ASSOCIATION CONNECTING
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IPC-TM-650
TEST METHODS MANUAL

Number	
1.9	
Subject	
Measurement Precision Estimation for Variables Data	
Date	Revision
01/03	**A**
Originating Task Group	
Measurement Precision Task Group (7-11a)	

1 Scope Tests performed on presumably identical samples under seemingly identical conditions do not always yield identical results. This is due in part to errors inherent in every measurement. During the development of a new test procedure or use of an existing test procedure, this variability must be understood and precautions taken to ensure that it is controlled to within necessary limits. Performance of this test method will help to estimate measurement error and troubleshoot possible causes. It can provide evidence that a new test procedure is suitable for use when submitted for review, or an existing test procedure is capable of measuring the applicable parameter.

This method provides a simple, easy to use, standard procedure for determining the precision of a test method using the average and range method. It can be used on tests that involve measurements that yield continuous data. The calculations shown in this procedure are streamlined versions; useful for situations where up to five repeated readings are taken on each of up to 10 samples by up to 10 test laboratories, operators or test conditions.

This procedure is not useful for measurements which result in binary data, such as pass-fail or go-no go results, or where more than five repeated measurements or more than ten laboratories or conditions are used. These situations are covered under other methods. (see 6.3)

1.1 Definitions

Accuracy (Bias) – The difference between an observed measurement and the true (but perhaps unknown) value being measured (see Figure 1).

Continuous Data – Numerical data that can take any conceivable value within an observed range and forms a distribution about a mean value.

Precision – The closeness to each other of repeated measurements of the same quantity.

Repeatability – Variation of a measurement system that is obtained by repeating measurements on the same sample(s) by the same procedure under the same measurement conditions (see Figure 1).

Reproducibility – Variation among the averages of measurements made under different measurement conditions such as different operators, equipment, and/or locations (see Figure 1).

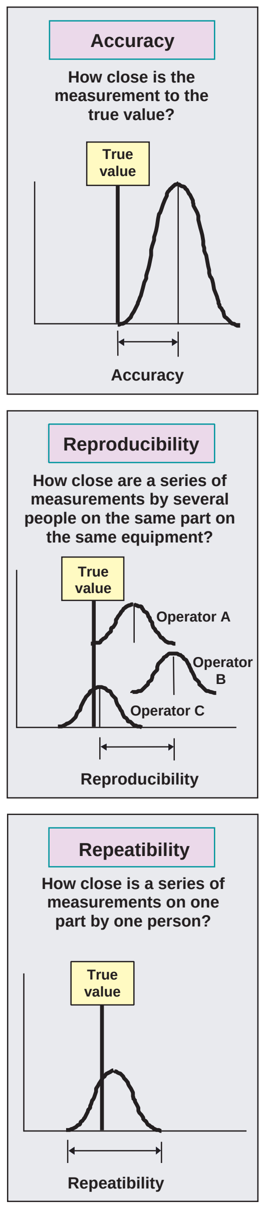

Figure 1 Measurement Repeatibility and Reproducibility

Resolution – The size of the smallest increment on the measurement instrument under examination. This value is frequently used in the advertising literature to classify the instrument.

2 Applicable Documents The applicable document will be the test procedure under evaluation.

3 Test Specimens The test specimens used will be as specified in the test procedure under investigation.

The number and types of test materials to be used will depend on the range of levels in the class of materials to be tested. If it is known that precision is worse at one end of the range, evaluations could be limited to that end of the range. In general, evaluations should be performed on all combinations of materials, levels, test set-ups, and test conditions. If resources are limited, begin the study with those combinations deemed to be the most critical, or where measurement error is likely to be greatest.

The number of samples will also depend on the difficulty involved in obtaining, processing, and distributing the test specimens, the difficulty, length of time required for, and expense of performing the test, and other prior known information.

This test method will assume that measurements can be repeated on the same sample. For situations where this is not possible or the sample is consumed during the test, see 6.3.

4 Apparatus The apparatus used will be as specified by the test procedure under investigation.

The resolution of the measurement apparatus should be sufficient to achieve the desired accuracy of the measurement. For example, if you were to measure mass, and expect to measure it to 1 gm, the balance should be able to measure to at least 0.1 gm.

5 Procedure

5.1 Planning the Evaluation Keep the evaluation as simple as possible to obtain estimates of within and between tester variability that are free of unintended secondary effects. A particular test condition could be different combinations of laboratories, operators, equipment, etc.

Be sure the procedure under evaluation is complete and describes the test parameters as well as recommended techniques for controlling variability. Include known best practices and draw extensively on the experience of test users.

The method used in this procedure allows for up to ten test conditions. Solicit participants from among the community of facilities with the proper test equipment, competent operators and familiarity with the test. In order to obtain representative precision estimates, do not select only from a small group of users who are considered exceptionally qualified. Be sure to specify any special calibration procedures or material preparation requirements.

The analysis method used in this procedure allows up to five repeated measurements per sample. The test samples should be carefully prepared in order to be as consistent and homogeneous as possible. Try to limit the lots of raw materials and processing facilities used. Randomize the samples prior to dividing into test groups. Prepare more than the material required to ensure adequate amount is available for the study in case of lost or damaged specimens, errors, test set-up, etc.

Carefully package and label the samples. Assign serial numbers, if possible. Identify the version of the test procedure and specify care and handling procedures. Provide a data sheet, and describe any documentation required. Require a test log, and insist that all observations of any unusual events be recorded.

5.2 Conducting the Evaluation Ensure the samples are inspected on receipt. Send replacement units if damaged or tests are performed improperly. Follow the documented test procedure carefully to ensure no unusual variation is introduced.

Inspect the data sheets when returned. Review the test logs for unusual events. Review the measurements for level and consistency. Question unusual data points. Incorrect readings and typographical errors must be corrected prior to analysis.

5.3 Analyzing the Data Analysis may be performed on the Measurement Precision data sheet or on other applicable software. A Measurement Precision Calculator has been prepared to perform the calculations using the equations shown below (see 6.5).

This evaluation technique is called the Average and Range Method and partitions the total measurement precision ($S_{R\&r}$) into two portions: the with-in test condition variation, called repeatability (S_r) and between test condition variation, called reproducibility (S_R). The method does this by calculating an estimate of the standard deviation of the measurement repeatability by using the range of the repeated measurements with-in each test condition, and by calculating an estimate of the standard deviation of the reproducibility by using the range between different test condition averages.

For normally distributed parameters, these two standard deviations are combined to estimate the total measurement precision by taking the square root of the sum of the squares.

This method is summarized by equations (1) through (3) below.

$$S_{R\&r} = (S_R^2 + S_r^2)^{1/2} \tag{1}$$

where,

$$S_r = \overline{\overline{R}} \times K_1 / 5.15$$

$$S_R = \left[(R_{\overline{X}} \times K_2)^2 - \left(\frac{28.1 \times S_r^2}{n \times k}\right)\right]^{1/2} / 5.15 \tag{2}$$

and where

$$\overline{\overline{R}} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} R_{ij}}{m \times n} \tag{3}$$

R_{ij} = Range of repeated readings for test condition i and sample j
m = number of test conditions
n = number of samples
$R_{\overline{X}}$ = Range of operator averages - the maximum Test condition average, minus the minimum test condition average.
k = number of repeated readings

The K factors, K_1, K_2, and K_3 are noted in Table 1 below.

Table 1 K Factors

K Factors					
Readings	K_1	Conditions	K_2	Samples	K_3
2	4.57	2	3.65	2	3.65
3	3.04	3	2.70	3	2.70
4	2.50	4	2.30	4	2.30
5	2.21	5	2.08	5	2.08
6	2.03	6	1.93	6	1.93
7	1.90	7	1.82	7	1.82
8	1.81	8	1.74	8	1.74
9	1.73	9	1.67	9	1.67
10	1.67	10	1.62	10	1.62

5.4 Evaluating Process Capability of Measurement System The estimated standard deviation of the total measurement precision, $S_{R\&r}$, can be used to evaluate the capability of the measurement process. This capability assessment is performed by comparing the estimated measurement precision to the specification tolerances and to total product variation.

5.4.1 Capability Assessment 1 – Gage Repeatability and Reproducibility (GRR) The precision-to-tolerance ratio, GRR, shows what percent of the specification window is consumed by measurement uncertainty, and is defined as:

$$GRR = \frac{5.15 \times S_{R\&r}}{USL - LSL} \times 100 \tag{4}$$

where,

USL = upper specification limit and
LSL = lower specification limit

This equation is defined for situations where both specification limits exist. It would not be evaluated where only an upper or lower limit exists. A factor of 5.15 is used to calculate the 99% confidence interval on the total measurement precision. Another commonly used factor is 6 used to represent a 99.975% confidence interval.

5.4.2 Capability Assessment 2 – Precision to Variation Ratio (PV) The precision-to-variation ratio shows what percentage of the total observed product variation can be attributed to measurement uncertainty. It is calculated as follows:

$$PV = \frac{S_{R\&r}^2}{S_T^2} \times 100 \tag{5}$$

Where

$$S_T^2 = S_{R\&r}^2 + S_P^2 \tag{6}$$

And where

$$S_P = R_P \times K_3 \tag{7}$$

R_p = The range between the maximum and minimum part measurement averages. K_3 is noted in Table 1, above.

5.4.3 Measurement Tolerance The measurement tolerance defines a confidence half interval around the measured value using the estimated measurement precision.

$$TOL = 2.57 \times S_{R\&r} \tag{8}$$

The factor 2.57 is used to give the 99% confidence half interval. Thus there is a 99% chance that the true (but unknown) value of the parameter being measured will fall with-in ± TOL of the measured value.

5.5 Preparing Analysis Conclusions Goals for measurement precision should be established before the study begins. The goals should be established using knowledge of the anticipated levels of product variability (or process capability), specifications, customer needs and the possible impact of dispositioning test samples improperly (see 6.4).

As a rule of thumb, the guidelines shown in Table 2 have been extensively applied.

Table 2 Recommended Evaluation Criteria for GRR and PV

GRR and PV	Rating
>30	Needs improvement
10 to 30	Marginal
<10	Acceptable

In this table, test measurement precision would be acceptable if it is less than 10% of the specification width and less than 10% of the total product variation. A test precision that is more than 30% of the specification width, or more than 30% of the total product variation, would need improvement. A test precision more than 10% but less than 30% of specification width or total product variation would represent marginal measurement precision, and should be improved. An illustration of the relationship between specification limits and measurement uncertainty is shown in Figure 2.

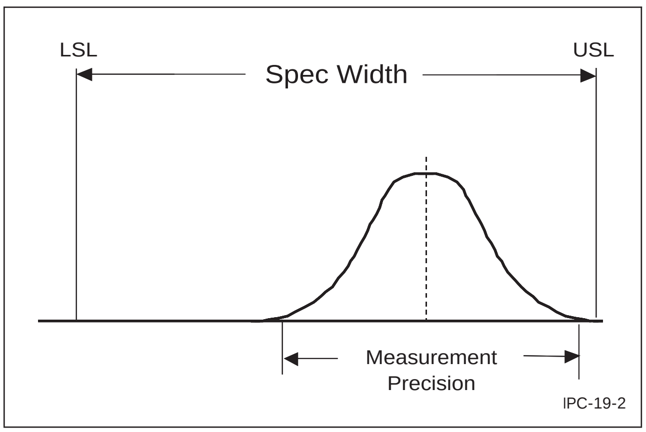

Figure 2 Depiction of the Relationship Between Measurement Precision and the Specification Limits

If measurement precision is judged to be marginal or worse, for either GRR or PV, steps should be taken to reduce the measurement variability. The repeatability and reproducibility estimates can be examined to determine the largest contributor to total measurement uncertainty. If the largest component of variation is repeatability, the cause of variability is with-in a given test condition. Probable causes include problems with calibration, lack of operator controls, excessive within part variation or equipment problems. If the largest component of variation is reproducibility, the cause of variability is between test conditions. The probable causes include difference in test procedural problems test methods, or equipment calibration.

An acceptable GRR or PV value indicates that the test method precision is adequate and should yield data with reasonable certainty.

6 Notes

6.1 Measurement System Properties An ideal measurement system would have a number of properties including the following:

a. The measurement system would have adequate resolution.

b. The measurement system would be in statistical control, the variation in the measurements would be due to common or random causes only, with all special or definable causes removed.

c. The variability of the measurement error would be small when compared to the manufacturing product variability.

d. The variability of the measurement error would be small when compared with the specification limits.

6.2 Sources of Measurement Variation A measurement system may exhibit several types of variation, including the following:

a. *Accuracy (or bias)* – The difference between an observed measurement and the true (but perhaps unknown) value being measured.

b. *Precision* – The closeness to each other of repeated measurements of the same quantity. Precision can be separated into two components:

   Repeatability – Variation of a measurement system that is obtained by repeating measurements on the same sample(s) by the same procedure under the same measurement conditions including the same operator.

   Reproducibility – Variation among the averages of measurements made under different measurement conditions such as different operators, equipment, and/or locations.

c. *Stability (or drift)* – The variation observed when repeating measurements on the same device and the same test set-up, over an extended period of time.

d. *Linearity* – The difference in bias values through the expected operating range of the measurement instrument.

This test method has addressed item 6.2.b above. The other sources of variation are addressed in the references (see 6.4).

6.3 Methods for Analyzing Repeatability and Reproducibility There are several methods for calculating the measurement precision from the data obtained during the measurement precision study. Two of the most commonly applied techniques are applied to measurements that result in variables data, and are called the Average and Range, and ANOVA methods.

a. *Average and Range Method* – This method is covered in this test method and provides an estimate of the standard deviation of the repeatability and reproducibility using the ranges between the highest and lowest measurements in a subgroup. This method allows measurement variability to be decomposed into two components, repeatability and reproducibility. It does not estimate the interaction effects.

b. *The ANOVA (Analysis of Variance)* – This method uses a components of variance technique to decompose the measurement variability into various categories, such as, parts, operators, test equipment, etc. It can calculate the interaction between any of these components. It is more flexible, but is more challenging to calculate. This method generally requires a computer and a certain degree of expertise to interpret. The analysis method is described in the references, see 6.4.

Measurements which result in binary data, such as go and no-go, or pass and fail tests, can be analyzed for consistency and correctness of disposition, see IPC Test Method IPC-TM 1.8.

In some cases, the measurement cannot be repeated more than once on the same sample. This is common where the sample is consumed during the test, such as chemical analysis, or changed during testing, such as solderability evaluations. In these cases, the analysis using a modified average and range method is possible. This method is currently under development.

6.4 References

a. ISO 5725-1 Accuracy (trueness and precision) of measurement methods and results (parts 1 to 6), 1998(E), International Organization for Standardization, Geneva, Switzerland (www.iso.org).

b. Measurement Systems Analysis, 2nd edition, June 1998, Automotive Industry Action Group (AIAG), 26200 Lahser Road, Southfield, MI 48034 (www.aiag.org).

c. Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method, E691-99, ASTM, Philadelphia, PA (www.astm.org).

d. Concepts for R&R Studies, Larry B. Barrentine, (ISBN 0-87389-108-2), ASQC Press, Milwaukee, WI (www.qualitypress.asq.org).

e. Statistical Process Control Guidelines, Texas Instruments, Dallas, TX

f. Introduction to Statistical Process Control, 3rd edition, Douglas C. Montgomery, 1997, John Wiley and sons, ISBN 0-471-30353-4, pages 455-467

g. Basic Statistics, 4th Edition, Mark J Kiemele, Stephen R. Schmidt, Ronald Berdine, Air Academy Press, 1997, ISBN 1-880156-06-7, pages 9-71 to 9-77.

h. ''Is 100% Test 100% Effective,'' W. Russell, 1998 IPC EXPO, San Jose, CA (gives methods for calculating the likely outcomes on product test for differing levels of measurement precision.)

6.5 Software Measurement precision studies are greatly facilitated by use of software to perform the calculations. Below are just a few of the many software packages that can be used for this purpose. Reference (a) is an Excel spreadsheet written to perform the calculations in this procedure.

a. Measurement Precision Calculator, Excel spreadsheet, available at http://www.ipc.org/html/testmethods.htm for free download.

b. Statgraphics Plus, Manugistics Corp, 2115 East Jefferson Street, Rockville, MD, 20852-4999 (www.statgraphics.com).

c. SPC XL, Air Academy Press, 1155 Kelly Johnson Blvd, Colorado Springs, CO 80920 (www.airacad.com).

d. Minitab, Minitab. Inc., 3081 Enterprise Dr, State College, PA 16801 (www.minitab.com).

e. Interlaboratory Data Analysis Software for E691, ASTM, 100 Barr Harbor Dr, West Conshohocken, PA 19428 (www.astm.org).

Measurement Precision Study - Information Sheet

Test Method	
Parameter Measured	
Company	
Name of Study Organizer	
Study Completion Date	
Instrument	
Measurement Units	
Lower Specification Limit, LSL	
Upper Specification Limit, USL	
Number of Conditions, m	
Number of Samples, n	
Number of Repeat Readings, k	

Measurement Precision Study - Data Sheet

Condition A	Reading	Sample										Average
		1	2	3	4	5	6	7	8	9	10	
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_A$ =
	Range											$\overline{R}_A$ =

Condition B	Reading	Sample										Average
		1	2	3	4	5	6	7	8	9	10	
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_B$ =
	Range											$\overline{R}_B$ =

Measurement Precision Study - Data Sheet (continued)

Condition C	Reading	Sample 1	2	3	4	5	6	7	8	9	10	Average
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_C$ =
	Range											$\overline{R}_C$ =

Condition D	Reading	Sample 1	2	3	4	5	6	7	8	9	10	Average
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_D$ =
	Range											$\overline{R}_D$ =

Condition E	Reading	Sample 1	2	3	4	5	6	7	8	9	10	Average
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_E$ =
	Range											$\overline{R}_E$ =

Condition F	Reading	Sample 1	2	3	4	5	6	7	8	9	10	Average
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_F$ =
	Range											$\overline{R}_F$ =

Measurement Precision Study - Data Sheet (continued)

Condition G	Reading	Sample										Average
		1	2	3	4	5	6	7	8	9	10	
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_G$ =
	Range											$\overline{R}_G$ =

Condition H	Reading	Sample										Average
		1	2	3	4	5	6	7	8	9	10	
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_H$ =
	Range											$\overline{R}_H$ =

Condition I	Reading	Sample										Average
		1	2	3	4	5	6	7	8	9	10	
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_I$ =
	Range											$\overline{R}_I$ =

Condition J	Reading	Sample										Average
		1	2	3	4	5	6	7	8	9	10	
	1											
	2											
	3											
	4											
	5											
	Average											$\overline{X}_J$ =
	Range											$\overline{R}_J$ =

Measurement Precision Study – Calculation Sheet

Sample Data

Sample	1	2	3	4	5	6	7	8	9	10	Average Part Average
Part Average											$\overline{\overline{X}} =$
									Max Part Avg		$\overline{X}_{Max} =$
									Min Part Avg		$\overline{X}_{Min} =$
									Range of Part Avgs		$\overline{R}_P =$

Condition Data

Condition	A	B	C	D	E	F	G	H	I	J	Average Condition Range
Average											
Average Range											$\overline{\overline{R}} =$
									Max Condition Avg		$\overline{X}_{Max} =$
									Min Condition Avg		$\overline{X}_{Min} =$
									Range of Condition Avgs		$R_{\overline{X}} =$

Variability Calculations

Topic	Equation	Calculation	Answer
Repeatability	$S_r = \overline{\overline{R}} \times K_1 / 5.15$		$S_r =$
Reproducibility	$S_R = \dfrac{\sqrt{(R_{\overline{X}} \times K_2)^2 - \left(\dfrac{28.1 \times S_r^2}{n \times k}\right)}}{5.15}$		$S_R =$
Total R&r	$S_{R\&r} = \sqrt{S_r^2 + S_R^2}$		$S_{R\&r} =$
Product Variation	$S_P = \overline{R}_P \times K_3 / 5.15$		$S_P =$
Total Variation	$S_T = \sqrt{S_r^2 + S_R^2 + S_P^2}$		$S_r =$

K Factors

Readings	K1
2	4.565603
3	3.041937
4	2.501214
5	2.214101
6	2.03236
7	1.904586
8	1.808922
9	1.734007
10	1.673164

Operations	K2
2	3.652482
3	2.696335
4	2.299107
5	2.076613
6	1.928839
7	1.819788
8	1.739865
9	1.672078
10	1.619497

Parts	K3
2	3.652482
3	2.696335
4	2.299107
5	2.076613
6	1.928839
7	1.819788
8	1.739865
9	1.672078
10	1.619497

Comparisons to Specifications (Used when both specifications exist)

Topic	Equation	Calculation	Answer
% Repeatability	$\frac{5.15 \text{ x } S_r}{USL - LSL} \text{ x } 100$		
% Reproducibility	$\frac{5.15 \text{ x } S_R}{USL - LSL} \text{ x } 100$		
% Measurement R&r	$\frac{5.15 \text{ x } S_{R\,\&\,r}}{USL - LSL} \text{ x } 100$		

Comparisons to Total Variation

Topic	Equation	Calculation	Answer
% Repeatability	$\frac{S_r^2}{S_T^2} \text{ x } 100$		
% Reproducibility	$\frac{S_R^2}{S_T^2} \text{ x } 100$		
% Measurement R&r	$\frac{S_{R \text{ x } r}^2}{S_T^2} \text{ x } 100$		

Measurement Tolerance

Topic	Equation	Calculation	Answer
Tolerance	$\pm 2.57 \text{ x } S_{R\,\&\,r}$		