **<u>FWDREFCL</u>** <u>User's Guide</u>. All of the unused higher order terms should have their coefficients entered as 0.0.

When the regression coefficients are entered in **FWDREFCL**, the unbalanced zero, the + B and -B calibration factors, the load cell signal conditioner gain factor, and the date of calibration should also be entered.