Cost Effective Calibration Intervals Using Weibull Analysis

H. Paul Barringer, P.E.
Barringer & Associates, Inc.
Humble, TX 77347-3985

SUMMARY

Calibration intervals are found from actual or forecasted time-to-failure along with both planned recalibration costs and unplanned failure costs by means of Weibull analysis using commercially available WeibullSMITH™ software. Calibration intervals are found for several examples.

KEYWORDS

Calibration Intervals, Weibull Analysis, Risk/Benefit Cost Analysis, Instrument Reliability

INTRODUCTION

How do you decide when it's time to calibrate an instrument? Most factories lack good business algorithms for answering this question cost effectively. They commonly use conservative calibration intervals so that efficacy questions are not raised by inspection agencies conducting quality surveys and thus costs are not considered in decisions about the recalibration interval.

ISO 9001 (ISO 1987) certification issues are bringing-out calibration anxieties. The rush to document calibration intervals for certification purposes is often driving-up costs. Both instrument manufactures and calibration services are benefiting financially from calibration anxiety brought on by "ISO systems requiring you to say what you do and do what you say to meet the ISO specifications". ISO standards for calibration are very similar to military standards MIL-STD-45662A (MIL 1988) as amplified in MIL-HDBK-52B (MIL 1989). Also ISO 10012-1 (ISO 1992) has similar calibration requirements for measuring equipment confirmation systems.

WHAT TO DO ABOUT CALIBRATIONS

Calibration is the set of operations which establish, under certain specified conditions, the relationship between values indicated by a measuring instrument or system, or values represented by a material measure, and the corresponding known values of a measurand (RP-1 1989). This tells "what to do" for calibration so that instrument output conforms to a known measurement input to get small errors between instrument and the standard.

New instruments require calibration for achieving accuracy (i.e., producing readings near the true value). Older instruments require recalibration to restore confidence in their abilities to measure accurately. During calibration, if instrument adjustments are available, detected errors are reduced by adjustment so fresh measurements are correct.

Calibration systems require prevention of inaccuracy by detection of deficiencies and timely positive action for corrections. Calibration assurance provisions require written descriptions covering measurement and test equipment and measurement standards which will satisfy the requirements for instrument accuracy.

Calibration procedures also require written details for the measurement standard used during calibration, enumeration of the required parameters, range and accuracy of the measurement standard, and the acceptable tolerance of each instrument characteristic being calibrated. Additionally instructions must be provided to enable calibration personnel to adequately calibrate each instrument characteristic or parameter.

Adequacy of measurement standards used during calibration requires traceability, by an unbroken chain, to national or international standards. Also collective uncertainty of measurement standards must not exceed 25% of the acceptable tolerance for each characteristic being calibrated (i.e., this is a statement about instrument precision or scatter errors). Use of the 4:1 minimum calibration test accuracy ratio rule avoids detailed calculations of estimating errors associated with measurements (Abernethy 1980) or as detailed in other established references (ANSI/ASME 1985), (ANSI/ASME 1983), (ISO/TAG 1992) and (RP-3 1989). For example, using a micrometer calibration standard accurate to ±0.000125", permits claiming the micrometer is suitable for ±0.0005" at accepted 4:1 ratio of accuracy.

What to do for calibration is obvious. Setting-up recalibrations systems (without strong considerations for costs/risks) is a routine well known to practitioners of quality assurance and quality control techniques. Clearly one criteria that must be established for calibration systems is what level of errors are permissible and what are rejectable for individual instruments or classes of instruments.

It is not appropriate to just say calibrate this instrument. End users of calibration services must describe the accuracy level or the accuracy of the instrument in terms of what errors are allowed for use of the instrument. Lack of specificity by the end user frequently results in establishment of unnecessarily rigid recalibration pass/fail criteria.

Setting recalibration requirements too tight results in a short calibration validity period with high recalibration costs to achieve idealistic tight results. In short, if the instrument user does not order the specific grade for instrument calibration, the calibration service will usually select a standard which may be too severe for the end users needs. If you need transducers rated for ±0.5% service, buying higher grade transducers capable of ±0.1% service is not usually cost effective. Say what you need to meet your calibration requirements.

WHEN TO DO RECALIBRATIONS

Most calibration systems have provisions for establishment of a validity period during which the instrument can be used without concern for major uncertainties in measurement output. Most calibration

Table 1: Recalibration Costs By Business Size And Business Complexity			
Size	Simple	Average	Complex
Quantity For Calibration (pieces/year):			
Small	100	500	2,500
Medium	1,000	5,000	25,000
Large	10,000	50,000	250,000
Costs For Calibration ($/year):			
Small	5,000	25,000	125,000
Medium	50,000	250,000	500,000
Large	500,000	2,500,000	5,000,000

systems also allow for shortening calibration intervals if errors larger than allowed are detected. Similarly, calibration periods are lengthened if instruments are well behaved within close limits of the original calibration as instruments are returned for recalibration. Conceptually these conditions address issues of when calibration intervals should occur.

Few organizations can establish a recall rational for timely return of instruments for recalibration using a logical and rational system. Even fewer organizations can establish methods for adjustment of recalibration intervals. Furthermore the number of organizations who can merge all three issues (1. recall intervals, 2. adjustment of recall intervals, and 3. cost consequences) into a risk/benefit analysis are very small. This is unfortunate considering financial impacts calibration efforts have on most industrial organizations. Table 1 shows typical recalibration situations. Recalibration costs are not clearly non-trivial.

Of course each business has specific quantities and specific costs different than the generalities of Table 1. High costs of recalibrations are often hidden in overhead costs so that hard questions about calibration costs and calibration intervals are seldom highlighted for aggressive cost reductions.

Perceptions exist that calibration costs can be reduced if calibration intervals can be stretched legitimately. However, the key business question is finding a cost effective interval considering risks rather than using the traditional ~one year recall interval. How do we find the appropriate cost effective interval?

The military standards and military handbook previously referenced provide guidance for setting recalibration intervals. These standards formerly used a good practice that 95% of all instruments returned for calibration must meet outgoing calibrations limits. Other practical industrial requirements can be established in quality assurance documents for requiring, say, 85% of the incoming instruments must meet out going requirements--after all, businesses must take risks to both survive and make profits for their stockholders. Treat these requirements for 80%, 95%, 90% or 95% of the instruments returned for calibration as a good manufacturing practice and use the criteria that best fits your business.

Most quality systems require an investigation and recall of product if instruments are found to be seriously out of tolerance at their recall interval. Seldom does the investigation result in affirmative action of product recall based on acceptance instruments which are seriously out of calibration. On paper, the risks exist. In reality, seldom is the high risk of a recall converted to an expenditure of cash once the product has left the plant. However, suspect parts still remaining in the plant are frequently reverified (at considerable costs) to show acceptance using the operating philosophy "it's OK to take the product but it's not OK to make the product with poorly calibrated instruments". Techniques exist for moving calibration intervals "closer to the edge of the cliff' using Weibull statistics.

CALIBRATION FAILURE DATA

On most instruments, when functioning and operational, the user cannot tell if the instrument is performing within specified tolerance limits (ISO/TAG 1992). However, when daily, weekly, or monthly cross checks are made against another instrument or against a known standard, instrument deterioration and failures are found. Then the instrument is returned for recalibration or authoritative verification of the out-of-tolerance condition which signals end-of-life using variables data.

Consider the following data for a similar class of pressure gages with end-of-life shown in Table 2. Note that classes of instruments are often considered because long intervals of study are required for meaningful results on individual instruments. This motivates use of classes of instruments to obtain calibration data and establish results in our life time.

Table 2:
Calibration Data On Age To Failure For A Pressure Gage.

Age To Failure(months)
30
38
45
58
64

Table 2's age to failure data is put into a Weibull chart as shown in Figure 1. Figure 1 is calculated by WeibullSMITH software (Fulton 1995).

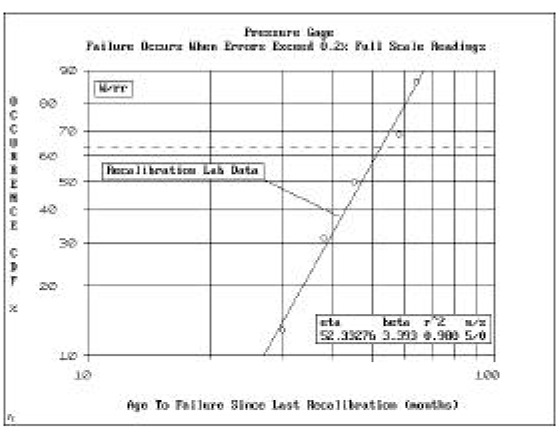

Figure 1: Age To Failure Data

For Figure 1, use a good manufacturing practice criteria that 95% of the instruments returned for recalibration must pass the out-going recalibration, i.e., the instrument is fit for continued use. Because of the complement equation for reliability, this means we can allow up to 5% cumulative failures. From Figure 1 read 5% cumulative failures occur in 21.8 months, and this establishes a requirement for the calibration interval. Thus calibration intervals found by use of a good manufacturing practice that 95% of the instruments returned must be fit for continued service and the calibration intervals is determined from the probability chart of age to failure data without costs considerations.

Figure 1's recalibration interval decisions can be supplemented with cost consequences for the business. Performing a planned calibration, costs $150. Instrument failure causes an unplanned event and cost consequences are $5,000. What is the optimum replacement time using both the expected failure times and the cost conditions?

Figure 2 is displayed by VisualSMITH™ (Fulton 1995) software where the cost curve is obtained from the Weibull renewal equation. The Weibulll renewal equation combines Weibull characteristics of failure and cost details. In plain English, the Weibull renewal equation has: 1) a numerator which at a given time is the planned calibration costs multiplied by instrument reliability plus the unplanned event costs multiplied instrument unreliability, and 2) a denominator which is the mean life.

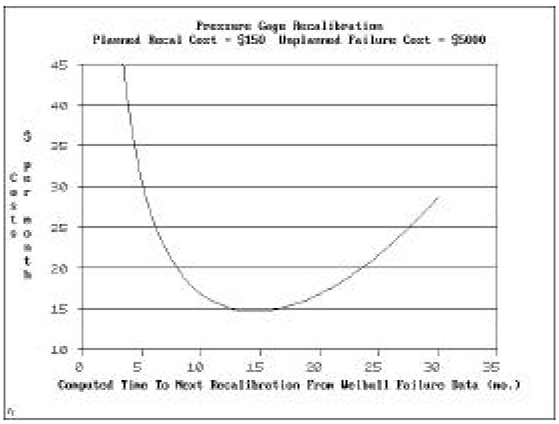

Figure 2: Cost And Recalibration Intervals

Figure 2 shows the cost effective recalibration interval is 14.5 months where least costs are $14.66 per month considering the risk of failure in service. Waiting until the 21.8 months recommended by the good manufacturing practices of Figure 1 (which ignores costs), increases costs to slightly over $18/month which is an extra 17% burden due to the high cost of delayed maintenance.

Figure 1 set recalibration time intervals for achieving an arbitrary failure level. Figure 2 set shorter (but less expensive) recalibration interval based on time considering both risks and cost consequences.

NO CALIBRATION FAILURE DATA

Table 3 shows a class of micrometer standard bars. Standard bars are used to set micrometers accurately on the shop floor.

Table 3: Frequency Table For 5” & 8” Micrometer Standard Bar Errors At Annual Recalibration -- Raw Data (Errors Shown In Microinches)

Error µ-inch	1st Yr.	2nd Yr.	3rd Yr.	4th Yr.	5th Yr.	6th Yr.	Total Count
-100				1	1		2
-90				1			1
-80				1			1
-70	1	1	2				4
-60		1					1
-50				3	1	1	5
-40	2	2	3	1	2	1	11
-30		1	2	2	1		6
-20	3	2	1	2	1		9
-10	5	3	1	1	1		11
0	**2**	**1**	**2**	**3**	**3**	**2**	**13**
10	5	3	3	2	3		16
20	4	4	4	3	1		16
30	5	3	4	3	5		20
40	2	4	3	1	3		13
50	2	5	2	3	1		13
60	4	1	4	2			11
70	2	3		2			7
80	1	2	1	2			6
90	1	2	2				5
100	2	2	2	1	1		8
110		1	1				2
120			2	2	1		5
130							0
140							0
150	1	1		1			3
Total	42	42	39	37	25	4	189

Rezeroing micrometers is required because each machinist has a slightly different “feel” as measurements are obtained, and machinist require access to standard bars for insuring their micrometers yield accurate results.

Each standard bar calibration measurement is shown as an error from ideal measurements in Table 3. Note that plus values show the bar is longer than ideal, and minus values show the bar is shorter than ideal.

Error results in the 5-inch and 8-inch bar lengths were shown to be similar, and results were pooled to achieve a large group of values for analysis as shown in Table 3. By USA Federal Specifications (USA 1989), the maximum allowed error in the bar length for this reference standard is ± 0.000150 inches or ±150 microinches. With bilateral tolerances, recalibration is highly motivated by dimension nearing the 150 microinch limits. Also note that errors near zero do not motivate recalibration. Thus Table 3’s data is simplified into the absolute values of Table 4.

Table 4: Frequency Table For 5” & 8” Micrometer Standard Bar Errors At Annual Recalibration -- Absolute Data (Errors Shown In Microinches-Absolute)							
Error µ-inch	1st Yr.	2nd Yr.	3rd Yr.	4th Yr.	5th Yr.	6th Yr.	Total Count
0	...	...	...	...	...	...	...
10	10	6	4	3	4		27
20	7	6	5	5	2		25
30	5	4	6	5	6		26
40	4	6	6	2	5	1	24
50	2	5	2	6	2	1	18
60	4	2	4	2			12
70	3	4	2	2			11
80	1	2	1	3			7
90	1	2	2	1			6
100	2	2	2	2	2		10
110		1	1				2
120			2	2	1		5
130							
140							
150	1	1		1			3
Total	40	41	37	34	22	2	176
Aveg	40.50	48.54	50.00	54.12	42.27	45.00	
Stdev	32.10	32.60	32.32	35.26	35.98	7.07	

Data from Table 4 is plotted in the probability plot of Figure 3 using rank regression and WeibullSMITH’s inspection feature since the data are clearly interval data recorded at 10 microinch intervals. Figure 3 predicts 99% of the data will be 150 microinches or less and 95% of the data will be less than 106 microinches. Of course Figure 3 lacks an age to failure interval required for recall of instruments. The age to failure interval at 150 microinches must be forecasted synthetically.

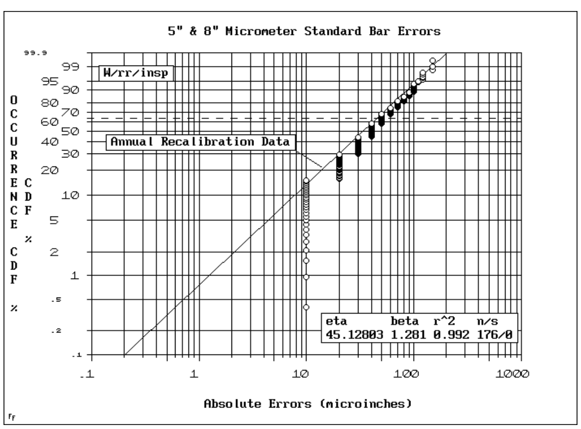

Figure 3: Weibull Plot Of Table 4

A scatter chart is constructed in Figure 4 to forecast synthetic failure intervals using the errors in Table 4 along with their age. The 5th and 6th year in Table 4 contain small portions of the information but exert high leverage on the trend line. Therefore on the basis of judgment, these data points (which show lack of recalibration motivation), were excluded—after all, good engineering combines both art, science, and good judgment.

The trend line of data from Table 4 is plotted in Figure 4 for introducing time into the decision process. Each data point is projected parallel to the trend line to reach the limit of 150 microinches for forecasting the synthetic time to failure. The synthetic age to failure is $[\{(150 - Error_n)/4.232\} + Age_n]$ where 4.232 is the slope of the trend line.

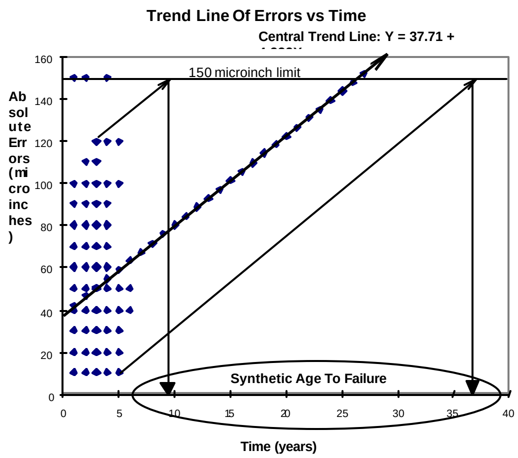

Figure 4: Synthetic Age To Failure

Synthetic age to failure times are shown in Table 5 along with the three actual pieces of actual data shown in bold as 150 microinches (it is a mute issue to set the fail limit at 151 microinches because of practical measurement limitations).

Table 5: 176 Sorted Values Of Synthetic Age To Failure Using Data From Table 4 and Trends From Figure 4							
1.0	17.5	24.3	28.0	30.4	32.7	34.1	38.1
2.0	18.2	24.3	28.0	31.0	32.7	34.1	
4.0	18.5	24.3	28.0	31.0	32.7	34.7	
10.1	18.5	24.3	28.0	31.0	32.7	34.7	
10.1	19.5	24.6	28.0	31.0	32.7	34.7	
11.1	19.9	24.6	28.0	31.0	32.7	34.7	
11.1	19.9	25.3	28.6	31.4	33.4	34.7	
11.5	19.9	25.3	28.6	31.4	33.4	35.1	
12.1	20.5	25.6	29.0	31.4	33.4	35.1	
12.5	20.5	25.6	29.0	31.4	33.4	35.1	
12.8	20.5	25.6	29.0	31.4	33.4	35.1	
12.8	20.9	25.6	29.0	31.4	33.4	35.1	
13.8	20.9	25.6	29.0	31.7	33.7	35.1	
13.8	20.9	26.6	29.0	31.7	33.7	35.7	
14.8	20.9	26.6	29.4	31.7	33.7	35.7	
14.8	21.9	27.0	29.4	31.7	33.7	36.1	
15.2	21.9	27.0	29.4	31.7	33.7	36.1	
15.8	22.3	27.0	29.4	31.7	34.1	36.1	
15.8	22.3	27.0	29.4	31.7	34.1	36.1	
16.2	22.3	27.6	29.6	32.0	34.1	37.1	
16.2	22.3	27.6	30.0	32.4	34.1	37.1	
16.8	22.9	27.6	30.0	32.4	34.1	37.1	
16.8	22.9	27.6	30.4	32.4	34.1	38.1	
17.2	23.3	27.6	30.4	32.4	34.1	38.1	
17.2	23.3	27.6	30.4	32.4	34.1	38.1	

Data from Table 5 gives the probability plot in Figure 5 for synthetic age to failure. Figure 5 shows an undesirable concave upward curvature most likely from plotting non-Weibull data on a Weibull probability plot.

Figure 6 shows a probability plot with a t_0 correction which straightens the curved line shown in Figure 5. Curved plots with concave upward requires a $-t_0$ shift to correct the concave upward curvature shown in Figure 6.

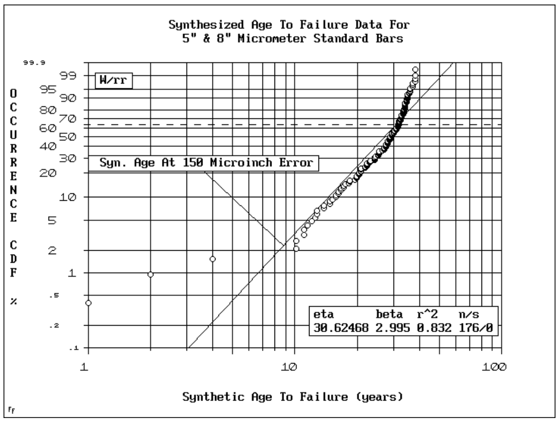

Figure 5: Weibull Plot Of Synthetic Age

Figure 6, shows -52.5671 years as the t_0 correction, to be subtracted from points on this Weibull plot to convert adjusted time into the real time domain.

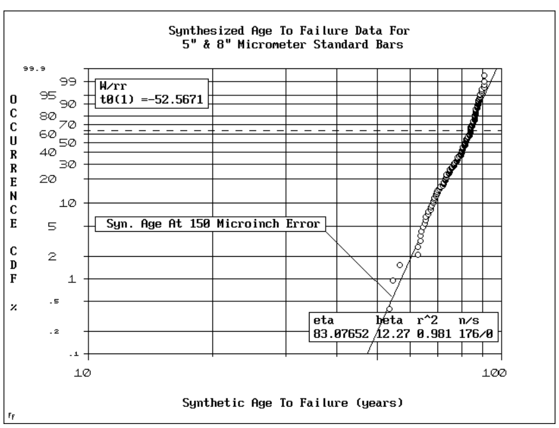

Figure 6: Weibull Plot Of Synthetic Age To Failures In The t_0 Time Corrected Domain

Characteristics of the t_0 corrected Weibull plot in Figure 6 are used with the renewal equation. The planned recalibration cost is $200 and the unplanned event is $20,000 to produce the cost curve shown in Figure 7.

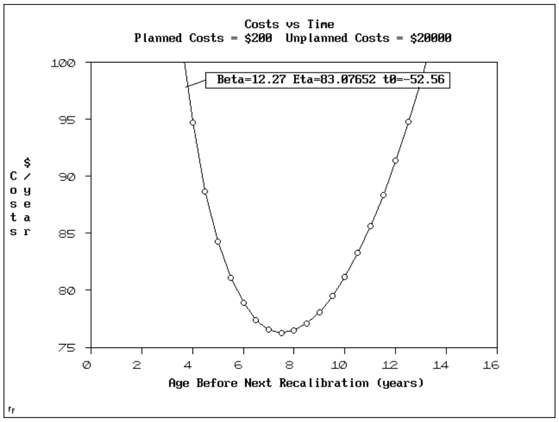

Figure 7: Least Cost Recalibration Interval

Figure 7 was calculated by Mathcad 5.0 (Mathcad 1994) and plotted in VisualSMITH using t_0 corrections for optimum replacement calculations. Figure 7 shows the least cost recalibration interval occurs every 7.5 years at a cost of $291.82 per year. Note that Figure 6 predicts 1.84% of the standard bars will fail at the t_0 time domain of 60.067 years (60.067 - 52.5671 = 7.5 years in the real time domain) where the reliability is 98.15% at 7.5 year recalibrations. This is a 283% cost savings based on the cost in Figure 7!

Why isn't the annual recalibration cost $200 per year rather than the $291.82 show above in Figure 7? The extra cost is due to the chances for failure of parts that may be discovered out of calibration which are not computed in the simple view that the costs are only $200 for an annual recalibration.

CONCLUSIONS

Weibull statistics and the related renewal equation which introduces costs into the decision process offers cost reduction opportunities for recalibration efforts. The answers are usually not obvious for setting the recalibration interval.

When no failures have occurred, synthetic age to failures are helpful for making recalibration decisions on the premise that instruments deteriorate with time and use. Straight line deterioration was shown in this paper, but other alternatives are envisioned for power curve wear deterioration, etc. depending on the level of pessimism required.

The cases presented show good cost reduction opportunities using Weibull statistics and commercially available software. The techniques shown are different and controversial. The author welcomes constructive criticism and written alternative strategies for finding and establishing cost effective calibration interval strategies using Weibull techniques when few or no failures have been discovered.

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