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Rounding by Patrick O. Moore*

Numbers are everywhere around us. They help us to decide on purchases, to plan our retirement, and to track everything from diet and exercise to services we buy. Numbers in the form of measurements are the lifeblood of industrial inspection. The field of NDT uses numbers to measure every physical phenomenon: electricity, thermal expansion, magnetism, light, pressure, viscosity, and ionizing radiation. For this reason, the NDT inspector needs math.

There are several situations in which a technician may need to round off a measurement datum.

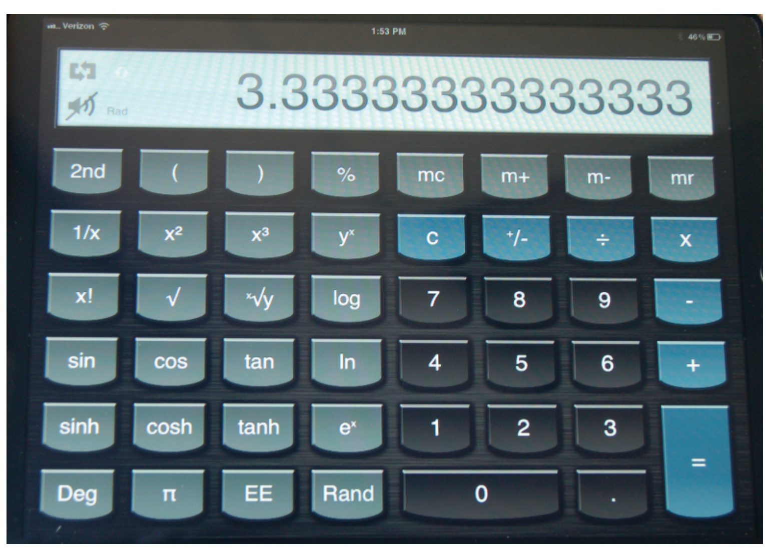
1. Several measurements may be averaged together.
2. A measurement from one system of units may be multiplied by a conversion factor to produce a measurement in another system of units. Microprocessor software such as the calculators preloaded on personal computers frequently provides a menu of metric conversions; your smart phone might too.
3. Fractional measurements today often need to be recorded or expressed digitally, for storage or processing. Changing to decimal expressions usually requires additional digits.
4. A mathematical calculation may give an irrational answer, with too many digits. That occurs, for example, any time a value that is not a multiple of three is divided by three. The same is true whenever a value is multiplied by pi, an irrational number approximately equal to 3.14159, expressed here with only six significant digits.
5. The readout (typically, a liquid crystal display) from a device may provide a numerical datum with too many digits. Programs on computers frequently do this.

A portable magnetic thickness gage typically measures thickness on a magnetic substrate to the nearest hundredth of a millimeter. The technician may be able change the settings to display only the desired number of digits, but how many should that be? To answer that question, the technician needs to understand the limits of his test equipment, as well as significant digits, the number of digits in a datum that express meaningful information rather than the mathematical noise of calculation.

Much more could be said about the mathematical idea of significant digits, but not here. Good tutorials are in many math textbooks and are easy to find online. A good one has been posted by a chemistry professor Frederick Senese of Frostburg State University, Maryland.

Precision and Accuracy

The terms *precision* and *accuracy,* and *precise* and *accurate,* can cause confusion if their meanings are not clear and defined, with reference as needed to specifications or standards. In statistics, several measurements of a given measured thing are called "precise" if they agree closely with each other, that is, if the values fall close to each other. Also in statistics, measurements are called "accurate" if they agree closely with the actual value. The explanation of these terms is provided in NIST TN 1297[1] and repeated in JCGM 200, IEEE/ASTM SI 10, and NIST SP 811.[2-4]



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The word *precision,* however, is commonly used in a different sense, analogous to *resolution* in imaging or *tolerance* in gaging. That is how it is used below. Precision can be communicated through care with significant digits, as well as by tolerances noted after a plus-and-minus sign in a measurement.

A spreadsheet program like Excel or Numbers lets you set the number of digits displayed, but some basic calculators do not. The most familiar rule of thumb with significant digits is that, when you multiply two or more values together, the product must not be more precise than the least precise multiplier.

Metric Conversions

Suppose you are working with an old specification that calls for a measurement to the nearest "mil," or thousandth of an inch, 0.001 in. But your overseas customer wants your procedure to specify millimeters, not inches. There are 25.4 millimeters in an inch (0.001 in. = 25.4 µm = 0.0254 mm), and keeping to the same degree of precision you would then need to round to the nearest hundredth of a millimeter.

A quick check of ultrasonic thickness gages shows that most offer a resolution to the nearest hundredth of a millimeter or thousandth of an inch. The user can toggle this setting to display the measurement in either system or with some other number of significant digits. Some systems are called more precise and boast measurements to the nearest micrometer (or to the nearest ten thousandth of an inch). The displayed resolution is a system default, so the inspector does not have to calculate significant digits.

It will take a moment to compare the columns in Table 1. The first column lists fractional measurements as are sometimes found today in old specifications, in which the inspector must trust to experience, common sense, or precedent to know the desired degree of precision. However, the log of maintenance history shows that thickness measurements have been desired to the nearest 10^{-3} inches, as in the second column. How then will the inspector convert and record the old measurements to millimeters? Rounding to 10^{-3} millimeter (third column) is too precise: there are 25.4 mm per inch, which is more precise by one significant digit. But to round off to the nearest tenth of a millimeter (fourth column) is too imprecise. The history shows the measurements had been rounded to the nearest 10^{-3} inch, roughly the width of a hair, very fine indeed. So we must settle on a hundredth of a millimeter (the final column), which for us, is probably just right. Why qualify that answer with the word "probably"? Because the precision desired always depends on the customer's specifications and acceptance criteria.

Precision of Datum Should Not Exceed Precision of Instrument

The assessment and recording of some measurements entail calculation — if not to convert the measurement system, then to calculate an angle of refraction, to revise an old specification with newer units, or to arrive at an average if more than one reading is taken. When the instrument is not doing the math automatically, the inspector must decide how many digits to record. This decision calls for an understanding of significant digits.

Occasionally a novice inspector or student will copy a converted value from a display readout and record an absurdly precise measurement, for example, a thickness reading with 11 numerals to the right of the decimal point. Such resolution would be the thickness of a hydrogen atom — if atoms had thickness. That's ridiculous, of course. No instrument used for NDT is that precise. What the novice needs to do is round off the measurement to a value that makes sense, that does not imply a greater precision than the sensor and instrument can provide.

The following example may sound familiar. Let's suppose an old specification calls for a coating thickness of at least 3/64 inch. That digitizes to 0.046875 inches or exactly 1.190625 mm. The original spec was written in 1957, however, and was written for a gage that measured to the nearest mil, or thousandth of an inch. Yet suddenly you are recording a measurement to the nearest millionth — far too precisely!

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Table 1. Too many, too few and correct number of rounding digits: conversion of inches to millimeters.

inches		millimeters		
fraction with unspecified precision	with 10^{-3} precision	too precise	too rounded	just right
1	1.000	25.400	25.4	25.40
5/32	0.156	3.969	4.0	3.97
3/16	0.188	4.763	4.8	4.76
3/8	0.375	9.525	9.5	9.53
7/8	0.875	22.225	22.2	22.23
1 3/8	1.375	34.925	34.9	34.93
1 9/16	1.563	39.688	39.7	39.69

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The equipment in question, your old gage, cannot resolve measurements so finely.

Always Calculate with All Available Digits before Rounding

In another example, let's suppose for a pressure test you are increasing a vessel's pressure by 55 pounds per square inch. To convert that to kilopascals, you multiply by roughly seven:

$$\text{(1)}\quad 55\ \text{lb}_f/\text{in.}^2 \times 7 = 385\ \text{kPa}$$

This measurement can give you a rough idea, and you may be able to do it in your head. The more precise conversion factor is 6.894757, and this is the best conversion factor to use:

$$\text{(2)}\quad 55\ \text{lb}_f/\text{in.}^2 \times 6.894757 = 379.21164\ \text{kPa}$$

Then you can round it off to the desired number of digits. Notice that using more digits gives a more accurate product: 379 rather than 385. If you use increments of ten (two significant digits), for example, you would round to 380 rather than 390. Whether that difference is meaningful would depend on how precise your measurements are expected to be.

Table 2 illustrates this idea: several examples show that multiplying with more digits sometimes produces greater accuracy. In short, calculate with all the digits you can; the recorded sum, however, should include only significant digits.

Table 2. Calculating with more digits produces greater accuracy.

$\text{lb}_f/\text{in.}^2$	× 7 to kPa	× 6.894757 to kPa	× 6.894757 rounded
45.00	315	310.26407	310
49.00	343	337.84309	338
50.00	350	344.73785	345
55.00	385	379.21164	379

Summary

In calculating and reporting measurements, care must be given to expressing values with a precision that does not exceed the resolution of the test equipment. This care requires both a mathematical understanding of significant digits and an appreciation of what sort of data are needed and possible from the sensors. A reasonable and useful number of significant digits should be reflected in the instrument settings, and this resolution may be specified in the written test procedure.

A comprehensive discussion of measurement units for nondestructive testing can be found in Volume 10 of the *NDT Handbook*, third edition.[5]

References

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2. JCGM 200, *International Vocabulary of Metrology — Basic and General Concepts and Associated Terms (VIM).* Sèvres, France: Bureau International des Poids et Mesures (2012).
3. IEEE/ASTM SI 10, *Standard for Use of the International System of Units (SI): The Modern Metric System.* New York, NY: IEEE (2011).
4. Thompson, A. and B.N. Taylor. NIST SP 811, *Guide for the Use of the International System of Units (SI).* Gaitherburg, MD: National Institute of Standards and Technology (2008).
5. *Nondestructive Testing Handbook,* third edition: Vol. 10, *Nondestructive Testing Overview.* Columbus, OH: American Society for Nondestructive Testing (2012): p 19-29.