APPENDIX

Uncertainties as determined from Calibrations

We wish to determine what uncertainty in test data to charge to a test instrument, based on the root-mean-square difference between successive calibrations on the same test instrument.

It is in order to assume that most of this difference, \( \Delta \), is caused by the test instrument. Suppose that the uncertainty of the test instrument itself whenever it is being used is only twice the uncertainty of the rest of the calibration setup. We can remove the uncertainty of the rest of the setup as the square root of the difference of the squares. Then we have the uncertainty of the test instrument, as used during a test, as \( \sqrt{\Delta^2 - \gamma^2} \) or 0.63 \( \Delta \).

If we have before-test and after-test calibrations, we may use their average for calculating test results. The uncertainty of this average of two calibrations can be estimated as 1.00 \( \Delta / \left( \sqrt{2} \sqrt{2} \right) \) or 0.50 \( \Delta \).

In each steam-consumption test, each instrument is read ten or more times on each of three or more runs. This reduces the uncertainty of those types of test instruments for which much of the calibration uncertainty may occur in reading the test instrument. This tends toward making the uncertainty of the test use of the test instrument somewhat less than the calibration uncertainty of the instrument itself, say, to 0.90 times \( \Delta \), or to 0.57 times the difference between two calibrations.

We will not distinguish between the accuracy with which calibration personnel and test personnel read a test instrument; presumably, calibration personnel read more carefully, but we have test-directing engineers observing the test readings for accuracy.

We can combine the uncertainties from one or two calibrations with the uncertainty from the use of the test instrument in a test, getting:

\[ \epsilon_1 = \sqrt{(0.57 \Delta)^2 + (0.71 \Delta)^2} = 0.91 \Delta \]

for a once-calibrated instrument, and

\[ \epsilon_2 = \sqrt{(0.57 \Delta)^2 + (0.5 \Delta)^2} = 0.76 \Delta \]

for a twice-calibrated instrument.

Discussion

N. R. Deming. 3 In presenting this description of test instruments and their calibrations the author has summarized for the electric-utility industry a wealth of testing “know how” accumulated over the years by his company in conducting precision economy tests on steam turbines of different sizes. Although he refers to tests on medium-sized units, most of the instruments and techniques described are equally applicable to tests on the largest central-station units. With the increasing amount of attention being given to the thermal performance of units this paper will be received with much interest.

According to the author’s 1954 paper (author’s reference 1), most of the tests referred to were conducted to obtain engineering data. The same instruments, with exception of the weigh tanks, however, were used in those tests required by the turbine purchaser. Thus use of the instruments described in this paper is not limited to the laboratory but extends to operating power plants when precision tests are desired.

Since the paper is sponsored by the ASME Power Test Codes Committee, it has been suggested that it would be appropriate to compare the instruments and methods described therein with those specified by the ASME Test Code for Steam Turbines. A general observation is that most of the instruments used by the author are mentioned either in the code or in the supplements on instruments and apparatus but that in many cases the author has established additional or more exacting standards of design specification and performance not covered by the code. A few examples will illustrate.

Weighted Flow. Two of the most important parts of water weighing are the accuracy of the scales and the measurement of the time intervals for each tank. The code states that weighing scales shall be checked prior to the test and caused to weigh with an accuracy within \( 2 \) in 1000. The author indicates that his scales are more accurate than this without calibration and that after the calibration is taken into account the remaining uncertainty is only \( 1 \) in 10,000.

With respect to measurement of the time interval the code requires that the time of diversion of water flow from one tank to another shall be determined to within \( 2 \) sec. The author has found that a trained operator can read this time to the nearest half second when automatic equipment is employed to do the switching.

Power. Apparently it is not so easy to meet the code requirements with respect to the magnitude of the permissible wattmeter calibrations. The great majority of the differences in the author’s Fig. 2, and also the root-mean-square values lie within a range of 0.1 per cent of full scale reading. There are several points where the difference is greater, but less than 0.3 per cent, the value at which the code requires further comparisons or even test rejection.

Temperature. The author’s choice of 6-in. immersion for thermocouples coincides with the recommendation in the code.

Chromel-constantan for thermocouples is not one of the pairs of metals suggested by the code, but no doubt one reason for the use of these two materials is the much greater emf they will generate. This amounts to about 70 per cent more than for the chromel-alumel combination and 40 per cent more than for the iron-constantan combination at the level of modern throttle temperatures. Of course this reduces the uncertainty in the temperature measurement.

It is interesting to note that in the code the use of standard melting points as a means of calibration is specifically not recommended for test-code accuracies, the reason given being difficulty in manipulation.

Pressures. No test code deals at length with pressure-measuring instruments and test connections. However, no limits on the magnitude of dead-weight gage calibrations or on the variation between successive calibrations are given.

The author’s instruments for measuring exhaust pressure conform with the code with respect to inside diameter of glass tubes and the use of orifrice disks.

Flow Nozzles. The code places the limit of possible error in flow measurement by either a flow nozzle or a thin-plate orifice at \( \pm 1.50 \) per cent and \( \pm 1.25 \) per cent for steam and water, respec-

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tively. No distinction is made as to type of primary element and no mention is made of calibrations.

The author does not say what methods, if any, are used to minimize the amount of pulsations of the mercury in the manometers used to measure the pressure drop across a flow nozzle. The code does prohibit attempts to reduce pulsations by damping means. However, solenoid-operated valves are currently being used in some tests to stop the pulsations completely at precisely measured time intervals to allow the observer to take careful readings.

Station Instruments. The author points out the uncertainty to be expected in the use of station instruments. Evidently greater errors can be expected in the measurement of power than in flow measurement. The errors are greater for steam flow than for condensate flow and greater when station meters are used rather than test manometers.

It may be that the Power Test Codes Committee will want to consider review of the code and make revisions to reflect current practice in running precision tests.

W. A. Pollock. This paper presents a very good outline of the steps which are necessary to obtain the desired reliability and accuracy from instruments used in turbine tests.

The author reports the percentages of uncertainty of measurements of flow, power, temperature, initial pressure, exhaust pressure, and the corresponding effect on over-all turbine efficiency.

It is quite evident that he is well aware of the difficulty of obtaining a close approach to so-called absolute accuracy. He describes the painstaking efforts that are made to insure precise measurement. He appreciates that to gather doubtful data is a waste of time and expense when positive methods can be used.

We are reminded that instruments of a high quality are essential, first to obtain the best accuracy, and then to retain this accuracy as long as possible. A high degree of accuracy is essential not only in tests to determine if the turbine meets its guaranteed heat rate, but also in those conducted later to determine the possible need for turbine maintenance.

Instrumentation for daily turbine operation requires ruggedness and reliability with some sacrifice of accuracy, but for testing a turbine accuracy should come first, within practical limitations, of course.

The most important measurements are those of input flow and output power. Measurement of condensate flow by weighing tanks is more accurate than by flow nozzles and their use in owner plants should be encouraged wherever possible.

AUTHOR'S CLOSURE

The author wishes to thank Messrs. Deming and Pollock for their comments. Mr. Deming's comparisons of the accuracies of these tests with those in the ASME code are quite interesting.

In answer to Mr. Deming's inquiry, the flow-nozzle manometer connections were open during each test run, with no dampers or quick-closing valves.

Mr. Deming comments that apparently station instruments are less accurate for measuring power than flow; this is true in the data in Table 1. On the other hand, the data in Fig. 11 are typical of what we often find in flow measurements by station instruments.