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Guidance for Evaluation of Measurement Uncertainty in Performance Tests of Steam Turbines

A Report by
Performance Test Code Committee No. 6
on Steam Turbines

PERFORMANCE
TEST
CODES
REPORT

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center
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Guidance for Evaluation of Measurement Uncertainty in Performance Tests of Steam Turbines

PERFORMANCE TEST CODES

ANSI/ASME PTC 6 Report-1985

SPONSORED AND PUBLISHED BY

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FOREWORD

(This Foreword is not part of ANSI/ASME PTC 6 Report-1985.)

The Test Code for Steam Turbines, ANSI/ASME PTC 6-1976 (R1982), hereafter called "the Code," provides for the accurate testing of steam turbines for the purpose of obtaining a minimum-uncertainty performance level. The Code is based on the use of accurate instrumentation and the best available measurement procedures. Use of test uncertainty as a tolerance to be applied to the final results is outside the scope of the Code. Such tolerances, if used, are chiefly of commercial significance and subject to agreement between the parties to the test.

It is recognized that Code instrumentation and procedures are not always economically feasible or physically possible for specific turbine acceptance tests. This Report provides guidance to establish the degree of uncertainty of the test results. Increased uncertainties due to departures from the Code procedures are also discussed.

The Report provides estimated values of uncertainty that can be used to establish the probable errors in test readings during steam turbine performance tests. It is recognized that the statistical method presented in this Report is different from and much simpler than the method presented in ANSI/ASME PTC 19.1-1985. ANSI/ASME PTC 19.1-1985, Measurement Uncertainty, includes discussions and methods which enable the user to select an appropriate uncertainty model for the analysis and reporting of test results. For the purposes of this Report, the committee has used a simplified version of the root sum square model presented in ANSI/ASME PTC 19.1. The possible errors associated with steam turbine testing are expressed as uncertainty intervals which, when incorporated into this model, will yield an overall uncertainty for the test result which provides 95% coverage of the true value. That is, the model yields a plus/minus interval about the tested value which can be expected to include the true value in 19 instances out of 20. It should be noted that, in general, measurement errors consist of two components — a fixed component, called the bias or systematic error, and a random component, called the precision or sampling error. Since Statistics deals with populations which are essentially randomly distributed, in a strict sense, only the random component is amenable to statistical analysis. Consequently, as illustrated in ANSI/ASME PTC 19.1-1985, the two error components should be treated separately throughout the uncertainty analysis and combined only in the calculation at the final test uncertainty after the individual error components have been propagated, through the use of the appropriate sensitivity factors, into the final result.

In compiling the possible errors associated with the myriad of measurements required for steam turbine performance testing, the committee has used the consensus of people knowledgeable in the field based on information published in the various documents of the PTC 19 series on Instrument and Apparatus Supplements and gleaned from numerous industry tests and manufacturers' supplied data. Unfortunately, the detailed information on these measurement errors which would allow separation into their fixed and random components is not available. Consequently, the accuracies associated with the various measurement devices and

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techniques given in Section 4 are expressed as uncertainty intervals providing 95% coverage and as such are presumed to include both the fixed and random components. In keeping with this simplifying assumption, the calculations described in Section 5 do not differentiate between fixed and random errors in the computation of the uncertainty of the final result. Accordingly, as stated in Section 5, caution should be used in applying statistical techniques such as reducing instrument errors by the use of multiple instruments or sampling errors by increasing the number of sampling locations, without sufficient knowledge of the relative importance of the fixed and random error components.

After approval by Performance Test Codes Committee No. 6 on Steam Turbines, this ANSI/ASME PTC 6 Report was approved as an American National Standard by the ANSI Board of Standards Review on November 27, 1985.

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This Report describes alternative instrumentation and procedures for use in commercial performance testing of steam turbines. Such tests do not fulfill the requirements of PTC 6 and cannot be considered acceptance tests unless both parties to the test have mutually agreed PRIOR TO TESTING, preferably in writing, on all phases of the test that deviate from PTC 6.

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ASME PERFORMANCE TEST CODES
Report on
GUIDANCE FOR EVALUATION OF MEASUREMENT UNCERTAINTY IN PERFORMANCE TESTS OF STEAM TURBINES

SECTION 0 — INTRODUCTION

0.01 ANSI/ASME PTC 6-1976 (R1982), Test Code for Steam Turbines (hereafter called "the Code"), provides for the accurate testing of steam turbines for the purpose of obtaining a minimum uncertainty performance level. The Code is based on the use of accurate instrumentation and the best available measurement procedures and is recommended for use in conducting acceptance tests of steam turbines.

0.02 For reasons of expediency and economics, alternative instrumentation and procedures are sometimes considered and frequently used. In such cases, prior agreement is necessary between the parties to a test on all phases of the test that deviate from PTC 6 if the results are compared with expected performance. Such alternatives affect the accuracy of the test results. The magnitudes of the resultant errors and their effects on the final results become subjects to be resolved between the parties to the test. It is recommended that the parties discuss and agree on all deviations from PTC 6 during the design and planning stage if at all possible. In no case should a test be started, where the results are compared to expected performance, without prior agreement. It is the intent of this Report to provide guidance to the parties to the test in arriving at values of uncertainty based on industry tests and statistical treatment of the data.

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SECTION 1 — OBJECT AND SCOPE

1.01 The object of this Report is to provide guidance for the parties to the test to establish the degree of uncertainty of the test results when there are deviations from requirements of PTC 6.

1.02 The parties to the test should become familiar with the Code. Since this Report does not contain a complete test procedure, it should be used only in conjunction with the Code. Compliance with the Code is expected where no alternative is shown in this Report.

1.03 In this Report, numerical values have been assigned to the uncertainty of instruments of various qualities. These numerical values, representing the consensus of knowledgeable professional people, cover 95% uncertainty intervals and therefore will be exceeded, on average, in one instance in 20.

1.04 Some of the references used in compiling these values are given in Section 6.

SECTION 2 — DESCRIPTION AND DEFINITION OF TERMS

2.01 The nomenclature given in Section 2 of the Code shall apply.

2.02 In this Report, *uncertainty* is a possible value of error selected by the Committee and is expected to be exceeded in not more than one instance in 20. *Error* is defined as the difference between the true value and the corrected value based on the instrument reading.

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SECTION 3 — GUIDING PRINCIPLES

3.01 When a test not in accordance with the Code is planned, the parties to the test must agree on the expected uncertainties in the test readings prior to the test and determine the expected overall combined uncertainty of the test results.

3.02 Numerical values to be used as guidance for agreement on instrumentation are given in Section 4 of this Report. Procedures for calculating the combined uncertainty of the test results are given in Section 5.

3.03 Calibration of Instruments. Instrument calibration plays an important role in the reduction of test uncertainty by minimizing fixed biases or displacement of measured values. In performance testing, *calibration* is defined as the process of determining the deviation of indicated values of an instrument or device from those of a standard with known uncertainty traceable to the National Bureau of Standards. A calibration should cover the range for which the instrument is used. The increment between calibration points and the method of interpolation between these points shall be selected to attain the lowest possible uncertainty of the calibration.

Tabulated data and a plot of the observed deviations for a series of measurements over a range of expected test values, and the values obtained from the instrument being calibrated, may be used as calibration data for determining the correction applied to a test value. The calibration report should be signed by a responsible representative of the calibration laboratory. When a formal report is required, the calibration report should include the identification of the calibration equipment and instruments, a description of the calibration process, a statement of uncertainty of the measuring standard, and a tabulation of the recorded calibration data.

Flow measuring devices shall be calibrated assembled with their own upstream and downstream pipe sections including flow straightener and recovery cone where applicable. If the existing calibration facilities cannot cover the entire range of Reynolds numbers expected during a test, extrapolation of the calibration data is permissible in accordance with Code Par. 4.33.

With accuracy ratio defined as the accuracy of the measuring standard compared to accuracy of the instrument being calibrated, a ratio of 10:1 is recommended for calibration work. New development of extremely accurate test instruments may necessitate lowering this ratio to 4:1.

Consideration shall be given to the calibration environment. Even under laboratory conditions, the measured quantity and the measuring instruments can be influenced by vibration, magnetic fields, ambient temperature, fluctuation, instability of the voltage source, and other variables.

3.04 If Code procedures relative to frequency of readings, allowable variation in test readings, and prescribed limits for cycle leakages cannot be established for the test, agreement must be reached to estimate the probable increase in uncertainty.

3.05 Frequency of Readings and Duration of Test. The frequency at which test readings are recorded and the running time required for a test is determined by the time variability in the test data [see Par. 5.02(b)]. When a test that deviates from the Code instrumentation requirements is run with a mutually agreed upon pretest uncertainty, the effect due to time variability must be minimal to prevent an increase in this uncertainty. To avoid an appreciable effect on the pretest uncertainty, Fig. 3.1 can be used as a guide to establish the maximum time variability effect each measured parameter may have on the results. This figure, used with Fig. 3.2 and Table 3.1, provides a means for estimating the number of readings required for a test to achieve this. An example for the use of Figs. 3.1 and 3.2 is given in Par. 5.12. The derivation of Fig. 3.2 is given in Appendix II in this Report. Nomenclature used in Fig. 3.2 are as follows.

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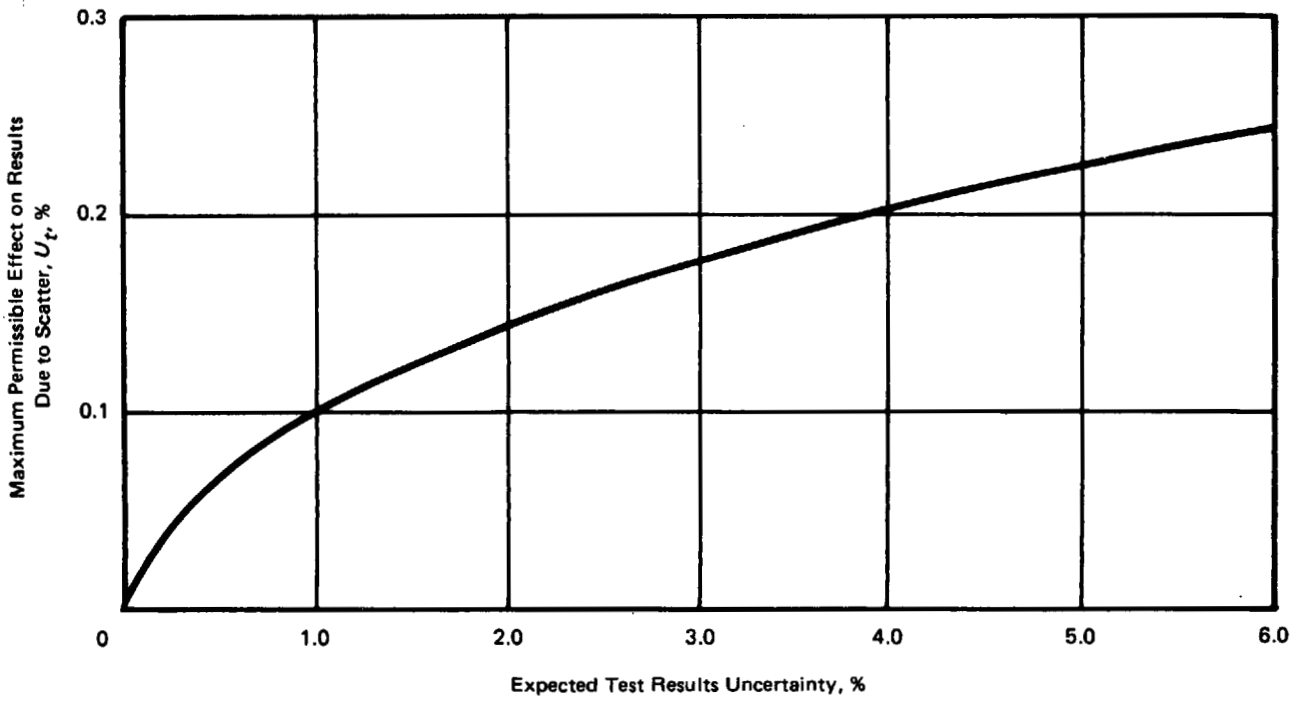


FIG. 3.1 MAXIMUM RECOMMENDED VALUES FOR THE EFFECT OF TEST DATA SCATTER ON TEST RESULTS FOR EACH TYPE OF MEASUREMENT

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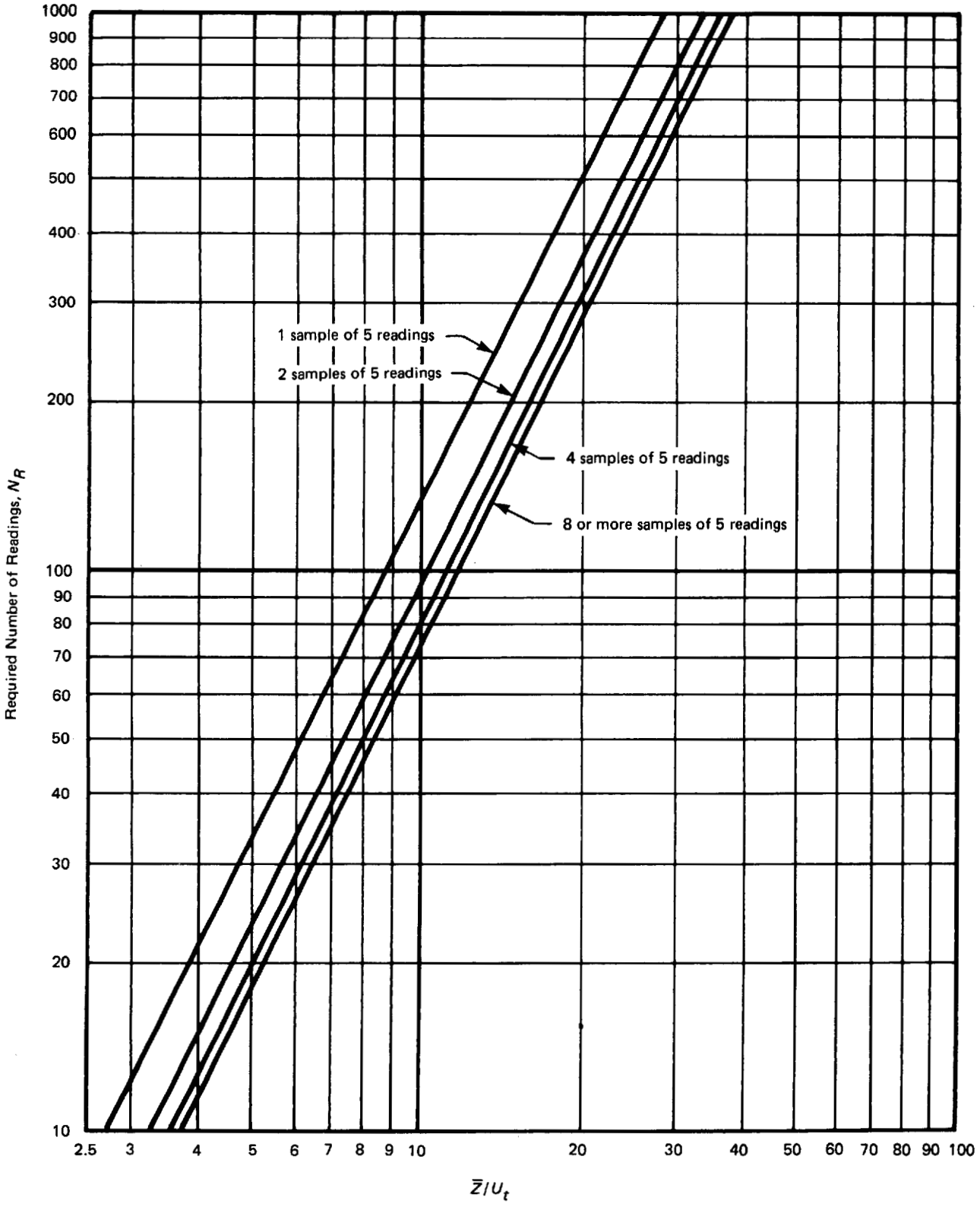


FIG. 3.2 REQUIRED NUMBER OF READINGS FOR MINIMUM ADDITIONAL UNCERTAINTY IN THE TEST RESULTS CAUSED BY TEST DATA SCATTER

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$\bar{Z}$ = effect of instrument readings (average range) on the test results for the number of samples of five readings being considered, expressed as:

$$\frac{\text{average of } \theta_1 (I_{max} - I_{min})\ 100}{0.5(I_{max} + I_{min})}$$

or average of $\theta_2 (I_{max} - I_{min})$

where

θ_1 = influence factor from Table 3.1 effect per percent of reading

θ_2 = influence factor from Table 3.1, effect per unit of reading

$I_{max} - I_{min}$ = maximum minus minimum readings in each sample of five readings being considered

$0.5(I_{max} + I_{min})$ = approximately the average of the five readings. A scanned average can be substituted for this term.

U_t = maximum permissible effect on results due to test data scatter, percent, from Fig. 3.1

TABLE 3.1
θ_1 AND θ_2 INFLUENCE FACTORS FOR CALCULATING $\bar{Z}$ FOR FIG. 3.2

Type of Data	θ_1	θ_2
Power	1.0	...
Flow (volumetric) by weigh tanks	1.0	...
Flow by flow nozzle differentials	0.5	...
Steam pressure and temperature	$\theta_1' + \theta_1''$	$\theta_2' + \theta_2''$
Feedwater temperature	...	θ_2''
Exhaust pressure	θ_1'	θ_2'

GENERAL NOTES:
(a) θ_1 is expressed as percent effect per percent of instrument reading.
(b) θ_2 is expressed as percent effect per unit of instrument reading.
(c) θ_1' and θ_2' are the slopes of the correction factor curves.
(d) θ_1'' and θ_2'' are used to take into account the effect of the instrument reading range for variability with time in measurements used to establish any enthalpy appearing in the heat rate equation. For θ_1'' and θ_2'' values, use the applicable Figs. 5.4, 5.5, 5.6, or 5.7 after converting the ordinate to percent effect per percent of absolute temperature for θ_1'' or percent effect per unit of reading for θ_2''.

TIMING OF TEST

3.06 Regardless of the calculated uncertainty agreed to for an acceptance test, the timing of the test should conform to Par. 3.04 of the Code. Timely testing will minimize additional uncertainty in the turbine performance due to normal-operation deterioration and deposit buildup.

3.07 The following guidelines for timing the test, listed in the order of preference, should be considered before testing.

(a) The test should be conducted as soon as practicable after initial startup per Code recommendations.

(*b*) If the tests must be delayed, they should be scheduled immediately following an inspection outage, provided any deficiencies have been corrected during the outage.

(c) If (a) and (b) are impossible, the condition of the unit can be determined by:

(*1*) comparing results of an enthalpy-drop efficiency test run on turbine sections in the superheat region with startup enthalpy-drop test results, to provide guidance on the action to be taken;

(2) reviewing operating and chemistry logs;

(3) reviewing operating data on pressure-flow relationships, particularly for first stage shell, reheat inlet, crossover, and extraction sections;

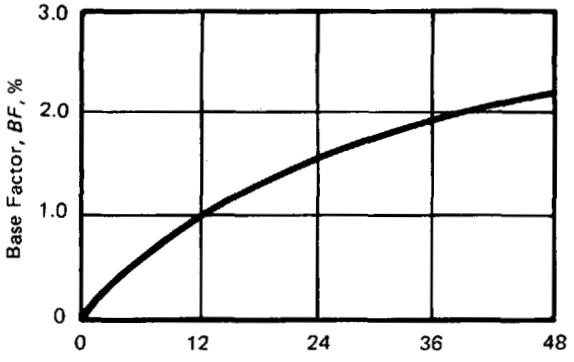
(*4*) inspecting flow measurement elements in the cycle for deposits; and

(*5*) inspecting the last stage from the exhaust end.

(*d*) If no initial operation benchmark data is available, the actual overall deterioration cannot be determined. However, if there is reasonable assurance that the unit has not been damaged and is free of excessive deposits, an estimated value of deterioration may be established by mutual agreement and taken into account in the comparison of the test results with guarantees.

For guidance purposes, Fig. 3.3 may be used to establish an estimated value of deterioration for turbines operating with superheated inlet steam. This curve is based on industry experience and represents an average expected deterioration for units with a history of good operating procedures and water chemistry. The curve was developed from the results of enthalpy-drop efficiency tests run periodically on a number of turbines of various sizes. The method cited in Appendix III, Ref. (13) was used to determine the effect of deterioration on the heat rate. The estimated deterioration was calculated using the enthalpy-drop test data on high pressure and intermediate pressure sections, and assuming

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GENERAL NOTES:

(a) Estimated percent deterioration in heat rate after N months of operation =

$$\frac{BF}{\log MW}\sqrt{\frac{\text{initial pressure, psig}}{2400}}\quad (f)$$

where

MW = megawatt rating of turbine
f = 1.0 for fossil units
= 0.7 for nuclear units

(b) Periods during which the turbine casings are open should not be included.

(c) This curve is for guidance purposes when no other data for establishing deterioration is available.

(d) Correct operation and good water chemistry practices notwithstanding, conditions beyond the operator's control may cause a greater heat rate deterioration than predicted by this curve.

FIG. 3.3 BASE FACTOR, %

that the low pressure section deterioration was one-half of the intermediate pressure section deterioration. The volumetric flow and size indicators were then factored into the mean of this data to develop the curve. The curve applies to both reheat and nonreheat fossil-fired units using an f factor of 1.0. A study of performance data on nuclear units published by the Nuclear Regulatory Commission indicates that the average expected deterioration of nuclear units is 0.7 times that expected on fossil-fired units. The Fig. 3.3 curve and formula multiplied by the factor 0.7 can, therefore, be used to predict the estimated percentage deterioration in heat rate of nuclear units with a history of good operating procedures.

As an example, to estimate the deterioration of a 150 MW, 1800 psi turbine with 12 months of normal operation, using Fig. 3.3, read the base factor from the curve at $N = 12$. Then calculate the estimated deterioration by the formula given with the figure using an f factor of 1.0 for fossil units. Using a base factor of 1.0 as read off the curve at $N = 12$, the estimated heat rate deterioration is 0.4%, determined thus:

$$(1.0/\log 150)\sqrt{(1800/2400)}\,(1.0) = 0.4\%$$

(e) For units with a history of detrimental incidences, the amount of deterioration cannot be determined and the course of action or the determination of deterioration allowance must be mutually agreed upon between the parties involved in the test. Examples of detrimental incidents are:

(1) existence of any turbine water induction incidents

(2) unusual shaft vibration and balance moves

(3) abnormal conductivity in the condenser hotwell

(4) excessive boiler water silica content

(5) presence of large excursions in throttle and reheat temperatures

(6) evidence of boiler tube exfoliation

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SECTION 4 — INSTRUMENTS AND METHODS OF MEASUREMENT

4.01 Paragraph 4.01 of the Code recognizes that special agreements may be needed. When it is agreed to deviate from Code requirements, this Report provides the basis for evaluating the influence of such special agreements and establishing the resultant loss of accuracy. The parties to a test must realize that the loss in accuracy will cause an increase in the uncertainty in the test results, and this must be recognized in the interpretation of the results.

4.02 The general instrumentation and location requirements outlined in Par. 4.03 of the Code should be followed, but variations in type may be used. The alternatives are discussed in the appropriate Sections of this Report.

MEASUREMENT OF THREE-PHASE AC ELECTRICAL OUTPUT

4.03 General Contents. The accuracy of three-phase power or energy measurement depends on the proper application of metering systems (either wattmeters or watthour meters) and the accuracy of all the devices used in the measurement. This Section discusses the following:

(*a*) types of generating system connections, applicable metering methods and uncertainties;

(*b*) alternative metering methods and uncertainties;

(*c*) meter constant and reading uncertainties;

(*d*) instrument transformers and their metering uncertainties;

(*e*) uncalibrated station meters and their metering uncertainties;

(*f*) overall uncertainty of power measurement.

4.04 Types of Generation System Connections and Applicable Metering Methods and Uncertainties. Blondel's Theorem for the measurement of electrical power or energy states that in an electrical system of N conductors, $N - 1$ metering elements are required to measure the theoretically true power or energy of the system. (This assumes ideal instruments and instrument transformers.) It is evident, then, that the connection of the generating system governs the selection of the metering system.

Connections for three-phase generating systems can be divided into two general categories: three-phase, three-wire connections with no neutral return to the generating source and three-phase, four-wire connections with the fourth wire acting as a neutral current return path to the generator.

To aid in the identification of the generating system connection, the following discussion describes some of the different types of three-phase, three-wire and three-phase, four-wire generator connections that are used.

(*a*) The most common three-phase, three-wire system consists of a wye connected generator with a high impedance neutral grounding device. The generator is connected directly to a generator transformer with a delta primary winding. Load distribution is made on the secondary, grounded wye side of the transformer [see Fig. 4.1(a)]. Load unbalances on the load distribution side of the generator transformer are seen as neutral current in the grounded wye connection. However, on the generator side of the transformer, the neutral current is effectively filtered out due to the delta winding, and a neutral conductor is not required.

An ungrounded wye generator is less common than the high impedance grounded wye generator, but when used with a delta-wye grounded transformer, it is also an example of a three-phase, three-wire generator connection [see Fig. 4.1(a)].

A final example of a three-phase, three-wire generation connection is the delta connected generator. The delta connected generator has no neutral connection to facilitate a neutral conductor; hence,

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it can only be connected in a three-wire connection [see Fig. 4.1(b)].

(*b*) Three-phase, four-wire generator connections can be made only with a wye connected generator with the generator neutral either solidly grounded or, more typically, grounded through an impedance. Load distribution is made at generator voltage rather than being separated from the generator by a delta-wye generator transformer. This type of connection has a separate fourth conductor that directly connects the generator neutral (or neutral grounding device) with the neutral of the connected loads [see Fig. 4.1(c)].

(*c*) For the generating system connections described in the preceding paragraphs, theoretically accurate metering (i.e., no uncertainty introduced due to the metering methods) will be provided under all conditions of load power factor and unbalance by the proper application of the following metering systems (also see Table 4.1 for metering method uncertainties summary):

(*1*) three-phase, three-wire generator connections — two single element (stator) meters or one two-element (stator) polyphase meter;

(*2*) three-phase, four-wire generator connections — three single element (stator) meters or one three-element (stator) polyphase meter.

4.05 Alternative Metering Methods and Uncertainties

(*a*) Not all existing three-phase, four-wire generator installations have enough instrument transformers to provide metering in accordance with Blondel's Theorem. Typically, for economic reasons, a potential transformer is omitted and power and energy measurements are made with what is known as a 2½-element (stator) meter utilizing three current coils, but only two potential coils [see Fig. 4.3(a)]. Under most conditions, the 2½-element meter gives a theoretically accurate measurement of power or energy. If, however, the phase voltages become unbalanced, the metered quantity is no longer theoretically accurate and is further affected by power factor and phase current unbalance.

Figure 4.2 gives a graphical representation of the error introduced into the reading of a 2½-element (stator) device over a broad range of voltage and current unbalance at various load power factors. This graph, however, assumes that instrumentation is available to measure the unbalance in the voltage and current. Unfortunately, this is usually not the case, but in practice the voltage at the generator terminals can be assumed to be balanced within 0.5% with a load power factor of 0.85 (lag) or better. These conditions lead to a maximum uncertainty of about 0.5% attributable to the metering method.

(*b*) Another alternative metering system that may be found in use on some three-phase, four-wire systems is the two-element (stator) meter utilizing two potential coils and two current coils, but receiving current input from three, rather than two current transformers [see Fig. 4.3(b)]. The third current transformer is connected to subtract its current from that fed into the two current coils by the other two current transformers. The net effect is a metering system that is electrically equivalent to the 2½-element (stator) system described in (a) above. The maximum expected uncertainty in applying this metering method on a three-phase, four-wire generator connection is the same as for the 2½-element (stator) system.

(*c*) The application of a two-element (stator) device to meter a three-phase, four-wire generator connection is inappropriate if only two current transformers are used. Under certain conditions (balanced phases), this metering arrangement may be theoretically accurate, but under certain conditions where neutral current is present, the two-element (stator) method becomes very inaccurate depending upon the amount of neutral current flowing and the generator load. In practical applications, the uncertainty in metering with the aforementioned system will be on the order of 5%.

(*d*) Alternative metering method uncertainties are summarized in Table 4.1.

(*e*) The number of current transformers and potential transformers required for each metering method is summarized in Table 4.1. This information is necessary in the uncertainty calculations described in Section 5.

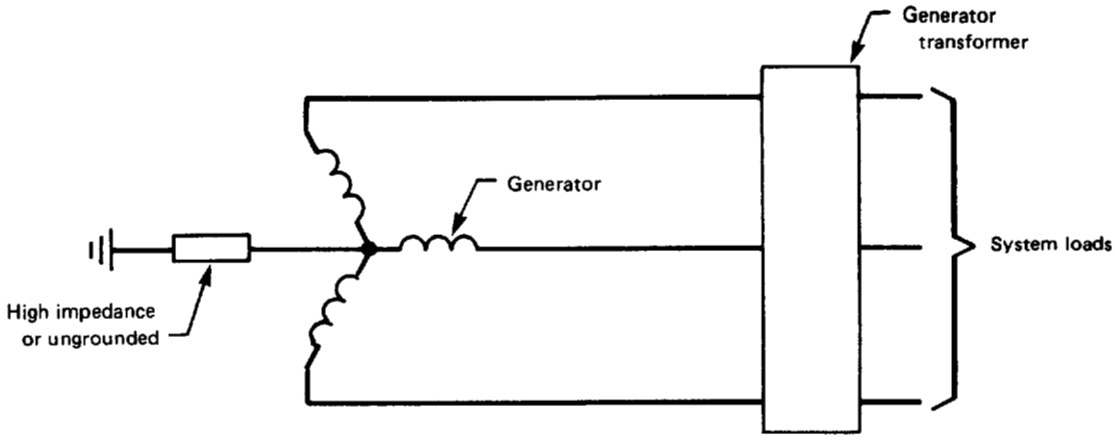
4.06 Meter Constant and Reading Uncertainties

(*a*) Aside from the uncertainties introduced when a metering system does not meet the full requirements of Blondel's Theorem, such as the 2½-element meter applied to a three-phase, four-wire system, all meters have additional uncertainties due to the inherent inaccuracies of the instruments themselves. The uncertainties for typical portable test and switchboard wattmeters and watthour meters are shown in Tables 4.2 and 4.3.

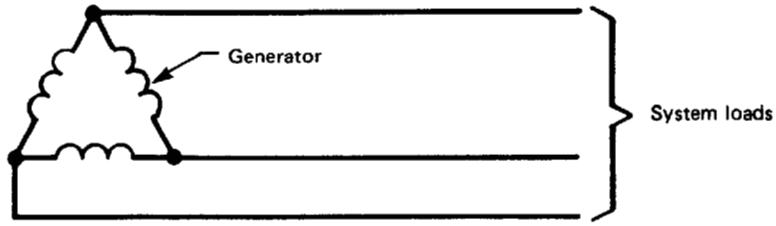
(*b*) Reading error uncertainties are included in

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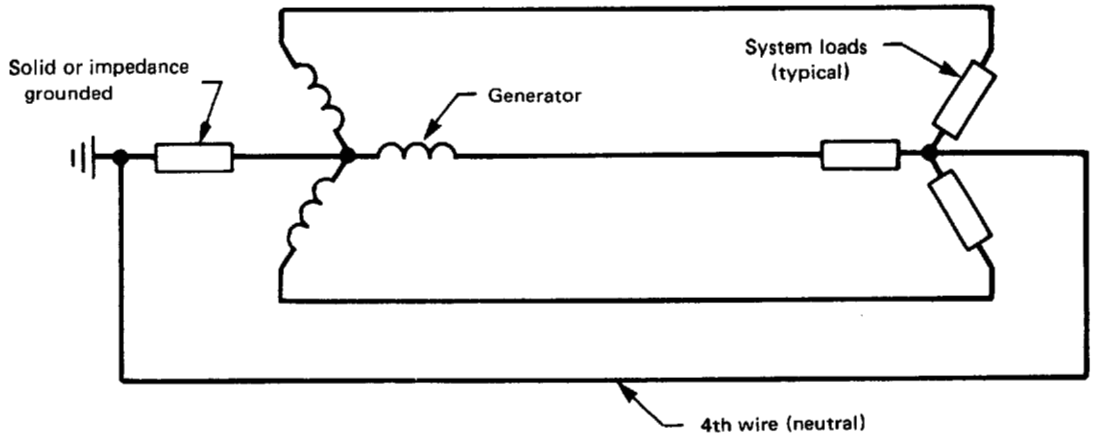
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(a) Wye Generator — 3-Phase, 3-Wire



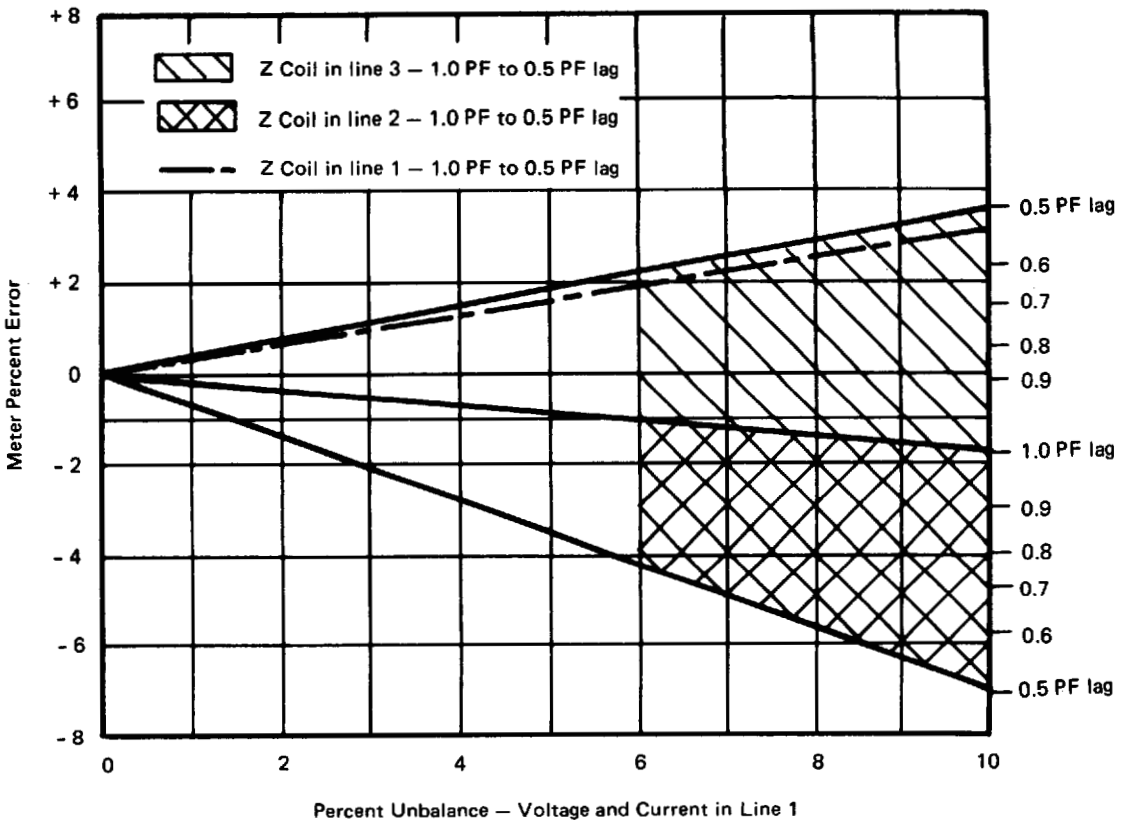
(b) Delta Generator — 3-Phase, 3-Wire



(c) Wye Generator — 3-Phase, 4-Wire

FIG. 4.1 GENERATOR CONNECTION TYPES

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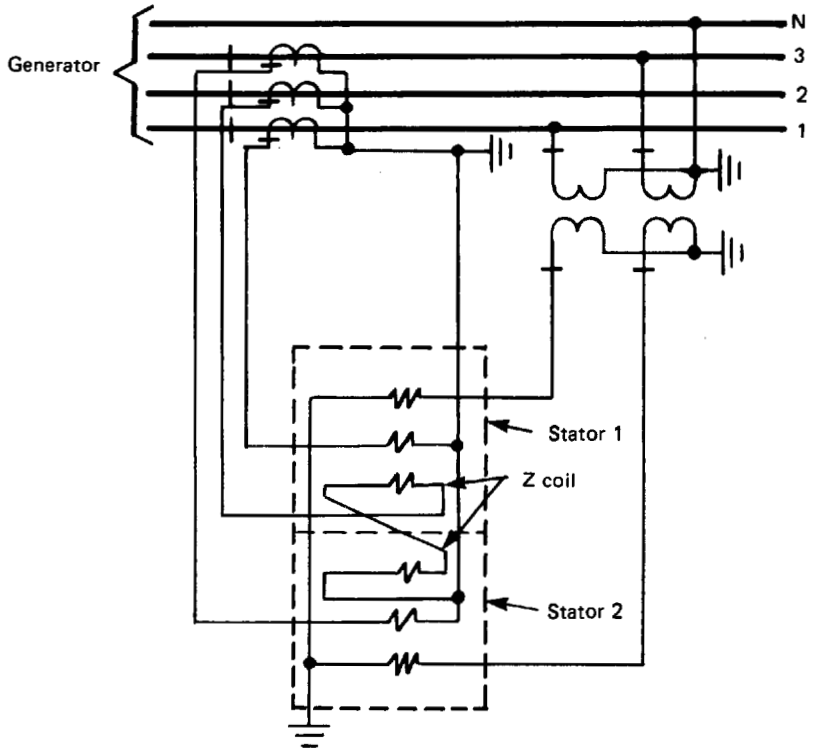


$$\% \text{ Unbalance} = \frac{\text{Maximum deviation from average}}{\text{Average}} \times 100$$

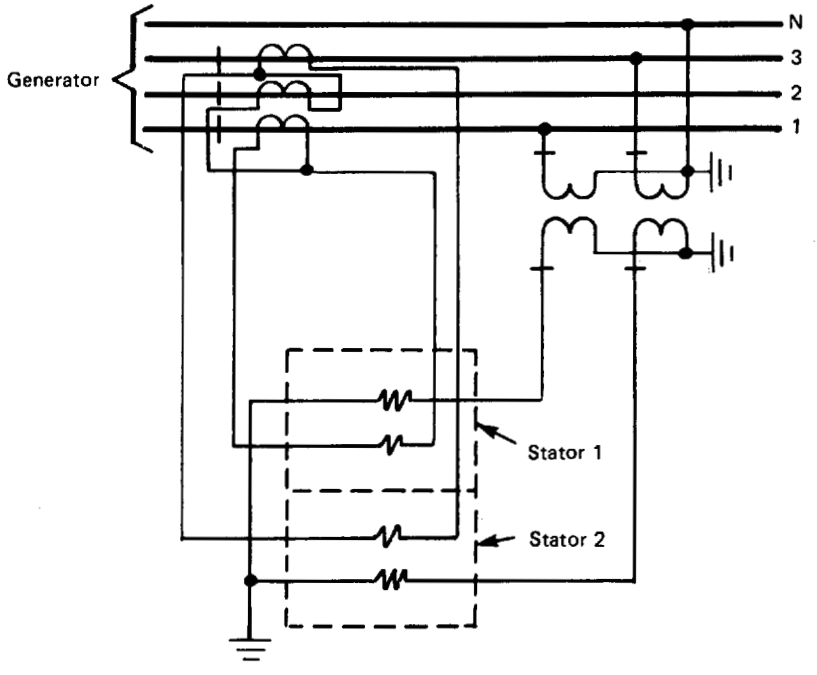
GENERAL NOTES:
(a) This figure is reproduced with permission from the Electrical Metermen's Handbook, Seventh Edition, by the Edison Electric Institute, 1965.
(b) See Fig. 4.3(a) for location of Z coils referenced in the legend on the above curve.

FIG. 4.2 ERROR CURVES FOR EQUAL VOLTAGE AND CURRENT UNBALANCE IN ONE PHASE AND FOR THREE POSSIBLE LOCATIONS OF Z COIL FOR 2½ STATOR WATTHOUR METERS

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(a) 2-1/2 Stator Watthour Meter With Z Coil in Line 2



(b) 2 Stator Watthour Meter With 3 Current Transformers

FIG. 4.3 WATTHOUR METER CONNECTIONS

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TABLE 4.1
NUMBER OF CURRENT TRANSFORMERS (CT'S) AND POTENTIAL TRANSFORMERS (PT'S) REQUIRED FOR EACH METERING METHOD AND METERING METHOD UNCERTAINTIES SUMMARY

Item	Generator Connections	Metering Methods	No. of CT's & PT's Required: Each Single Element Meter CT's	Each Single Element Meter PT's	Polyphase Meters CT's	Polyphase Meters PT's	Metering Method Uncertainty
(a)	Three-phase, three-wire generator connections, Figs. 4.1(a) and 4.1(b)	Power measured by two single-element (stator) meters or one two-element (stator) polyphase meter	1	1	2	2	Zero
(b)	Three-phase, four-wire generator connections, Fig. 4.1(c)	Power measured by three single-element (stator) meters or one three-element (stator) polyphase meter	1	1	3	3	Zero
(c)	Three-phase, four-wire generator connections, Fig. 4.1(c)	Power measured by one 2½-element (stator) polyphase meter	NA	NA	3	2	±0.5%
(d)	Three-phase, four-wire generator connections, Fig. 4.1(c)	Power measured by one two-element (stator) polyphase meter utilizing three current transformers and two potential transformers, Fig. 4.3(b)	NA	NA	3	2	±0.5%
(e)	Three-phase, four-wire generator connections, Fig. 4.1(c)	Power measured by two single-element (stator) meters or one two-element (stator) polyphase meter utilizing two current transformers and two potential transformers	1	1	2	2	5% Not recommended

TABLE 4.2
WATTMETER UNCERTAINTIES

Item	Wattmeter	Uncertainty
(a)	Meeting Code requirements	±0.20% of reading
(b)	High accuracy watts transducers with comparable accuracy high resolution digital readout	±0.20% of reading
(c)	Portable single-element wattmeter, calibrated before test	
	0.25% accuracy class [Note (1)]	±0.25% of full-scale value
	0.50% accuracy class [Note (1)]	±0.50% of full-scale value
	1.0% accuracy class [Note (1)]	±1.0% of full-scale value
(d)	Switchboard type, 1- and 2-element wattmeters, calibrated before test	
	1.0% accuracy class [Note (1)]	±1.0% of full-scale value
(e)	Uncalibrated wattmeters	May be 5%, not recommended for tests

NOTE:
(1) From ANSI C39.1-1981.

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TABLE 4.3
WATTHOUR METER UNCERTAINTIES

Item	Watthour Meter	Uncertainty
(a)	Meeting Code requirements	±0.15% of reading
(b)	Electronic watthour meters with high accuracy digital readout	±0.15% three phase ±0.20% single phase
(c)	Portable three-phase watthour meter in temperature controlled enclosure without mechanical register, calibrated before test	
	Three-phase calibration [Note (1)]	±0.25%
	Single-phase calibration [Note (1)]	±0.50%
(d)	Switchboard three-phase watthour meter with mechanical register, calibrated before test	
	Three-phase calibration [Note (1)]	±0.50%
	Single-phase calibration [Note (1)]	±1.00%
(e)	Uncalibrated watthour meters	May be ±5%, not recommended for tests

GENERAL NOTE: Accuracy class designations are not established for watthour meters as they are for wattmeters and instrument transformers.

NOTE:
(1) From ANSI C12-1975 and ANSI C12.10-1978.

TABLE 4.4
POTENTIAL TRANSFORMER UNCERTAINTIES

Item	Current Transformers	Uncertainty
(a)	Meeting Code requirements	±0.10%
(b)	Type calibration curve available, burden volt-amperes and power factor available	±0.2% for 1.00 pf ±0.3% for 0.85 pf
(c)	Uncalibrated metering transformer with known burdens [Note (1)] 0.6% to 1.0% lagging power factor of metered load, 90% to 110% rated voltage and metering class as follows:	
	0.3%	±0.3% [Note (2)]
	0.6%	±0.6% [Note (2)]
	1.2%	±1.2% [Note (2)]
(d)	Uncalibrated metering transformer with unknown burdens but not overloaded; 0.6% to 1.0% lagging power factor of metered load, 90% to 110% rated voltages, 0.3 metering class	±1.5%

GENERAL NOTE: Uncertainties are based on the assumption that the burden is the highest permissible value for the transformer without overload.

NOTES:
(1) Known burdens include check on wiring and contact resistance for the transformer wiring.
(2) From ANSI C57.13-1978.

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the uncertainties described for wattmeters. For these meters, the error is a function of the change in register reading magnitude during the test. Generally, it is possible to read the meter with an error not exceeding one unit of the meter scale. For example, if the change in register reading is 100 units, the uncertainty in reading is one unit or 1%. Reading error can be reduced by extending the test period or by using the register based on smaller registration units. To obtain accurate readings it frequently becomes necessary to count the turns of the watthour meter disc (or measure the time for a specified number of disc revolutions) to achieve acceptable sensitivity in the reading process. It is usually desirable to plan the test so that the reading error for the watthour meters is one order of magnitude smaller than the largest uncertainty introduced by the instrument transformers or the watthour meter.

4.07 Instrument Transformers and Uncertainties. Instrument transformers are almost universally applied to reduce electric-system voltage and current levels to values appropriate for metering equipment. Errors in power measurement are introduced by the instrument transformers through transformer ratio variations, and phase displacements between primary and secondary voltages or currents.

Both of these effects are governed by the following operating conditions:

(*a*) exciting current of the instrument transformer;

(*b*) percentage of rated voltage or current;

(*c*) power factor of the electric system load;

(*d*) impedance (usually called *burden*) of the devices connected to the secondary windings of the instrument transformers.

The percentage of rated voltage or current and the power factor of the system load can be determined during tests by reference either to the station instruments or to test instruments. While the Code recommends the use of test instruments for voltage and current measurements, the readings of station instruments are usually of sufficient accuracy for the purposes described here.

The Code permits no burden on the potential transformers other than the test instruments and their leads. Since separate test transformers frequently are unavailable, it may be necessary to connect the test instruments to the potential and current transformers serving the station instruments. The resulting total burdens on the transformers must be determined and this data used for reference to transformer calibration curves. It is sufficient to use the manufacturer's published data to determine the burden of each station instrument and each test instrument connected to the instrument transformers. Since the voltage regulator burden is variable, its removal from service during the test is desirable. If this is impossible, the limits of burden variation due to regulator action must be estimated. The resistance of connecting wiring and fuses is best determined by actual measurement.

The Code requires the calibration of potential and current transformers prior to the test. Depending on the test accuracy desired, the use of calibrated transformers may not be necessary. Type calibration curves for current transformers are generally satisfactory, and calibration of individual transformers usually is justified only for Code tests.

Current transformer cores may be permanently magnetized by inadvertent operation with open secondary circuit, resulting in a change in the ratio and phase-angle characteristics. If magnetization is suspected, it should be removed by procedures described in Ref. (56) of Appendix III under "Precaution in the Use of Instrument Transformers."

Current transformers used for protective relaying should not be used for tests. The uncertainties for typical instrument transformers used for generator power output measurement are shown in Tables 4.4 and 4.5.

4.08 Uncalibrated Station Meters. Uncalibrated station metering installations may have uncertainties substantially greater than those instruments and transformers just described. A frequent source of error is high resistance in potential transformer circuits, resulting in lower than acutal power readings. High resistance may be in the fuses or wire terminations and can be readily detected by measurements prior to test. Errors in uncalibrated station metering installations may be as much as 5%; therefore, these installations are not recommended for test.

4.09 Overall Uncertainty of Power Measurement. Measurements of electric power when using wattmeters should be conducted in accordance with instructions given in PTC 19.6-1955, Par. 5.85. If watthour meters are used, the instructions given in Par. 6.70 will apply. A typical instrument connection diagram is shown in Fig. 4.4 of this Report.

The overall uncertainty of the power measure-

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TABLE 4.5
CURRENT TRANSFORMER UNCERTAINTIES

Item	Current Transformers	Uncertainty
(a)	Meeting Code requirements	±0.05%
(b)	Type calibration curve available, burden volt-amperes and power factor available	±0.10%
(c)	Uncalibrated metering transformers with unknown burdens but not overloaded, 0.6% to 1.0% lagging power factor of metered load, and metering accuracy classes as follows at 100% rated current of transformer:	
	0.3% accuracy class	±0.3% [Note (1)]
	0.6% accuracy class	±0.6% [Note (1)]
	1.2% accuracy class	±1.2% [Note (1)]
	At 10% rated current of transformer:	
	0.3% accuracy class	±0.6% [Note (1)]
	0.6% accuracy class	±1.2% [Note (1)]
	1.2% accuracy class	±2.4% [Note (1)]

GENERAL NOTE: Uncertainties are based on the assumption that the burden is the highest permissible value for the transformer without overload.

NOTE:
(1) From ANSI C57.13-1978.

ment should be calculated as shown in Section 5 of this Report.

MEASUREMENT OF MECHANICAL OUTPUT

4.10 General. This Section provides guidance for the measurement of the transmitted power from mechanical drive steam turbines. The driven equipment includes power absorption equipment that sometimes does not directly lend itself to highly accurate performance measurements. Driven machinery of this type includes fans, pumps, and compressors. Electrical generation equipment has been covered in Pars. 4.03 through 4.09.

Power can be defined as the time rate of doing work. The power being transmitted and the angular velocity are both assumed to be constant with time; that is, there are no transients in either torque or angular velocity within the time interval required for the measurement.

The direct method for measuring power, utilizing a dynamometer or a torque meter, involves determination of the variables in the following equation.

Power expressed in SI units

$$P = T\omega$$

where

P = power, watts
ω = angular velocity, radians/sec
T = torque, newton-meters

Power expressed in customary units

$$P = \frac{2\pi nT}{550}$$

where

P = power, horsepower
n = rotational speed, revolutions/sec
T = torque, foot-pounds

4.11 Methods of Mechanical Power Measurement

(a) *Direct Methods Suitable for Measuring Steam Turbine Shaft Power Output*

(1) Reaction Torque Measuring Systems
  (a) Cradled dynamometers
    (1) eddy current types
    (2) waterbrake types
    (3) electric generators
  (b) Uncradled dynamometers
    (1) movable table type
    (2) flanged reaction type
(2) Transmission Torque Measuring Systems

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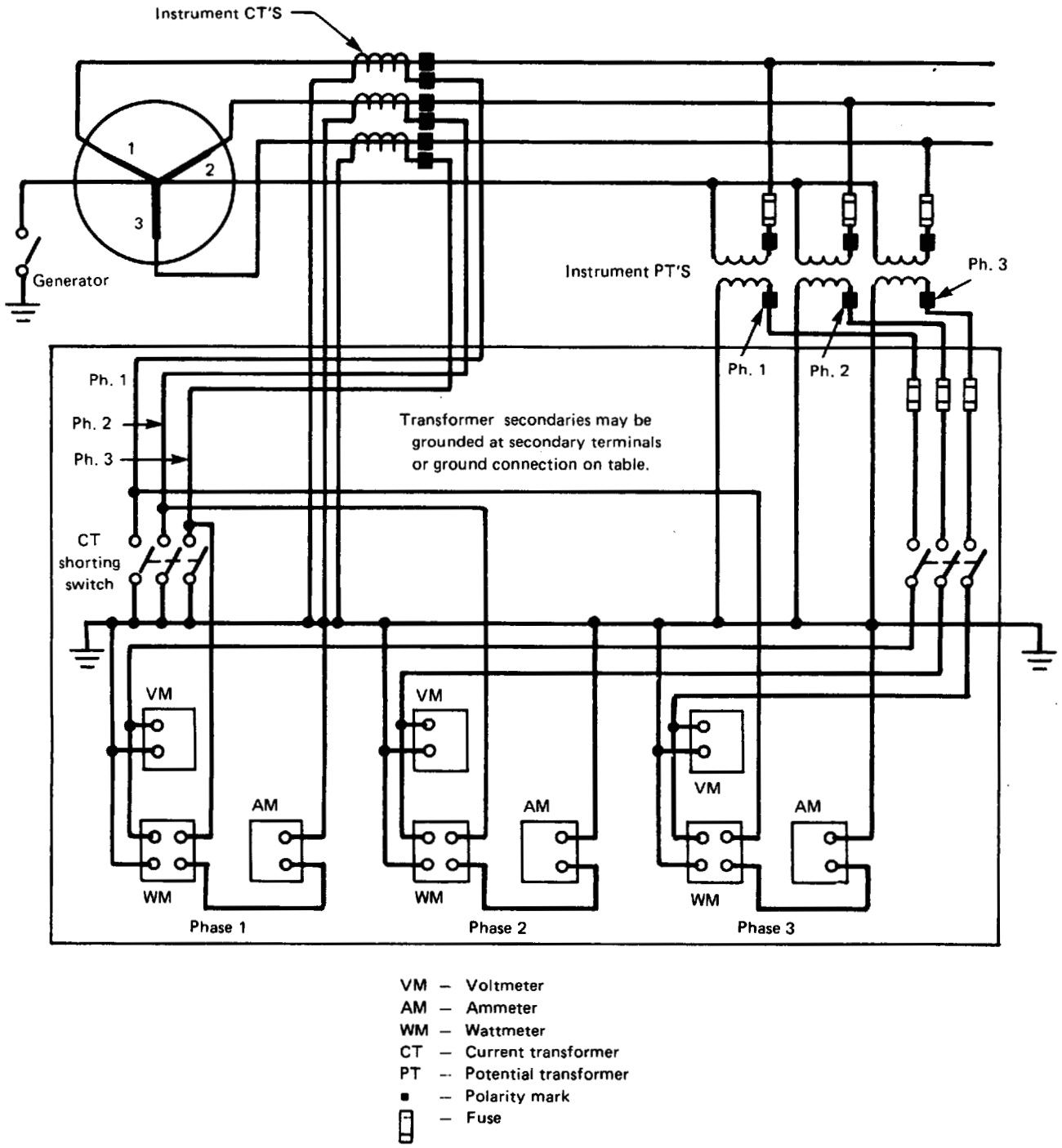


FIG. 4.4 TYPICAL CONNECTIONS FOR MEASURING ELECTRICAL POWER OUTPUT BY THE THREE-WATTMETER METHOD

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(a) Shaft torque measurement systems
(1) surface strain gage systems
(2) slip rings (contacting)
(3) rotating transformer (noncontacting)
(b) Torsional variable differential transformer, magnetic type (noncontacting)
(c) Angular displacement systems
(1) mechanical
(2) electrical
(3) optical

Appendix III, Ref. (57) provides information on power measurements using reaction torque measuring systems listed under (a)(1) above. These are best utilized for factory tests. Reference (57) also contains information on shaft torque measurements by means of transmission torque measuring systems listed under (a)(2) above. These are better adapted and more economical for use on field tests.

Transmission dynamometers (shaft-torque meter) generally consist of a metal shaft to which a signal sensor is attached. This shaft is inserted between the mechanical driver and its load. When the shaft is twisted by loading, the signal sensor provides an output voltage directly proportional to the applied load. Signal sensors are generally, but not necessarily, limited to strain gages or other devices that measure angular deflection by magnetic fields.

Shaft torque measuring systems generally utilize the shear modulus of the test section along with a twist measurement to establish the transmitted torque.

The shear modulus will vary from one type of metal to another. However, there usually is no detectable difference in modulus due to shaft diameter, chemical composition variations for any one alloy, physical properties, methods of manufacture, or slight variations in heat treatment. Paragraph 104, Ref. (44) of Appendix III discusses ultrasonic means of determining the shear modulus.

The uncertainty in shear modulus of shafting with known chemical composition can vary by $\pm 2.0\%$; therefore, calibration is required for greater accuracy. The accuracy of the calibration measurement is on the order of $\pm 0.50\%$.

Although some types of shaft torque systems are temperature compensated, the temperature effect on elastic properties of the stressed element must be considered when temperature compensation is not included. The shear modulus of most low alloy carbon steels decreases about 1.5% per 100°F (2.7% per 100°C) increase in temperature. These thermal sensitivity rates are not precisely established and calibration at operating temperature is preferred when possible.

(b) *Indirect Methods of Mechanical Power Measurements, Energy Balance.* The power measurements derived from tests on the driven equipment can be used in the calculations for field tests on mechanical drive turbines. An example is found in ANSI/ASME PTC 6A-1982, Section IX. Examples of driven equipment in this category include centrifugal pumps, fans, compressors, and exhausters. ASME PTC 8.2-1965 (R1985) for centrifugal pumps, ASME PTC 10-1965 (R1985) for compressors and exhausters, and ANSI/ASME PTC 11-1984 for fans should be consulted when planning field tests on mechanical drive turbines powering such devices.

A further discussion on measurements for mechanical output of steam turbines driving boiler feed pumps in steam turbine cycles is given in Par. 4.13.

(c) *Advantages and Disadvantages.* Advantages and disadvantages of each of the above shaft power measuring methods are summarized in Table 4.6.

4.12 Testing Uncertainties. Table 4.7 summarizes typical uncertainties for the various shaft power measurement methods described in Appendix III, Ref. (57). These can be used as a guide for the accuracy of the instrumentation required for the various measuring methods.

4.13 Measurements of Mechanical Power Output to Drive a Feedwater Pump by Energy Balance. The output of a nonextracting mechanical drive turbine supplying power to a feedwater pump can be determined by applying either of the two procedures outlined in Code Par. 4.09. The first procedure consists of balancing the heat and flow around the driven apparatus and solving for power input. This involves, as a primary measurement, the temperature rise in the feedwater flowing through the pump. The second procedure involves measuring the pump suction and discharge pressure, using an assumed pump efficiency in the appropriate power equation. The appropriate equations for both procedures are included in the Code. Another source of guidance in the heat balance method of power measurement is found in ASME PTC 19.7-1980 (R1983).

The test of a drive turbine is best coordinated with that of the main unit, since much of the data required for the drive turbine is also required for the main unit. The instrumentation used for pump

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TABLE 4.6
SUMMARY — ADVANTAGES AND DISADVANTAGES OF DIFFERENT TORQUE OR POWER MEASURING DEVICES

Method	Advantages	Disadvantages
Reaction Systems		
Cradled dynamometer	Highly accurate; calibration performed in place	Expensive; not readily transportable; size and weight requirements; trunnion bearing error at low torque; water and electrical line interference
Uncradled dynamometer	No trunnion bearing inherent friction and hysteresis losses; portable	Complex support structures required for large machines; metal elastic characteristics vary with temperature
Transmission Systems		
Shaft torque	Relatively low cost; relatively good accuracy; good frequency response; maximum load flexibility	Metal elastic characteristics vary with temperature, percent error increases with decreasing load for given system
Angular displacement	Small in physical size; adaptable to removable pieces such as spacer couplings	Difficult calibration procedures required, usually cannot be done in place; metal elastic characteristics vary with temperature
Energy Balance	Can be performed when direct methods are not possible or practical	Less accurate than direct methods; large amount of data; uncertainty of fluid thermodynamic properties

measurements should be selected to produce the desired test uncertainty. Of critical importance is the instrumentation used to measure the temperature rise in the feedwater as this rise is usually of small magnitude. Multiple measurements with calibrated multijunction thermocouples, installed in properly designed adequately insulated thermocouple wells, are necessary. The feedwater flow passing through the pump should be measured with a calibrated flow section. For multiple pumps operating in parallel, total flow may have to be apportioned in accordance with the relative values of nozzle pressure drop through the respective minimum-flow monitoring devices.

When pump power is calculated using an assumed or previously determined efficiency, suction and discharge pressures must be measured with deadweight gages or equally accurate instruments.

The heat balance about the pump also requires measurements of shaft sealing injection flows, shaft seal leakoff flows, and any other outgoing pump flows, such as desuperheating water, when these do not leave at pump discharge enthalpy. Pressures and temperatures of these miscellaneous flows must be measured for enthalpy determination.

Data collection for a drive turbine test should span a two hour period, or the duration of the coincident test on the main unit. The required duration for an independently conducted drive turbine test may be determined by consulting a graph similar to Fig. 3.1 of the Code. The reader should note that the 0.05% effect shown in Fig. 3.1 may be too restrictive for a drive turbine test and that values for K or S may have to be derived for each test. Data averages and scatter, combined with the number of instruments and the number of locations for each measurement must be used to arrive at a test uncertainty value. Reference (24) of Appendix III is a good source for making the required uncertainty calculation.

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TABLE 4.7
SUMMARY OF TYPICAL UNCERTAINTY FOR DIFFERENT SHAFT POWER MEASUREMENT METHODS

Method	Uncertainty for 2 h Test
Reaction Torque Systems	
Cradled dynamometers	±0.1% to ±0.5%
Uncradled dynamometers	±0.5% to ±1.0% for torque
Shaft Torque Measurement	
Surface strain systems, shaft calibrated	±1.0% for torque
Angular displacement systems, shaft calibrated	
mechanical	Depends on design and application
electrical	±1.0%
optical	Low intrinsic error, but subject to large error from environmental sources
No shaft calibration	±3.0% for torque
Energy Balance Methods	
Open cycle systems	Depends on uncertainty analysis
Closed cycle systems	Depends on uncertainty analysis

Table 4.8 summarizes measurement uncertainties for testing of boiler feed pump drive turbines.

4.14 Measurement of Rotary Speed. Speed may be defined as the time rate of change of position of a body without regard to direction. Rotary speed and torque are the two variables required for direct measurement of mechanical power output. The relations of speed and torque with power are given in Par. 4.10. The accuracy of the speed measurement is as important as the torque measurement for an accurate power measurement. Some power measuring devices have self-contained rotary speed and torque measuring instruments that are combined within the mechanism and visually display or print the measured shaft power. Typical methods for measuring rotary speed and estimated uncertainties are given in Table 4.9.

A pulse generator and pickup with a crystal-controlled time base counter will provide a measurement of minimum uncertainty and is recommended for conducting a Code test. The pulse generator should have a minimum of 60 teeth providing pulses, which in turn are sensed by noncontacting magnetic or eddy current transducers. The digital speed measuring device will measure

TABLE 4.8
MEASUREMENT UNCERTAINTIES FOR TESTING OF BOILER FEED PUMP DRIVE TURBINES

Measurement	Instrument	Quality and Grade	Uncertainty
Pump suction flow	Calibrated flow section	Calibrated	±0.2%
Feedwater temperature rise	Multijunction thermocouples	Calibrated	±0.1°F
Pump suction temperature	Thermocouple and digital voltmeter	Calibrated	±1.0°F
Pump suction pressure	Deadweight gage	...	±0.1%
Pump discharge pressure	Deadweight gage	...	±0.1%
Pump shaft seal leakoff flow	Orifice flow section and manometer	Calibrated	±1.0%
Pump shaft seal injection flow	Orifice flow section and manometer	Calibrated	±1.0%
Pump shaft speed	Stroboscope	...	±1.0%
Desuperheating water flow	Orifice flow section and manometer	...	±1.0%
Temperatures of miscellaneous flows	Thermocouple and digital voltmeter	Calibrated	±1.0°F
Pressures of miscellaneous flows	Bourdon gage	Station	±2.0 to 5.0%
Pump efficiency	From pump manufacturer	Not available	Not available

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TABLE 4.9
MEASUREMENT UNCERTAINTY — TYPICAL ROTARY SPEED INSTRUMENTATION

Speed Instrument	Type and Method	Uncertainty
Frequency Sensitive		
Electronic	Shaft mounted 60 tooth gear, magnetic or eddy current pickup; pulse counter, crystal time base, digital display	±1 pulse count
Mechanical	Vibrating reed tachometer mounted on frame of machine, nonrecording	±1.00% to ±2.00%
Tachometer		
Electric generator	Shaft mounted AC or DC generator, with output voltage proportional to speed, connected to an indicator	±1.00% to ±2.00%
Eddy current	Test rotor connected to three-phase generator and connected to three-phase sync motor which drives the tachometer	±1.00% to ±2.00%
Centrifugal	Flyball governor built into hand-held tachometer	±1.50% to ±3.00%
Counters		
Accumulators	Digital display connected to pickup obtaining signal from shaft mounted 60 tooth gear	±1 count
Timepieces		
Electronic	Crystal time base with digital display and gate time of 1 sec to 5 sec	±0.005% to ±0.010%
Electric	Time base using an analog clock locked into AC supply	±0.10% to ±0.20%
Other		
Stroboscope	Rotating reference mark on shaft illuminated by periodic light flashes	±0.50% to ±1.00%
Photocell	Light reflective mark on shaft, reflecting a light source to the photocell, then to meter	±0.50% to ±1.00%

the speed by summing the number of pulses of the input signal for a precisely known time period. The rotary speed accuracy should include the crystal time base uncertainty (on the order of ±0.0075%), and also the uncertainty of the count. Since fractional counts are not included, the count uncertainty is expressed as:

$$\pm \frac{1}{\text{count time (sec)} \times \text{number of teeth/rev.}}$$

For a 60 tooth pulse generator with the counter set on a one second time base, the uncertainty becomes

$$\pm \frac{1}{1 \text{ sec} \times 60 \text{ teeth/rev.}} = \pm 0.0167 \text{ r/s} = \pm 1 \text{ rpm}$$

Other types of speed measuring devices can be found in ASME PTC 19.13-1961. It includes a general discussion, methods, and applications relative to speed measurement.

Rotary speed measurements must be coordinated with torque measurements to obtain the test power. The frequency of calibration, number of observations, and other similar items should accord with the test objectives outlined in the Code. All measuring apparatus must be calibrated before and after a test in accordance with Code requirements.

The measurement uncertainty for typical rotary speed instrumentation is presented in Table 4.9.

4.15 Measurement of Primary Flow. Since the publication of ANSI/ASME PTC 6R-1969 (R1985), much additional data on flow measurements, using flow nozzles and orifices permanently installed in straight pipe runs in steam turbine installations, has become available. This expanded data base of both published and unpublished data represents industry's experience to date. From the analysis of this data, the method of estimating flow uncer-

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tainties described in this Section was developed. The material given in this Section is based primarily on comparison of flows measured with Code flow sections (after compensation for heat and water balance flows) with corresponding flows measured with flow sections that did not meet Code requirements and were installed in the same steam turbine cycle arrangement. The primary intent of this Section, therefore, is to provide a means of deriving the estimated additional expected uncertainty in flow measurements for steam turbine tests when flow sections that do not meet Code requirements are used and the installation configurations are similar to those typically found in power plants.

4.16 Many factors determine the accurate measurement of primary flow as described in the Code, Pars. 4.19 through 4.47. The more important factors affecting absolute accuracy in this measurement are given in Tables 4.10 and 4.11 and Figs. 4.5 through 4.9 in this Report. Table 4.10 lists the estimated uncertainty in flow under various circumstances when all flow section configuration details meet the Code requirements. Figures 4.5 through 4.9 pertain to the flow section configuration details, and the curves on the figures indicate the expected uncertainties for selected deviations from the Code flow section configuration. A flow section's estimated overall uncertainty is calculated by taking the square root of the summation of the squares of the applicable percentage from Table 4.10, and the applicable percentages to the flow section from Figs. 4.5 through 4.9. In Table 4.10, uncertainties are tabulated in percent for both water and steam flow measurement. For water flow measurement, the uncertainties shown are based on flow coefficients only. For steam flow measurements, the uncertainties are for differential pressure to inlet pressure ratios of 0.10 or less, and include both flow coefficient and expansion factor.

(*a*) Comments on the items in Table 4.10 follow.

(*1*) *Group 1 items in Table 4.10 apply when a flow section is calibrated.*

Item A. Calibration meets Code requirements. Application of uncertainties may be required for the instrumentation detailed for pressure measurement in Pars. 4.22 through 4.27 and for temperature measurement in Pars. 4.29 and 4.30 of this Report.

Item B. Calibrated, but the shape of the curve and numerical value specified in Par. 4.31 of the Code do not meet requirements.

Item C. The device was in service between time of calibration and test and its condition may have changed, although there is no evidence of deterioration.

Item D. The flow section was installed after initial system flushing. It was in service before the test and has not been inspected since installation. The given values represent possible deposit buildup or roughening of surfaces during service before the test.

Item E. The flow section was calibrated, then permanently installed, and not inspected thereafter. For liquid measurement, the assigned values represent the effect of possible damage during initial flushing or from deposits that accumulate during operation. For steam measurement, the values include the additional effect of an extrapolated curve, and some damage from initial blowing of the steam line, cleaning out welding beads, and other contamination. These values increase with prolonged service if there is scaling, deposit accumulation, or erosion. For measuring steam flow, usual practice employs a pipe-wall tap nozzle.

(*2*) *Group 2 in Table 4.10 applies to uncalibrated flow sections.*

Item F. An inspection immediately before and after the test includes checking for correct diameter, damage due to passing debris, and change in diameter due to deposit buildup. For throat tap nozzles, the inspection includes a very close scrutiny of the throat taps. They should be sharp and free of burrs.

Item G. If not inspected after test, the uncertainty from possible damage and deposit buildup is increased.

Item H. This measuring section will be in place during the initial flushing and blowing of the pipe and initial operation. Considerable damage in the form of nicks and scratches is possible and deposit buildup is common, thus increasing the uncertainty of the flow-measuring device. For example, a piece of welding rod across a nozzle may produce a 10% error. There should be a certificate of inspection stating that the diameter was correct, the unit was clean, the taps were straight, and the installation, in general, complied with ASME PTC 19.5-1972, Fluid Meters, Part II, when originally installed.

Item I. The absence of the minimum inspection of Item H precludes few errors. For example, a beveled orifice installed backwards will

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TABLE 4.10
BASE UNCERTAINTIES OF PRIMARY FLOW MEASUREMENT

Item	Base Uncertainty, U_B,%	Liquid			Superheated Steam (at Least 25° Superheat)		
		Flow Nozzle			Flow Nozzle		
		Throat Tap	Pipe Wall Tap	Orifice	Throat Tap	Pipe Wall Tap	Orifice
	Group 1 — Calibrated Flow Sections						
A	Meeting Code requirements	0.15 [Note (3)]	0.25 [Note (4)]	0.25 [Note (4)]	0.25 [Note (4)]	0.35 [Note (4)]	0.45 [Note (4)]
B	Calibrated immediately before test and inspected after test, coefficient curve extrapolated	0.25	0.50	0.60	0.50	0.75	1.10
C	Calibrated before installation and inspected before and after test assuring no visible or measurable changes in the flow element	0.35	0.60	0.80	0.70	1.05	1.65
D	Calibrated before permanent installation and installed after initial flushing [Note (1)]	1.25	1.25	1.55	1.60	1.70	2.30
E	Calibrated before permanent installation [Notes (1) and (2)]	2.50	2.50	3.00	2.75	2.80	3.70
	Group 2 — Uncalibrated Flow Sections						
F	Inspected immediately before and after test	0.80	2.00	1.00	1.20	2.50	2.00
G	Inspected immediately before test	1.15	2.50	2.50	1.50	3.00	3.00
H	Inspected before permanent installation [Notes (1) and (2)]	2.60	3.20	3.20	3.00	3.70	4.20
I	No inspection and permanent installation	See Par. 4.16(a) (1), Item I					

GENERAL NOTE: Overall uncertainty of flow sections:

With no flow straightener = $\sqrt{(U_B)^2 + (U_{LNS})^2 + (U_\beta)^2 + (U_{DSL})^2}$

With a flow straightener = $\sqrt{(U_B)^2 + (U_\beta)^2 + (U_{LS1})^2 + (U_{LS2})^2 + (U_{DSL})^2}$

Where U_B is from this table, U_{LNS} is from Fig. 4.5, U_β is from Fig. 4.6, U_{LS1} is from Fig. 4.7, U_{LS2} is from Fig. 4.8, and U_{DSL} is from Fig. 4.9.

NOTES:

(1) Good water chemistry, no after test inspection, less than six months in service (see Par. 4.17).

(2) Reasonable assurance that minimal damage was caused to flow element during initial flushing.

(3) 0.15% pertains to flow sections located in the lower temperature part of the cycle. The 0.15% may increase to 0.25% when the flow section is located in the higher temperature part of the cycle, such as in the boiler feedwater line downstream of the top heater.

(4) Information relative to the construction, calibration, and installation of other flow-measuring devices is described in ASME PTC 19.5-1972. Although these devices are not recommended for the measurement of primary flow, they may be used if they conform to the general requirements of Par. 4.22 of the Code with the following exceptions:

(a) For the requirement of Par. 4.22(a) of the Code, the β ratio shall be limited to the range 0.25 to 0.50 for wall tap nozzles and venturis and 0.30 to 0.60 for orifices.

(b) For the requirement of Par. 4.22(d) of the Code, the appropriate reference coefficient for the actual device given in PTC 19.5 shall be used. The parties to a test should become familiar with the contents of PTC 19.5 regarding these devices.

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TABLE 4.11
MINIMUM STRAIGHT LENGTH OF UPSTREAM PIPE FOR ORIFICE PLATES AND FLOW NOZZLE FLOW SECTIONS WITH NO FLOW STRAIGHTENERS

[Minimum Straight Lengths of Pipe Required Between Various Fittings Located at Inlet and Outlet of the Primary Device, and Device Itself (based on information in ASME MFC-3M-1985 and ASME PTC 19.5-1972).]

	On Inlet Side of Primary Device						
Diameter Ratio	Column 1 Single 90 deg. Bend or Tee (Flow From One Branch Only)	Column 2 Two 90 deg. Ells in Same Plane	Column 3 Two 90 deg. Ells in Same Plane, Separated by 10 Diameters of Straight Pipe [Note (1)]	Column 4 Two 90 deg. Ells Not in Same Plane [Note (2)]	Column 5 Reducers and Expanders	Column 6 Valve or Regulator [Note (3)]	Column 7 On Outlet Side (For All Inlets)
0.10	6	8.5	6	14	6	16.5	2.5
0.15	6	8.5	6	14	6	17	2.5
0.20	6	8.5	6	14.5	6	18	2.5
0.25	6	8.5	6	15.5	6	18.5	3
0.30	6	8.5	6	16	6	19.5	3
0.35	6	8.5	6	17	6	20.5	3
0.40	6	8.5	6	18	6	22	3.5
0.45	6.5	9	6.5	19.5	6.5	23.5	3.5
0.50	7	10	7.5	21	7	25	3.5
0.55	8	11.5	8.5	22.5	8	27	3.5
0.60	9.5	14	9.5	25	9.5	30	4
0.65	11.5	16	11	29.5	11.5	34	4
0.70	14	19	12	31	14	39	4
0.75	16.5	21.5	13.5	35	16.5	44	4.5

GENERAL NOTES:
(a) All straight lengths are expressed as multiples of pipe diameter *D* and are measured from the upstream end of the inlet section.
(b) The radius of curvature of a bend or elbow shall not be less than 0.75 times the pipe diameter *D*.

NOTES:
(1) If this length is less than 10 diameters, Column 2 shall apply.
(2) If the two ells in Column 4 are closely preceded by a third ell not in the same plane as the second ell, the piping requirements shown by Column 4 should be doubled.
(3) The valve or regulator in Column 6 restricts the flow; however, a *wide open* gate valve or plug valve may be considered as not creating any serious disturbance, and it may be located according to the requirements of the fitting preceding it, as permitted in Column 1, 2, 3, or 4.

produce a very large error. Hence, no numerical uncertainty value for Item I is tabulated.

(*b*) Comments on the curves in Figs. 4.5 through 4.9 follow. Figure 4.5 is applicable to flow sections containing no flow straighteners. Locating flow sections with no flow straighteners where severe upstream swirl disturbances may be encountered should be avoided. Examples of such locations are:

(*1*) near pump discharge;

(2) after and near partially open control valves;

(3) preceded by two or more elbows in different planes with no run between the elbows.

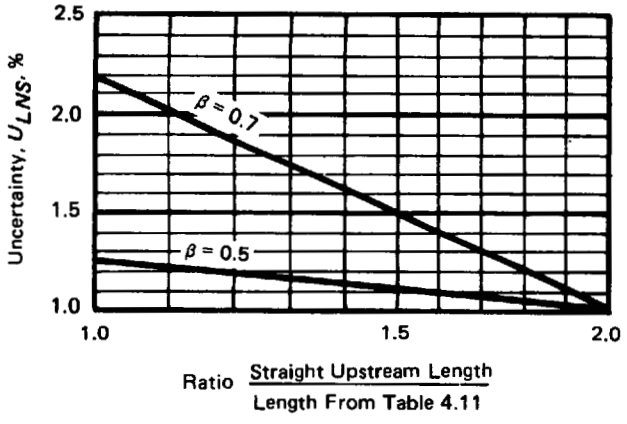
In some instances, if a flow section without a flow straightener is used in these locations, uncertainties of over 20% may result. For flow measurements where severe upstream disturbances may occur, the use of a multiplate-type flow straightener preceding the flow section is recommended.

Figure 4.5 used with Table 4.11, Columns 1 through 6, estimates the flow section uncertainty for the straight length of pipe preceding the primary flow element.

Figure 4.6 is applicable to flow sections with and without flow straighteners. The curves on the figure give the additional uncertainty for calibrated and uncalibrated flow sections when the β ratio is greater than that recommended by the Code.

Figures 4.7 and 4.8 are for flow sections with flow

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GENERAL NOTE: Curves are for flow section arrangements where only moderate upstream disturbances are expected (see Par. 4.16).

FIG. 4.5 MINIMUM STRAIGHT RUN OF UPSTREAM PIPE AFTER FLOW DISTURBANCE, NO FLOW STRAIGHTENER

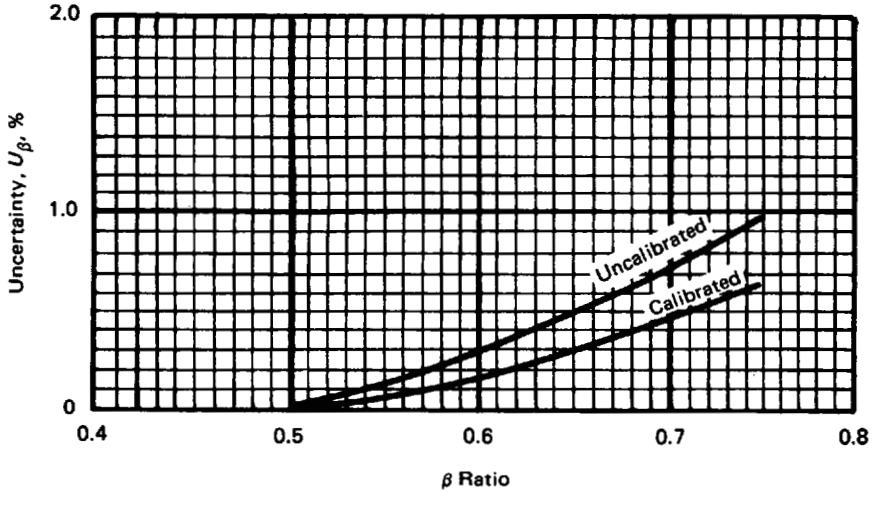


FIG. 4.6 β RATIO EFFECT

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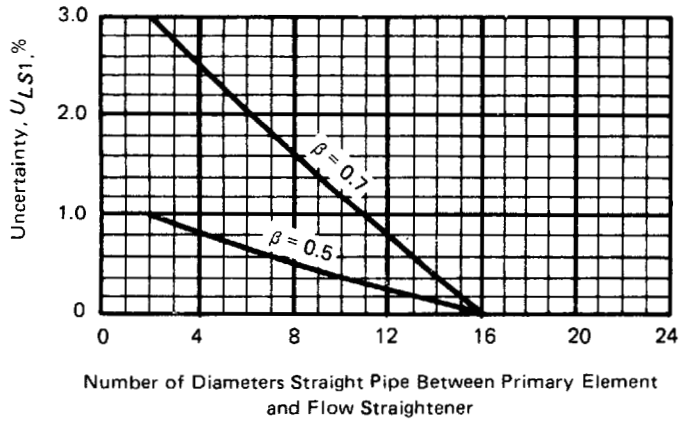


FIG. 4.7 EFFECT OF NUMBER OF DIAMETERS OF STRAIGHT PIPE AFTER FLOW STRAIGHTENER

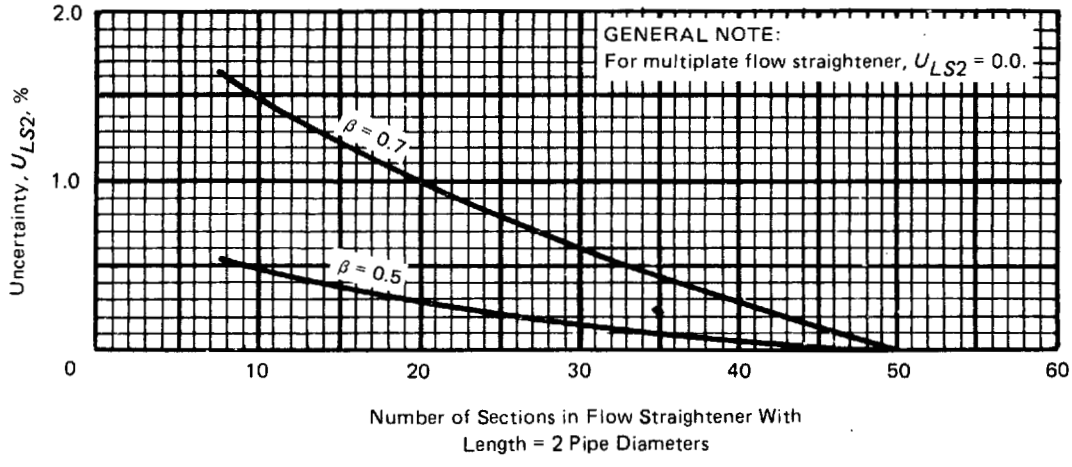


FIG. 4.8 EFFECT OF NUMBER OF SECTIONS IN FLOW STRAIGHTENER

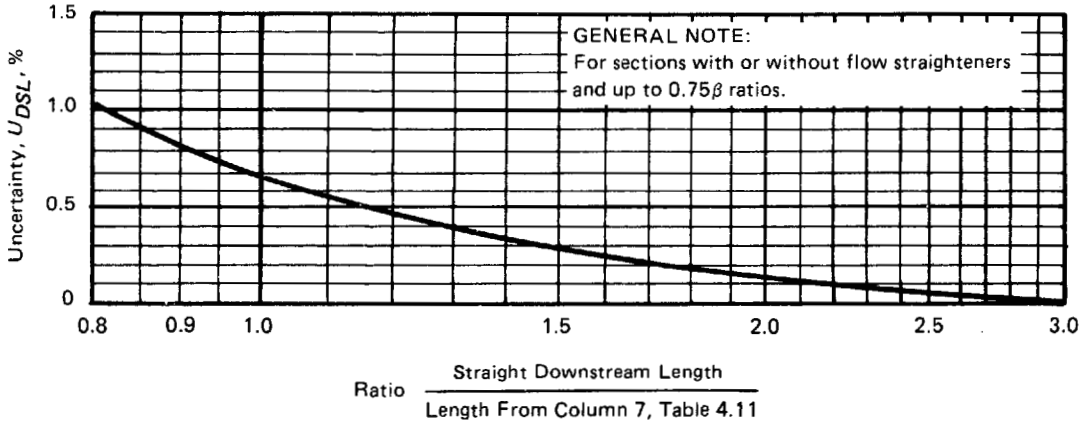


FIG. 4.9 EFFECT OF DOWNSTREAM PIPE LENGTH

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straighteners. These curves give estimated uncertainties for the upstream length between the straightener and flow element that are shorter than the 16*D* specified by the Code and when the straightener has less than the Code specified 50 section 2*D* long straightener. For multiplate flow straighteners with a large number of small holes, U_{LS2} in Fig. 4.8 is equal to 0.0. The curves on the figures apply when the length of straight pipe ahead of the flow straightener is at least 2 pipe diameters and the straight length of pipe downstream of the flow element is at least 4 pipe diameters. In locations where flow profiles may encounter severe separation, such as when the flow section is installed in a branch leg of a tee, use of tubular flow straighteners can cause large errors in measurements. Such locations should be avoided. Otherwise, use of a multiplate-type straightener is recommended.

Figure 4.9 applies to flow sections with and without flow straighteners. This figure, used with Table 4.11, Column 7, estimates the flow section uncertainty due to the straight pipe length following the primary flow element.

4.17 Flow Sections That Cannot Be Inspected After Installation. Table 4.10, Items D, E, and H are for sections containing flow elements permanently welded in the pipe without inspection ports. This makes it difficult to inspect the flow element after the flow section is assembled. It is subsequently impossible to establish whether the flow elements are free of deposits or if damage has occurred since assembly. In general, initial surface deposits and scratches on flow nozzles and damage to orifices in the form of distortion or nicks to the sharp edge have an immediate effect on the flow coefficient; thereafter, if further deposits or damage occur, the change in coefficient with time is probably much reduced. For noninspectable flow sections in service for more than 6 months, the base uncertainty is likely to change much less with time than indicated for the initial 6 months in Table 4.10. When the base uncertainties for these flow sections with more than 6 months in service must be established, mutual agreement between the parties to the test must be reached after considering the plant's water chemistry and maintenance history.

4.18 The procedure for determining the total expected uncertainty using the tables and figures is shown in the following examples.

(a) A flow section containing a pipe-wall tap flow nozzle is installed in a boiler feedwater line. The flow section is not calibrated and the flow nozzle was inspected before permanent installation. The flow nozzle β ratio is 0.65 and the flow section has no flow straightener. The pipe inside diameter D is 8.5 in. There is a single 90 deg. bend preceding the flow section. The flow section upstream length is 107 in. The straight length of pipe downstream of the flow nozzle is 50 in. The upstream length expressed in pipe diameters is 107/8.5 = 12.6. Table 4.11, Column 1, indicates that for $\beta = 0.65$, the required minimum straight length of pipe between the upstream elbow and the flow nozzle inlet face should be at least 11.5 pipe diameters. The upstream length ratio to be used to enter Fig. 4.5 is therefore 12.6/11.5 = 1.1, resulting in a U_{LNS} value of ±1.8%. The downstream length, expressed in pipe diameters, is 50/8.5 = 5.9. Table 4.11, Column 7, indicates a minimum requirement of 4 pipe diameters. The downstream length ratio to be used to enter Fig. 4.9 is therefore 5.9/4 = 1.5, resulting in a U_{DSL} value of ±0.3%.

(1) From Table 4.10, Item H for U_B applies and is ±3.2%.

(2) From Fig. 4.6, U_β at $\beta = 0.65$ and the uncalibrated curve = ±0.5%.

The combined uncertainty becomes:

$$\sqrt{(1.8)^2 + (0.3)^2 + (3.2)^2 + (0.5)^2} = \pm 3.7\%$$

(*b*) For the same flow nozzle calibrated before permanent installation, and assembled in a flow section with a 30 tube flow straightener assembled 12 pipe diameters upstream of the flow element, the uncertainties become:

(1) From Table 4.10, Item E for U_B applies and is ±2.5%.

(2) From Fig. 4.6, U_β at $\beta = 0.65$ and calibrated = ±0.3%.

(3) From Fig. 4.7, U_{LS1} at 12 and $\beta = 0.65$ = ±0.6%.

(4) From Fig. 4.8, U_{LS2} at 30 and $\beta = 0.65$ = ±0.4%.

(5) From Fig. 4.9, U_{DSL} at 1.5 = ±0.3%

The combined uncertainty becomes:

$$\sqrt{(2.5)^2 + (0.3)^2 + (0.6)^2 + (0.4)^2 + (0.3)^2} = \pm 2.6\%$$

4.19 Measurements Using Radioactive Tracers. The uncertainty in flows or qualities measured with radioactive tracers is dependent on the uncertainty

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TABLE 4.12
RADIOACTIVE TRACER UNCERTAINTIES

Measurement	Instrument Quality and Grade	Combined Uncertainty for Quality and Grade Instruments Indicated
Counting	Two precision calibrated detectors, ±0.3%	Throttle quality 0.01%
Injection rate	Instrument quality positive displacement minipump, ±0.3% Calibrated analytical balance scale (0.1% accuracy class), ±0.4%	Extraction quality 0.2%
		Heater leakages 0.05% of throttle flow
		Flow ±0.75%
Counting	One precision calibrated detector, ±0.6%	Throttle quality ±0.1%
Injection rate	Medium accuracy positive displacement minipump, ±1.0% Calibrated medium accuracy balance scale (0.14% accuracy class), ±1.2%	Extraction quality ±0.5%
		Heater leakage ±0.1% of throttle flow
		Flow ±1.75%

in the individual measurements that are made. These measurements are counting, injection rate, background, and other similar measurements. This Section discusses these uncertainties and their effects on the final computations.

The radiation that is emitted from the tracer is a random decay and follows a Poisson distribution. The uncertainty is dependent on the size of the sample. About 10^4 counts are necessary to achieve 1% uncertainty. To decrease this uncertainty to 0.1%, 10^6 counts are necessary, and counting time is increased by a factor of 100. All counting for a test must be completed within a finite time interval. This is governed either by test timing or by the half-life of the tracer. In either case, a counting uncertainty of 0.1% is generally not possible.

Another source of uncertainty stems from the preparation of standards. Because of the high activity of the injection solution, it cannot be counted directly and must be diluted with demineralized water to form a countable standard. It is extremely important that this dilution be done accurately, since a 1% error in the dilution will result in a 1% error in the final result. Normally, four standards are prepared and counted. Experience shows that a 1% spread from maximum to minimum can be expected. The uncertainty produced is on the order of 0.5%.

Tracer injection rate also has a direct effect on final results and must be carefully watched. Accurate positive displacement metering pumps should be used and the tracer injected should be measured. The most reliable method is to continually weigh the injection containers and record the weight loss every five minutes. If injection rates are not constant, an error will be introduced.

Radiation background is also a possible source of error. There are two types of background which must be considered. The first is natural radiation in the atmosphere. This normally requires about a 1% correction and the resulting uncertainty is about 0.5%. The second is radiation in the cycle due to the tracer. This can range from 0% to 10% depending on reactor carryover, demineralizers, and other similar sources. The latter uncertainties are usually larger than those due to natural radiation.

Listed below are Code test expected uncertainties:

(*a*) Standards — ±0.5%
(*b*) Counting — ±1.0%
(*c*) Injection rate — ±1.0%
(*d*) Natural background — ±0.5%
(*e*) Cycle background -- ±1.0%

These uncertainties can be used to estimate the overall uncertainty in tracer measured water flows and steam qualities. Water flows based on these values have a 2% uncertainty, and steam qualities have less than 0.5% uncertainty.

It is possible to reduce these uncertainties in sev-

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eral ways. Counting errors can be reduced significantly by increasing the counting time by a factor of 100 or by utilizing two detectors. Injection rate can be more precisely controlled using an instrument-quality positive displacement minipump. The pump can be fed from a container mounted on an analytical balance calibrated to 0.02%. If, in addition, the balance is read to ±0.1 grams at five minute intervals measured to ±0.2 seconds, the uncertainty can be further reduced.

Preparation of more standards will reduce the uncertainty in this area, and two or three measurements of background will almost eliminate the uncertainty.

With the above techniques, water flows can be measured to better than 1% using tracers.

4.20 Measurements Using Nonradioactive Tracers. The sampling technique of nonradioactive tracers has several advantages that make this method more adaptable for use at nonnuclear installations, where the licensing and personnel required for using radioactive tracers may not be available.

However, uncertainties from the following sources can be introduced and might be expected during a Code test:

(*a*) preparation of standards;
(*b*) variation in injection rate;
(*c*) contamination of samples;
(*d*) sampling and analysis.

Experience to date is based on limited field tests using a sodium tracer which yielded promising results. The sampling techniques were generally in accordance with ASTM D 1428-64, Method B, modified to allow a larger number of samples during a two hour test period.

Other limited testing indicates that steam enthalpies can be determined within 0.01 Btu/lbm, which would have a negligible effect on test results. However, such accuracy most probably will require raising the level of sodium in the system to one possibly objectionable to manufacturers of some major system components. Accordingly, the allowable sodium level in each individual system must be established and coordinated with other test requirements.

Because of the potentially detrimental effects of raising the system sodium level, studies are underway to identify a more desirable tracer material. This material, along with a suitable tracer detection technique and associated instrumentation, must be practicable and must provide the desired uncertainity at a reasonable cost. Uncertainties resulting from use of nonradioactive tracer materials must be agreed to by the parties to the test based on information available at the time.

4.21 Steam Quality Measurements Using Throttling Calorimeters. Throttling calorimeters operate on the principle that the initial and final enthalpies are equal when steam passes through an orifice from a higher to a lower pressure, providing there is no heat loss and the initial and final kinetic energies are negligible.

Steam samples should be taken in accordance with ASTM D 1066, or as described in ASME PTC 19.11-1970.

The calorimeter alone, with properly calibrated instruments, is capable of an uncertainty of ±0.2%; however, a statement of overall uncertainty is not valid because of the uncertainties involved in the sampling technique. Throttling calorimeters have a limited range of use which varies with pressure (see ASME PTC 19.11-1970).

4.22 Measurement of Pressure. The instruments to be used for measuring the various fluid pressures in the cycle are listed in Code Par. 4.64. The types of instruments used for measuring pressures at various locations, such as at the throttle, first stage, extraction stages, feedwater heaters, and exhaust, are discussed in the following paragraphs.

4.23 The quality and grade of the test instruments should be coordinated. For example, if primary flow is measured as in Item H of Table 4.10, whether pressure is measured by Bourdon gage or deadweight gage will make little difference in the uncertainty of the result. Improvement in the method of flow measurement would be necessary before highly accurate pressure measuring devices would be justified.

4.24 The uncertainties for different types and calibrations of deadweight gages are addressed in Table 4.14.

4.25 The uncertainties for different types of manometers are addressed in Table 4.13.

4.26 Transducers and their applications are mentioned in Code Par. 4.83. High quality transducers properly installed in controlled temperature environments and used with high resolution digital readouts can yield low uncertainties, but the

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TABLE 4.13
MANOMETER UNCERTAINTIES

Instrument	Quality and Grade	Uncertainty
Test manometer	7/16 in. diameter or larger, precision-bored; compensated-scale, with optical or servo-follower reading aid	±0.02 in.
Test manometer	Precision-bored, compensated-scale, without reading aid	±0.05 in.
Station manometer	Commercial compensated scale, without reading aid	±0.10 in.

GENERAL NOTES:
(a) For additional information, see ANSI/ASME PTC 19.2-1986 and, in particular, note the capillary error in small bore tubing.
(b) When manometers are used to measure turbine exhaust pressures, the spatial uncertainty from Table 4.17 also applies.

TABLE 4.14
DEADWEIGHT GAGE UNCERTAINTIES

Area Ratio	Quality and Grade	Uncertainty
10:1	Laboratory calibrated	±0.10% of reading
	Uncalibrated	±0.10% of rated capacity
100:1	Laboratory calibrated	±0.10% of rated capacity
	Uncalibrated	±0.25% of rated capacity

GENERAL NOTE: For additional information, see ANSI/ASME PTC 19.2-1986.

initial and continued precision of this equipment should be demonstrated by frequent in-place calibration or by use in parallel with suitable precision equipment. If transducers are installed improperly or are in service for long periods without calibration, the uncertainty will be indeterminate.

Transducers and the uncertainties for different measuring systems and calibrations are addressed in Table 4.16.

4.27 The uncertainties for different types and calibrations of Bourdon gages are addressed in Table 4.15.

4.28 Exhaust pressure measurement and the factors affecting measurement uncertainty are presented in the Code, Pars. 4.92 through 4.98. A minimum of two basket-type probes for each exhaust annulus, located 1 ft away from the wall of the exhaust annulus or from any major flow restriction, is recommended for measurement of the exhaust pressure. Normally, the probes should be adjacent to the plane of the last stage blading and close to the turbine exhaust flange. The station vacuum gage connection is seldom located to comply with this requirement, and is generally placed in the casing wall. If such a connection is used, the uncertainty is ±0.5 in. Hg. The uncertainties for different numbers of probes for exhaust pressure measurement are addressed in Table 4.17.

4.29 Temperature Measurement. Refer to the Code, Par. 4.100. For a Code performance test, only calibrated integral cold-junction thermocouples or platinum resistance temperature detectors with calibrated leads are recommended for temperatures with the greatest influence on test results.

Examples of influential temperatures are throttle

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TABLE 4.15
BOURDON GAGE UNCERTAINTIES

Instrument	Quality and Grade	Uncertainty
10 in. test gage	Laboratory, 24 in. scale length calibrated in place and temperature compensated	±0.5% of full scale
8 in. station gage	Commercial, 16 in. scale length, calibrated in place under operating conditions	±1.0% of full scale
Station gage	Commercial, uncalibrated	Indeterminate

GENERAL NOTE: For additional information, see ANSI/ASME PTC 19.2-1986.

TABLE 4.16
TRANSDUCER UNCERTAINTIES

Use	Quality and Grade	Uncertainty
Primary flow differential pressure transducer for test [Note (1)]	Quartz element or equivalent, output reading on high impedance integrating voltmeter, laboratory calibrated	±0.005% of full scale ±0.01% of reading
Secondary flow differential pressure transducer for test [Note (1)]	Medium accuracy laboratory calibrated	±0.25% of full scale
Transducer for gage pressure or absolute pressure for test [Note (1)]	Medium accuracy laboratory calibrated	±0.10% of full scale
Transducers for absolute gage or differential pressures for station use	Deadweight tester calibrated	±0.25% to 0.50% of full scale

GENERAL NOTE: Transducer uncertainties can be reduced by placement in a temperature controlled enclosure or by in-place calibrations at the test enviroment temperature.

NOTE:
(1) Zero and span checked before and after each test with transfer standard having an accuracy certified to 0.03%.

and reheat steam temperatures, final feed temperature, primary flow element fluid temperature, and, when primary flow is calculated by heat balance, temperatures around all heaters downstream of the flow measuring section. For these temperatures, the Code-recommended measuring instruments should be used with the temperature element. A high resolution potentiometer of 0.03% accuracy, or a high resolution bridge of 0.03% accuracy, or an equivalent digital microvolt meter should be used as applicable.

For extensive treatment of thermocouples, refer to ANSI/ASME PTC-19.3-1974 (R1985), Chapter 3.

For a test that deviates from the Code, uncertainty of the temperature measurements should be consistent with the overall expected uncertainty of

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TABLE 4.17
NUMBER OF EXHAUST PRESSURE PROBES

Number of Probes	Exhaust Joint Area: Less Than 32 sq ft	Exhaust Joint Area: 64 sq ft	Exhaust Joint Area: 128 sq ft	Spatial Uncertainty
Required by Code	2	4	8	±0.08 in. Hg
Used	1 [Note (1)]	1 [Note (1)]	2 [Note (1)]	±0.1 in. Hg
Used	–	–	1 [Note (1)]	±0.2 in. Hg

NOTE:
(1) Probe location is at a point whose accuracy has been demonstrated as an average of exhaust pressures in accordance with the Code, Par. 4.93. If not so located, the uncertainty may be as high as ±0.5 in. Hg.

TABLE 4.18
THERMOCOUPLE AND RESISTANCE THERMOMETER UNCERTAINTIES

Instrument	Quality and Grade	Uncertainty
Test thermocouple	Continuous leads, calibrated before and after test in accordance with Par. 4.106 of the Code and used with ±0.03% potentiometer or equivalent microvoltmeters	±1.0°F
Test resistance thermometer	Calibrated before and after test in accordance with Par. 4.106 of the Code and used with ±0.03% bridge	±1.0°F
Test thermocouple	Continuous leads, calibrated against secondary standard and used with ±0.05% potentiometer	±2.0°F
Test thermocouple	Separate test leads of best grade wire, calibrated against secondary standard and used with ±0.05% potentiometer or equivalent digital thermometer	±3.0°F
Thermocouple	Assembled from standard grade wire, not calibrated and used with ±0.20% potentiometer or equivalent digital thermometer	±7.0°F
Station recording thermocouple	Assembled from standard lead wire, not calibrated and used with ±0.30% station recording potentiometer	±10.0°F

the test. The quality and grade of the various test instruments should be coordinated. For example, if primary flow is measured as in Item H of Table 4.10, it will make little difference whether the temperature is measured by commercial thermocouple or laboratory thermocouple.

Tables 4.18 and 4.19 include the general types of instruments used for measuring the temperature of the fluid at various locations in the cycle, such as throttle, extraction stages, heaters, and exhaust.

For thermocouples, the uncertainty of the measurement depends upon the combination of the thermocouple, the wiring, the reference junction, and the reading instrument. Potentiometers are available as follows (values are percentages of readings):

Instrument	Limits of Uncertainty
Precision laboratory potentiometer	±0.01%
Precision portable potentiometer	±0.03%
Industrial potentiometer	±0.20%
Recording potentiometer for a switchboard	±0.30%

When a digital indicating instrument is used, the accuracy and resolution of the instrument must be consistent with the expected uncertainty of the thermocouple element.

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TABLE 4.19
LIQUID-IN-GLASS THERMOMETER UNCERTAINTIES

Instrument	Quality and Grade	Uncertainty
Glass stem thermometer	Etched-stem laboratory type	
	to 300°F	±0.5°F
	to 600°F	±2.0°F
Glass stem thermometer	Industrial type, calibrated	
	to 300°F	±2.0°F
	to 600°F	±3.0°F
Station thermometer	Industrial type, not calibrated	
	to 300°F	±5.0°F
	to 600°F	±10.0°F

GENERAL NOTE: See ANSI/ASME PTC 19.3-1974 (R1985), Table 5.4, page 49 and Par. 4.29.

For temperature measurement systems using separate test leads, precautions must be taken to ensure that the connecting wire terminals at the thermocouple are clean and tight.

For calibration purposes, a secondary-standard thermocouple is one whose calibration is traceable to the National Bureau of Standards using a precision potentiometer, or one calibrated in accordance with the Code, Par. 4.106. The time elapsed since calibration of this standard should not exceed 12 months.

4.30 For liquid-in-glass thermometers, an emergent-stem correction must be added algebraically to the indicated temperature. For a total immersion mercury-in-glass thermometer, the correction can be calculated from the following equation:

$$K = 0.00009\ D\ (t_1 - t_2)$$

where

K = correction, °F
D = length of emergent stem expressed in °F on the thermometer stem
t_1 = temperature indicated by the thermometer, °F
t_2 = mean temperature of the exposed emergent stem, °F. Values of t_2 are measured using an auxiliary thermometer mounted on the emergent stem.

NOTE: Inasmuch as t_1 is not the true temperature of the bulb of the immersed thermometer, the correction K is only approximate upon substitution in the above equation. If a new substitution in the equation is made using $t_1 + K$ as the new value for t_1, the new correction K will be more nearly correct. Further recalculation with t_1, corrected for the new value of K, will result in a more correct value for K. Seldom are more than two recalculations necessary and then only for high temperatures and long emergent stems. Refer to ANSI/ASME PTC 19.3-1974 (R1985), Chapter 5, Par. 48, for sample calculations of emergent-stem corrections.

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SECTION 5 — COMPUTATION OF RESULTS

5.01 The uncertainty of an overall result is dependent upon the collective influence of the component uncertainties of the test data. Since various combinations of measurements will be required for any test, a method is given for determining how individual test data uncertainties may be combined into an overall uncertainty for the result. This can be done in four steps.

First, the uncertainty of each measured parameter (throttle temperature, pressure, and other similar items) must be determined by considering the contribution of the three sources of uncertainty discussed in Par. 5.02.

Second, some variables that affect heat rate are calculated from several measured parameters. The determination of the uncertainty of these calculated variables must be based on the uncertainty of each of the measured parameters from which they are calculated and the effect each of the parameters has on the variable. The second step is discussed in Par. 5.03.

Third, the effect each variable has on the final test result (so-called influence factors) must be determined as discussed in Par. 5.04. Three methods for obtaining influence factors are recommended: the use of a generally applicable table (Par. 5.06), the use of a computer to perform a perturbation analysis (Par. 5.07), and analytical differentiation (Par. 5.08).

Fourth, the uncertainties of each variable are combined to determine the overall uncertainty for the test results as explained in Par. 5.05.

A numerical example of the methods discussed is given in Pars. 5.09 and 5.10 and in Appendix I.

5.02 Uncertainty of Individual Measurements. First, the uncertainty of the individual measurements must be determined. In general, the uncertainty of a measurement is the combination of uncertainties from as many as three sources. These are instrument uncertainty due to the measuring device itself and sampling uncertainties introduced by measuring parameters that vary with time and space using a limited number of readings and sampling points. Procedures for determining the magnitude of each of these uncertainties are described in items (a), (b), and (c) below. In item (d), the contributions from each source of uncertainty on a particular parameter are combined into an overall measurement uncertainty.

(a) Usually, the most significant source of uncertainty is that of the measuring device. Values of uncertainty for the various instruments used were given in the previous Section. However, it should be noted that if the value of a parameter is obtained by averaging the readings of several instruments of the same kind and grade, then the effect of the uncertainty in the averaged reading of a measurement is reduced by a factor equal to the square root of the number of duplicate instruments used:

$$U_I = U_I'/\sqrt{M}$$

where

U_I = uncertainty in the average value of the measurement due to uncertainty of each instrument used
U_I' = basic uncertainty of the instrument given in Section 4
M = number of duplicate instruments used in obtaining the average

For example, if throttle temperature is measured by averaging the readings of three test thermocouples with separate test leads:

$$U_I' = \pm 3.0°F \text{ (Table 4.18)}$$

$$U_I = 3.0/\sqrt{3} = \pm 1.73°F$$

It is emphasized that averaging the readings of several instruments to reduce uncertainty is valid only if the errors are randomly distributed so that

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high readings tend to offset low readings. Generally, instrument errors are composed of two components, namely a random component and a systematic component. The random component may be due to scale readability (or precision) and nonrepeatability of response. The systematic component may be due to drift in calibration and nonlinear response. This is a fixed bias causing errors which produce consistently high or low readings. In a well-designed instrument, the random component is small and can be further reduced by using multiple instruments and, when readability has an effect, by multiple readings of the same instruments. In uncertainty analysis, the systematic component is usually treated as random since its direction, high or low, is unknown. (If the direction were known, its effects could be eliminated by correcting the reading.) However, the systematic component will not always be reduced by the use of multiple instruments. For example, if two Bourdon gages are used to measure the same pressure, nonlinearity in response over the scale range will cause similar errors in both gages; if the gages are not temperature-compensated, then calibration drift errors will also exist. Similarly, all thermocouples calibrated in the laboratory using a secondary standard will contain the same calibration bias as the secondary standard. In each of these cases, factors such as design characteristics and calibration accuracy introduce errors that will not be reduced by the use of multiple instruments. Hence, judgment must be used when determining the uncertainty in averaged readings.

(*b*) The magnitude of test parameters may vary over time. The magnitude and frequency of the variations will depend on the nature of the measured parameter and the manner in which the test is conducted. The variations may be at relatively high frequency, such as pressure pulsations due to flow instabilities, or slow oscillations caused by hunting of an under-damped automatic control system. Although the accuracy of the measurement at the instant of reading is not affected by the variations, they will introduce another source of uncertainty into the final test result. This is because the measurements of many parameters must be combined to obtain the final result and all the required readings cannot be taken simultaneously. For example, throttle enthalpy is determined from measured pressure and temperature. If these two parameters vary with time and are not read simultaneously, throttle enthalpy will be affected by the variability. Paragraph 3.05 provides a method for determining the number of readings required to minimize the time variability effect on the combined uncertainty of the result. However, if this requirement cannot be satisfied, the effect of this source of uncertainty must be accounted for separately, based on the number of readings available (see Par. 3.05). The method presented in this Report utilizes statistical methods to estimate data variability. The variability estimate is then translated into an uncertainty by considering the assumed distribution of the data and the desired confidence level.

There are two statistical methods for estimating variability, each with its own distribution. The preferred method utilizes the standard deviation estimator and requires at least 10 readings:

$$S = \sqrt{\sum_{i=1}^{N} (X_i - \bar{X})^2/(N - 1)}$$

where

S = standard deviation estimation
X_i = individual reading
$\bar{X}$ = average of all readings
N = number of readings

The variability in the average reading is given by $S/\sqrt{N}$ and the uncertainty interval is constructed by multiplying this term by the appropriate value of the Student's *t*-distribution. The *t*-distribution for a 95% confidence level (consistent with the definition of uncertainty throughout this Report) is shown in Table 5.1, Column (a) as a function of degrees of freedom (defined as the number of readings minus 1).

Thus:

$$U_t = t_\nu (S/\sqrt{N})$$

where

U_t = uncertainty in average value of the readings due to time variability
t_ν = value of *t*-distribution for 95% confidence and ν degrees of freedom
ν = degrees of freedom = $N - 1$

If duplicate readings are taken on several instruments which are then averaged into a single value, the uncertainty is:

$$U_t = t_\nu \bar{\bar{S}}/\sqrt{MN}$$

where

$\bar{\bar{S}}$ = the average of the S values computed from the readings of each instrument

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$$\bar{\bar{S}} = \sqrt{\sum_{i=1}^{M} S_i^2/M}$$

where

M = number of instruments
$\nu = M(N - 1)$

As an example, consider a throttle temperature obtained by averaging the combined 10 readings from each of three thermocouples.

THROTTLE TEMPERATURE, °F

Reading No.	Thermo-couple 1	Thermo-couple 2	Thermo-couple 3
1	901.0	901.5	900.5
2	900.0	900.5	899.5
3	898.0	897.5	896.5
4	897.0	895.5	895.5
5	896.0	894.5	895.0
6	899.0	898.5	898.0
7	903.0	903.5	902.5
8	904.0	902.5	903.0
9	902.0	901.5	901.0
10	905.0	904.5	903.5
Average, $\bar{T}_{it}$	900.5	900.0	899.5
Standard Deviation Estimator, S_i	3.028	3.375	3.127

Overall Average $\bar{\bar{T}}_{it} = (\bar{T}_1 + \bar{T}_2 + \bar{T}_3)/3 = 900.0°F$

Average S_i $\bar{\bar{S}} = \sqrt{(3.028^2 + 3.375^2 + 3.127^2)/3} = 3.180$

Degrees of freedom, $\nu = M(N - 1) = 3\,(10 - 1) = 27$

t-distribution, $t_{27} = 2.052$

The uncertainty due to variability with time is $U_t = 2.052 \times 3.180/\sqrt{3 \times 10} = \pm 1.2°F$

Another method of estimating variability is less accurate but can be used with a small number of readings (fewer than 10). This method utilizes the range of the sample, which is defined as the difference between the largest and smallest readings, and a Substitute t-distribution, shown in Table 5.1, Column (b):

$$U_t = t'_\nu R$$

where

t'_ν = value of substitute t-distribution for degrees of freedom
R = range (largest minus smallest reading)
ν = degrees of freedom

Similarly, if the average of several instruments is used:

$$U_t = t'_m \bar{R}/\sqrt{M}$$

TABLE 5.1
VALUES OF THE STUDENT'S t- AND SUBSTITUTE t-DISTRIBUTIONS FOR A 95% CONFIDENCE LEVEL

Degrees of Freedom, ν	Column (a) Student's t-distribution	Column (b) Substitute t-distribution
1	12.706	· · ·
2	4.303	6.353
3	3.182	1.304
4	2.776	.717
5	2.571	.507
6	2.447	.399
7	2.365	.333
8	2.306	.288
9	2.262	.255
10	2.228	.230
11	2.201	.210
12	2.179	.194
13	2.160	.181
14	2.145	.170
15	2.131	.160
20	2.086	.126
25	2.060	· · ·
30	2.042	· · ·
40	2.021	· · ·
60	2.000	· · ·
120	1.980	· · ·
α	1.960	· · ·

where

$\bar{R}$ = average of the ranges of each instrument

$$\bar{R} = \sqrt{\sum_{i=1}^{M} R_i/M}$$

(c) In some cases, the measured value of the parameter varies with the location. Turbine exhaust pressure for a condensing turbine is an example. Since it is impractical to measure at a very large number of points, a computed average based on a limited number of measurements must be accepted. Hence, a third uncertainty source results from the variability over space. If we assume these variations are randomly distributed, the magnitude of this uncertainty source can be calculated using the procedures described above for variation with time. In this case, the standard deviation estimator should be used if more than 10 measuring locations are available; and the range estimate used for fewer than 10 locations. For example, assume pressure is measured by four static pressure probes in the exhaust annulus of a condensing turbine. Readings, from precision-bored, compen-

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sated-scale mercury manometers without reading aids, are as follows:

Probe Location	Exhaust Pressure, in. Hg
1	1.50
2	1.43
3	1.55
4	1.47

Range, $R = 1.55 - 1.43 = 0.12$
Number of locations, $L = 4$
Substitute t-distribution, $t'_L = 0.717$

The uncertainty in the average due to the variability with space is:

$$U_s = t'_L R$$

$$= 0.717 \times 0.12 \text{ in. Hg}$$

$$U_s = \pm 0.09 \text{ in. Hg}$$

However, since a different instrument is usually used at each location, some of the variability apparently due to location will in fact be due to instrument uncertainty. Therefore, unless multiple instruments are used at each location, the instrument uncertainty and the spatial uncertainty should be compared and only the larger of the two used to determine the overall measurement uncertainty. In the example of throttle temperature, if the three thermocouples were installed in the same plane perpendicular to the center line of the pipe, a maximum observed space variability (range) of 1.0°F could be noted for three spatial locations:

$$U_s = t'_L R$$

$$= 1.304 \times 1.0°\text{F}$$

$$U_s = \pm 1.3°\text{F}$$

The uncertainty due to the instrumentation, U_I, was computed as ± 1.7°F. Since $U_I > U_s$, only the instrument uncertainty is combined with the time uncertainty to obtain the overall uncertainty. For the exhaust pressure example, however, the spatial uncertainty is larger than the instrument uncertainty (Table 4.13); hence, only U_s would be used.

(*d*) Once the uncertainty contributions from each source have been determined, they can be combined into an overall measurement uncertainty for each parameter. Since instrument uncertainty and spatial variability were assumed as independent of time, the overall uncertainty of a parameter P equals the square root of the sum of the squares:

$$U_P = \sqrt{U_{Pt}^2 + (U_{PI} \text{ or } U_{PS})^2}$$

where

U_P = overall uncertainty in parameter P
U_{Pt}, U_{PI}, U_{PS} = uncertainty due to variability with time, instrumentation, and space, respectively

For the example of throttle temperature:

$$U_T = \sqrt{U_{Tt}^2 + U_{TI}^2} = \sqrt{(1.2)^2 + (1.7)^2}$$

$$U_T = \pm 2.1°\text{F}$$

5.03 Uncertainty of Calculated Variables. The combined uncertainty of variables calculated from the measurement of several parameters (such as those required to calculate flow and power) is determined by summing the component uncertainties of each parameter, using the square root of the sum of squares method. The component uncertainties are calculated by multiplying the overall uncertainty of each parameter by the effect of a change in that parameter on the variable (sensitivity). If R is a variable calculated from the measurement of K parameters, P_1, P_2, ... P_k then:

$$U_R = \sqrt{\sum_{I=1}^{K} \left(\frac{\partial R}{\partial P_i} U_{pi}\right)^2}$$

where

U_R = uncertainty in calculated variable R
$\frac{\partial R}{\partial P_i}$ = sensitivity of R to a change in P (influence factor)
U_{pi} = overall uncertainty in measured parameter due to instrumentation, spatial, and time variability

5.04 Effect of Uncertainty in Each Variable on the Overall Test Result. Due to the nature of steam turbine performance, certain test variables such as

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TABLE 5.2
EFFECT ON HEAT RATE UNCERTAINTY OF SELECTED PARAMETERS

Parameter	*Effect on Corrected* Heat Rate Uncertainty
Throttle temperature	+0.07% per °F
Cold-reheat temperature	−0.04% per °F
Hot-reheat temperature	+0.05% per °F
Final feedwater temperature [Note (1)]	+0.03% to +0.04% per °F
Final feedwater temperature [Note (2)]	−0.12% per °F
Temperature of condensate to deaerator [Note (1)]	−0.11% to −0.13% per °F
Temperature of feedwater to top heater [Note (1)]	+0.02% to +0.04% per °F
Temperature of feedwater to first high-pressure heater [Note (1)]	−0.05% to −0.08% per °F
Temperature of condensate from deaerator [Note (1)]	+0.06% to +0.12% per °F
Throttle pressure	+0.02% to +0.04% per %
Cold-reheat pressure	−0.05% to −0.08% per %
Hot-reheat pressure	+0.08% per %
Low-pressure-turbine exhaust pressure	Derive from correction curve
Main-condensate flow	+1.0% per %
Power	−1.0% per %

GENERAL NOTE: Effects are for +1°F or +1.0%.
NOTES:
(1) This value applies only when extraction flows are used to determine feedwater flows, as when the main flow measured is in the condensate line to the deaerator.
(2) This value applies only when the main flow measurement is essentially final feedwater flow, as when all heaters are the tube-and-shell type and the drains cascade to the condenser or low-pressure heater.

flow and power affect the overall test result on a 1:1 ratio; i.e., a 1% uncertainty in flow or power causes a 1% uncertainty in steam rate or heat rate. Other test variables, such as pressures, temperatures, and secondary flows, affect the overall test results to a lesser extent. These ratios may also be termed influence factors. The development of these ratios is discussed in Pars. 5.06 through 5.08. The reader is cautioned against the inappropriate use of the familiar correction-factor curves for throttle and reheat steam conditions to determine these ratios. Since uncertainties in these steam conditions affect steam enthalpies used in the heat rate equation, these curves will not reflect the effects of measurement uncertainties. Therefore, a specified change and an equal uncertainty will not produce the same correction to the test results. However, for a condensing unit, the exhaust pressure correction to heat rate can be used to determine the exhaust pressure uncertainty effect, since the heat rate equation values are unaffected.

5.05 Obtaining an Overall Uncertainty for the Test Result. For the same confidence level (i.e., 95%) in the overall uncertainty as in the component uncertainty, the square root of the sum of squares component uncertainty is calculated. Hence, overall uncertainty:

$$U_{HR} = \sqrt{\sum_{i=1}^{K} U_{HRi}^2}$$

where

U_{HRi} = uncertainty of each variable used to determine the final test result (heat rate)

As discussed in Pars. 0.02 and 3.01, agreement should be reached prior to testing on the expected uncertainty due to deviations from the Code. Using the methods presented herein, instrumentation uncertainty and, in some cases, spatial uncertainty can be predetermined. For example, Table 4.17 allows the determination of spatial uncertainty in turbine exhaust pressure when the number of probes is less than that recommended by the Code. However, in cases where few previous test results exist, spatial and time uncertainties cannot be determined. Nevertheless, adherence to the requirements of Par. 3.05 will assure that the effect of this source of uncertainty on test results is minimized. If test measurements significantly exceed the test uncertainty agreed to before the test, a new uncertainty agreement and test may be indicated.

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5.06 Table 5.2 can be used to determine the effects of individual measurements on the test results required to determine the influence factors discussed in Par. 5.04.

Table 5.2 contains results of calculations made for reheat regenerative turbine generator units with throttle pressures ranging between 1800 psig to 2400 psig and throttle and reheat temperatures between 1000°F to 1100°F. Since many combinations of steam conditions and cycles are possible, a range of probable values is given. The list includes only those variables having the greatest influence on test results.

5.07 When the effect of the individual measurement cannot be obtained from Table 5.2, it can be determined by following an appropriate calculation procedure. One procedure evaluates a test twice, using each of the two values of a particular variable and noting their difference. Since this must be done for each variable of significance, it is best to use a computer. An alternative approach involves an analysis which is outlined in the following paragraph and should be used for the less complex cases.

5.08 An alternative approach to evaluating the effects of uncertainties in test measurements upon the overall uncertainty employs analytical or numerical differentiation. The method is outlined as follows.

(*a*) Define the test result to be evaluated, including correction factors to contract conditions, if applicable. An example is selected with the following data:

Steam conditions of 850 psig, 900°F, 1.5 in. Hg abs, 141,590 lbm/h throttle flow, 16,500 kW, at 0.85 power factor, 351.8°F final feedwater temperature, with a specified heat rate of

$$HR = \frac{141{,}590(1453.1 - 325.0)}{16{,}500} = 9680 \text{ Btu/kWh}$$

For this example, the uncertainty in the corrected heat rate will be evaluated. The corrected heat rate is defined as:

$$HR_c = \frac{w_{lt}(h_{lt} - h_{11})}{P_g \times CF_{P1} \times CF_{T1} \times CF_{p6}} \quad (1)$$

where

w_{lt} = test value for throttle flow
h_{lt} = test value for throttle enthalpy
h_{11} = value of final-feedwater enthalpy including Group 1 corrections (specified cycle corrections, see Code Par. 5.22)
P_g = value of generator output including Group 1 corrections
CF_{P1} = heat-rate-divisor correction factor for throttle pressure
CF_{T1} = heat-rate-divisor correction factor for throttle temperature
CF_{p6} = heat-rate-divisor correction factor for exhaust pressure

(*b*) Determine the effect of a change in each variable in the right-hand side of Eq. (1) on the overall test result. This may be readily done by inspection for flow, power, and each of the correction factors; but a general approach follows.

(*1*) Rewrite the overall test result expression in logarithmic form. For example:

$$\ln HR_c = \ln w_{lt} + \ln (h_{lt} - h_{11}) - \ln P'_g - \ln CF_{p1} - \ln CF_{T1} - \ln CF_{po} \quad (2)$$

(*2*) Differentiate term by term, noting that $d(\ln u) = du/u$, and replace the differential d with difference Δ

$$\frac{\Delta HR_c}{HR_c} = \frac{\Delta w_{lt}}{w_{lt}} + \frac{\Delta h_{lt}}{(h_{lt} - h_{11})} - \frac{\Delta h_{11}}{(h_{lt} - h_{11})} - \frac{\Delta P'_g}{P'_g} - \frac{\Delta CF_{p1}}{CF_{p1}} - \frac{\Delta CF_{T1}}{CF_{T1}} - \frac{\Delta CF_{po}}{CF_{po}} \quad (3)$$

Each of the terms in Eq. (3) except the two containing enthalpy variables represents the fractional change for the respective variable; and, in the context of this analysis, they represent the uncertainty of that variable expressed as a fraction. It should be noted that an uncertainty in flow affects the uncertainty in heat rate in the same direction, whereas uncertainty in power and correction factors affect the heat rate in the opposite direction. This is denoted in the following analysis by the use of plus or minus coefficients, respectively.

(*3*) The effect of uncertainty in each correction factor due to uncertainties in the corresponding test variable is determined from correction curves. Typical correction curves in Figs. 5.1 through 5.3 are used to illustrate this procedure. From these curves the following effects on corrected heat rate uncertainty are established by determining the slope of the curve at the test values of 850 psig,

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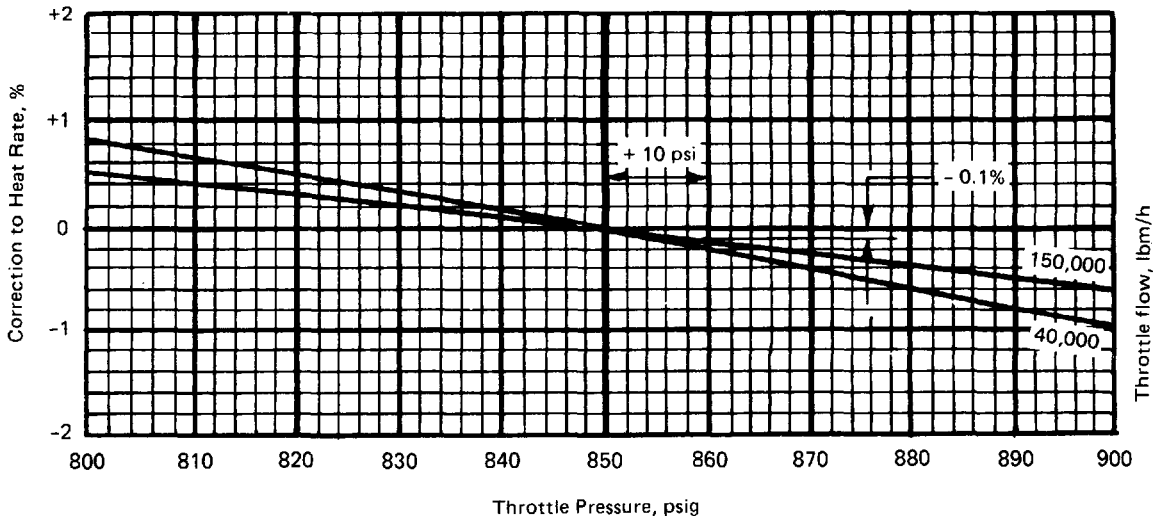


FIG. 5.1 TYPICAL THROTTLE PRESSURE CORRECTION CURVES FOR TURBINES WITH SUPERHEATED INITIAL STEAM CONDITIONS

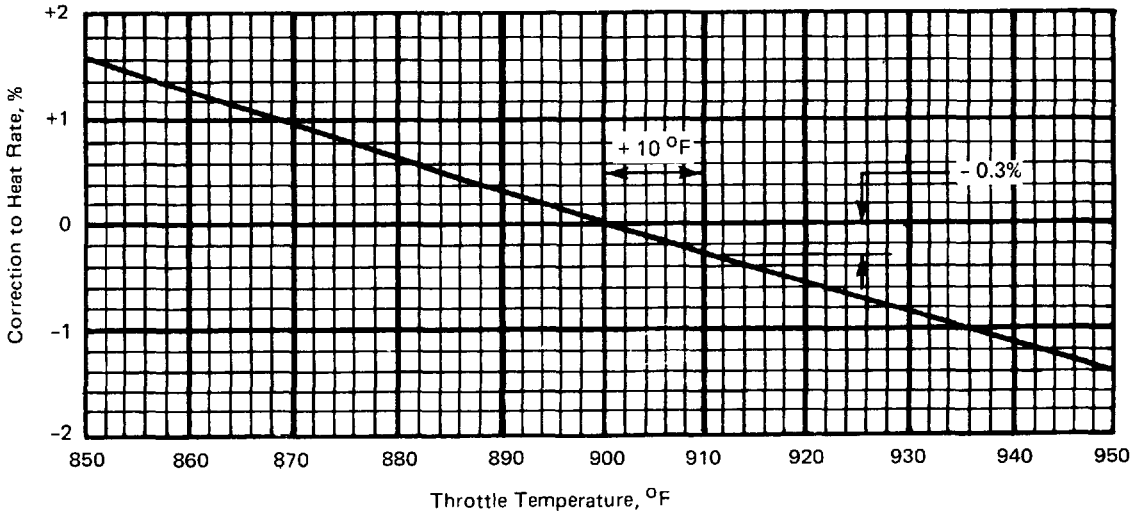


FIG. 5.2 TYPICAL THROTTLE TEMPERATURE CORRECTION CURVE FOR TURBINES WITH SUPERHEATED INITIAL STEAM CONDITIONS

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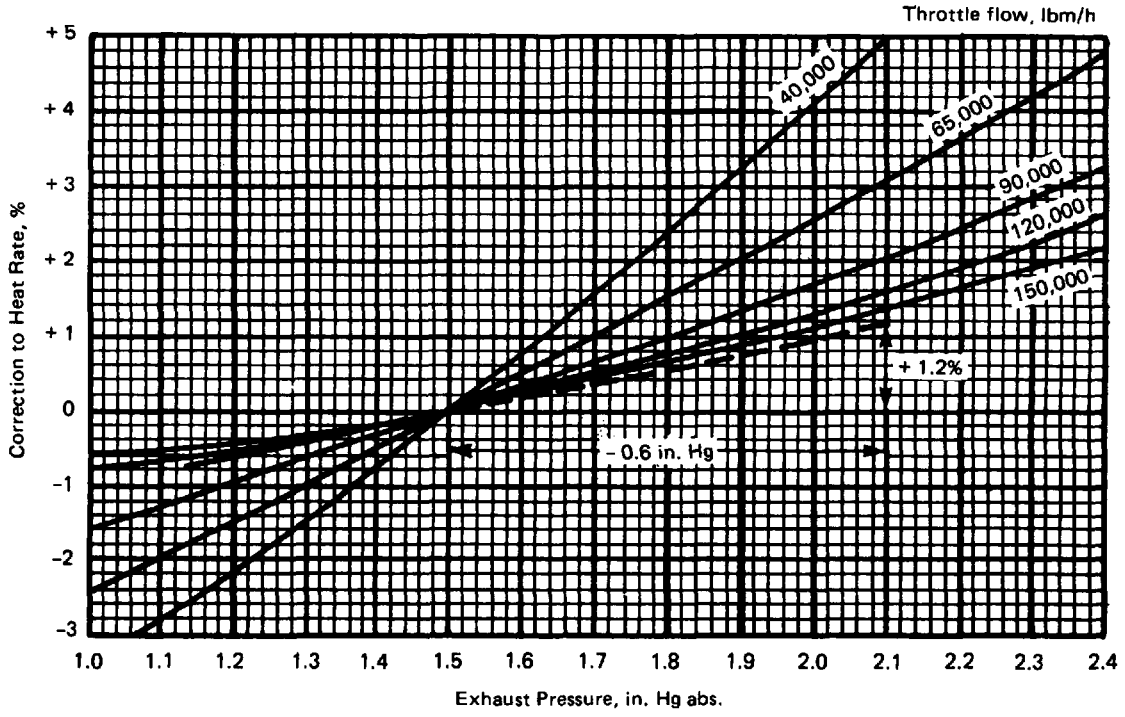


FIG. 5.3 TYPICAL EXHAUST PRESSURE CORRECTION CURVES

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900°F, 1.5 in. Hg abs and 141,590 lbm/h throttle flow (using the 150,000 lbm/h curve).

(*a*) *Throttle pressure.* A change of +10 psi = −0.10% on heat rate. This becomes +0.010% on heat rate per psi when the negative coefficient from Eq. (3) is applied.

(*b*) *Throttle temperature.* A change of +10°F = −0.30% on heat rate. This becomes +0.030% on heat rate per °F when the negative coefficient from Eq. (3) is applied.

(*c*) *Exhaust pressure.* A change of +0.6 in Hg = 1.20% on heat rate. This becomes −2.0% on heat rate per in. Hg when the negative coefficient from Eq. (3) is applied.

(*4*) The two terms in Eq. (3) containing enthalpy must be converted to actual test measurement as follows.

(*a*) Throttle enthalpy is generally determined from direct pressure and temperature measurements at that location. Therefore, the uncertainty in throttle enthalpy may be expressed as:

$$\Delta h_{lt} = \left[\frac{\partial H_{SH}}{\partial p}\right]_T \Delta p_{lt} + \left[\frac{\partial H_{SH}}{\partial T}\right]_p \Delta T_{lt} \qquad (4)$$

where

Δh_{lt} = uncertainty in throttle enthalpy in units of Btu/lbm

$\left[\frac{\partial H_{SH}}{\partial p}\right]_T$ = slope of the superheated steam enthalpy versus pressure curve at constant temperature. This slope is given in Fig. 5.4. For the example 850 psig, 900°F, it is −0.036 Btu/lbm-psi.

$\left[\frac{\partial H_{SH}}{\partial T}\right]_p$ = slope of the superheated steam enthalpy versus temperature curve at constant pressure. This slope is given in Fig. 5.5. For the example 850 psig, 900°F, it is 0.565 Btu/lbm-°F.

Δp_{lt}, ΔT_{lt} = the uncertainties in test throttle pressure and temperature in units of psi and °F, respectively

(*b*) This uncertainty in throttle enthalpy affects the corrected heat rate uncertainty as determined in Eq. (3), as follows:

$$\frac{\Delta h_{lt}}{(h_{lt} - h_{11})} = \frac{\left[\frac{\partial H_{SH}}{\partial p}\right]_T \Delta p_{lt}}{(h_{lt} - h_{11})} + \frac{\left[\frac{\partial H_{SH}}{\partial T}\right]_p \Delta T_{lt}}{(h_{lt} - h_{11})} \qquad (5)$$

For example, on a percent heat rate uncertainty basis:

$$\frac{\Delta h_{lt} \times 100}{(h_{lt} - h_{11})} = \frac{-0.036 \times 100}{(1453.1 - 325.0)} \Delta p_{lt} + \frac{0.565 \times 100}{(1453.1 - 325.0)} \Delta T_{lt} = -0.003\Delta p_{lt} + 0.050\Delta T_{lt} \qquad (6)$$

(*c*) The basis for final feedwater enthalpy determination differs with the type of test conducted. For the example for the specified cycle, the value is taken after Group 1 corrections have been applied; as such, it is based upon the pressure measurement at the turbine flange in the extraction line feeding the final heater, with specified line pressure drop and specified heater terminal difference applied.

For routine tests, where the specified cycle is not considered, the final feedwater enthalpy depends on the temperature and pressure measurements of that feedwater.

For example, the effect of an uncertainty in the turbine extraction pressure measurement upon the final feedwater enthalpy will depend upon the thermodynamic relationship between enthalpy of compressed liquid and saturation pressure. For practical purposes, the slope of the saturated liquid enthalpy versus pressure relation can be used. The difference between the slopes of the compressed liquid and saturated liquid enthalpy-pressure relations is negligible.

$$\Delta h_{11} = \left[\frac{\partial H_{SL}}{\partial p_{SL}}\right] \Delta p_x \qquad (7)$$

where

Δh_{11} = uncertainty in final feedwater enthalpy in units of Btu/lbm

$\left[\frac{\partial H_{SL}}{\partial p_{SL}}\right]$ = slope of saturated liquid enthalpy versus saturation pressure curve. This slope is plotted on Fig. 5.6 for saturated liquid [Note (1)]. For the example it is 0.566 Btu/lbm-psi (at 147 psia) [Note (2)].

NOTES:

(1) The companion slope ($\partial H_{SL}/\partial T_{SL}$) is given in Fig. 5.7 for use when the final feedwater enthalpy is based upon a temperature measurement.

(2) This is the pressure equivalent to measured pressure at the turbine extraction flange (164.9 psia), less 5% specified line pressure loss and less 5°F specified heater terminal temperature difference.

Δp_x = uncertainty in test pressure at turbine extraction flange connected to final heater, in units of psi

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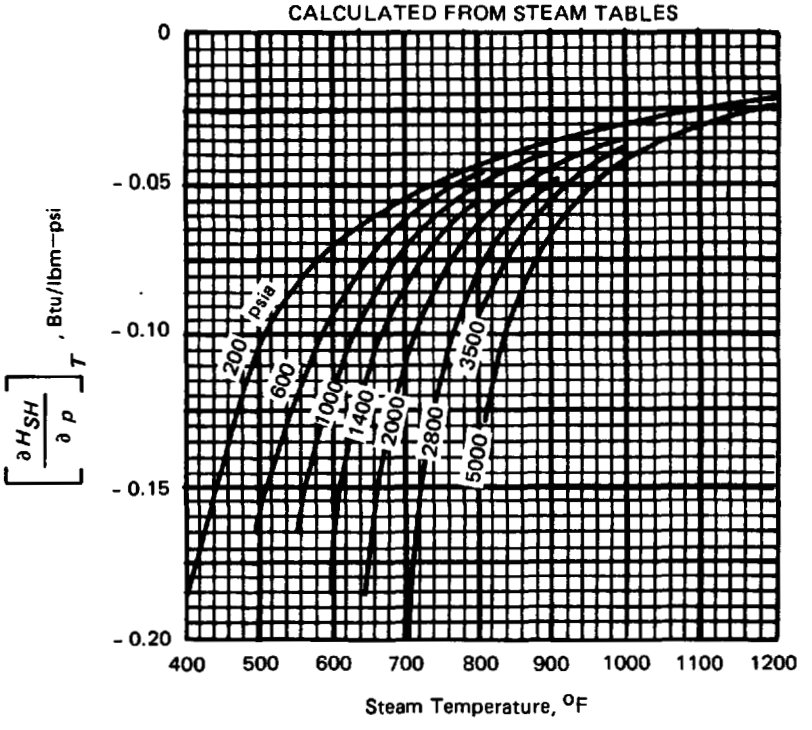


FIG. 5.4 SLOPE OF SUPERHEATED STEAM ENTHALPY AT CONSTANT TEMPERATURE

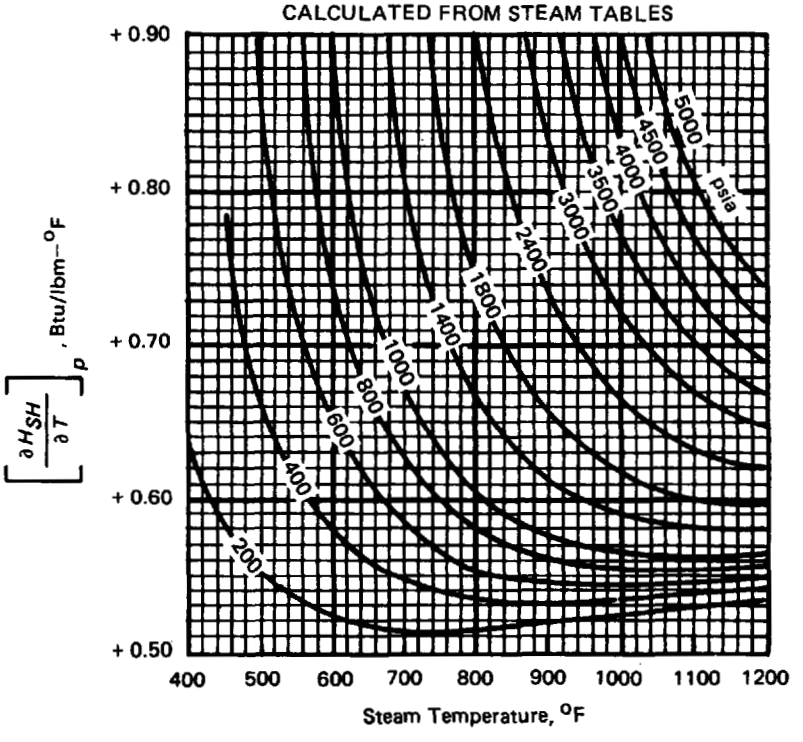


FIG. 5.5 SLOPE OF SUPERHEATED STEAM ENTHALPY AT CONSTANT PRESSURE

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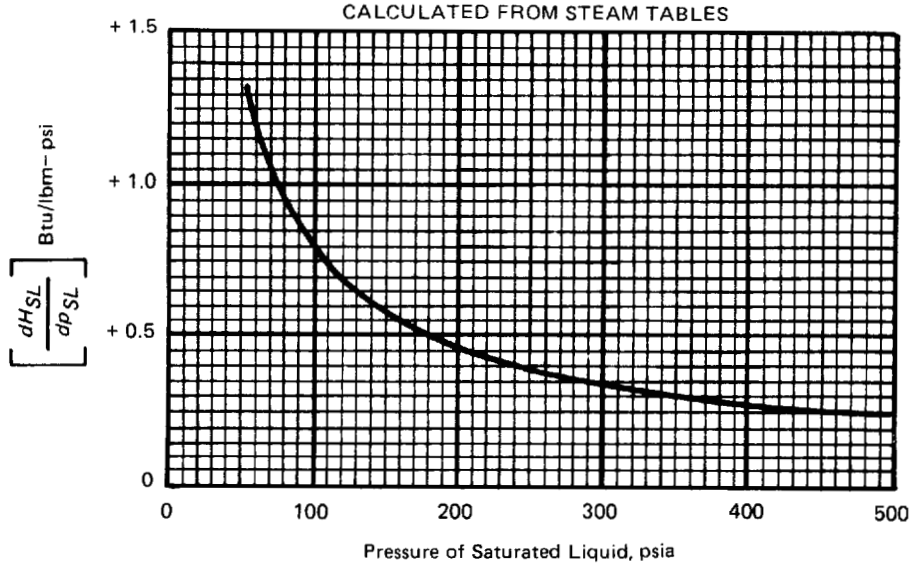


FIG. 5.6 SLOPE OF SATURATED LIQUID ENTHALPY (PRESSURE)

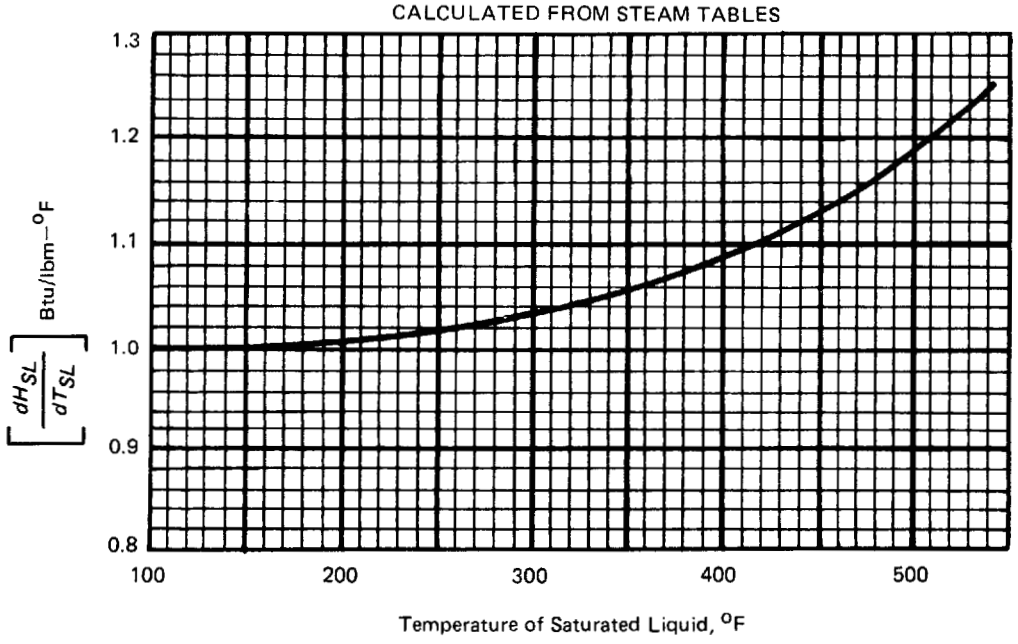


FIG. 5.7 SLOPE OF SATURATED LIQUID ENTHALPY (TEMPERATURE)

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(*d*) This uncertainty in final feedwater enthalpy affects the corrected heat rate uncertainty as determined in Eq. (3) as follows:

$$\frac{-\Delta h_{11}}{(h_{lt} - h_{11})} = \frac{-\left[\frac{\partial H_{SL}}{\partial p_{SL}}\right] \cdot \Delta p_x}{(h_{lt} - h_{11})} \tag{8}$$

For example, on a % heat rate uncertainty basis:

$$-\frac{\Delta h_{11} \times 100}{(h_{lt} - h_{11})} = \frac{-(0.566)(100) \cdot \Delta p_x}{(1453.1 - 325.0)} = -0.0502\Delta p_x \tag{9}$$

5.09 To illustrate the use of the data and procedures in the foregoing paragraphs, an example of a pretest uncertainty estimate follows. Table 5.3 presents a summary of the results. In this table, Column A is the measurement under consideration, Column B is the calculated effect of that measurement on heat rate as discussed in Pars. 5.6 through 5.8, Column C is the resulting instrumentation uncertainty, and Column D is the component heat rate uncertainty in percent. In Par. 5.10, the example is continued to demonstrate the techniques for reassessing the uncertainty after performing the test.

(*a*) Throttle measurement employs an 8 in. station gage with 1000 psig full scale (Table 4.15). Uncertainty of ±1% of full scale gives ±10 psi for instrument uncertainty.

Net effect on heat rate uncertainty = 0.007% per psi (Table 5.3, Column B, line 3).

Heat rate uncertainty = 0.007 × ±10 = ±0.07% (Column D).

(*b*) Throttle temperature measurement uncertainty due to instrument uncertainty is ±1.73°F as previously determined in Par. 5.02.

Net effect on heat rate uncertainty = 0.080% per °F (Table 5.3, Column B, line 4).

Heat rate uncertainty = 0.080 × ±1.73 = ±0.14% (Column D).

(*c*) Exhaust pressure is sampled by four static pressure probes installed in an exhaust annulus with a 64 ft^2 area. A separate mercury manometer is used on each probe.

The manometers are precision-bored and scale compensated, without optical reading aids. The basic instrument uncertainty is ±0.05 in. Hg (Table 4.13, Item 2), and since four manometers and four probes are used, the average uncertainty of the readings is ±0.025 in. Hg (i.e., $0.05/\sqrt{4}$).

Net effect on heat rate uncertainty = −2% per in. Hg (Table 5.3, Column B, line 5).

Heat rate uncertainty = −2 × ±0.025 = ±0.05% (Column D).

Although the number of probes satisfies the Code criteria for minimum uncertainty, the spatial uncertainty has not been previously demonstrated as required by the Code. This may increase the uncertainty of the average exhaust pressure measurement. Consequently, the readings should be checked after the test to determine if sampling uncertainties due to spatial variations should have been accounted for.

(*d*) Extraction pressure is measured with an 8 in., 300 psig full scale station gage (Table 4.15). Uncertainty of ±1% of full scale gives ±3 psi instrument uncertainty.

Net effect on heat rate uncertainty = −0.05% per psi (Table 5.3, Column B, line 6).

Heat rate uncertainty = −0.05 × ±3 = ±0.15% (Column D).

(*e*) Electrical power is measured with one 2½-element polyphase watthour meter which measures the total power of three phases and is applied to a three-phase, four-wire connected generator as shown in Fig. 4.1(c).

The following instruments will be used:

(*1*) watthour meters — three-phase portable meter without mechanical register, calibrated before testing;

(*2*) potential transformers — type calibration curve available, burden power factor is 0.85, 0.3% metering accuracy class;

(*3*) current transformers — type calibration curve available, burden power factor is 0.85, 0.3% metering accuracy class.

The equation for power as read by a watthour meter is:

$$P_T = [(K_h)(R)(CTR)(PTR)]/t$$

where

P_T = total power
K_h = meter constant
R = number of meter disc revolutions
CTR = current transformer ratio
PTR = potential transformer ratio
t = time interval for R revolutions

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The above equation is correct if the metering method meets Blondel's Theorem as discussed in Par. 4.04. If the metering does not meet Blondel's Theorem, the power calculated by the above equation should be multipled by a correction factor. That factor is unknown but, within the context of this analysis, only that factor's uncertainty is required. Let the variable M represent the correction factor. Rewriting the above equation to include the correction factor results in the following equation:

$$P_T = [M(K_h)(R)(CTR)(PTR)]/t$$

Following the procedure outlined in Par. 5.08, and writing the power equation in logarithmic form:

$$\ln P_T = \ln M + \ln K_h + \ln R + \ln CTR + \ln PTR - \ln t$$

$$\Delta P_T/P_T = (\Delta M/M) + (\Delta K_h/K_h) + (\Delta R/R) + (\Delta PTR/PTR) + (\Delta CTR/CTR) - (\Delta t/t).$$

Each bracketed right-hand term in this equation can be identified as an instrument or measurement uncertainty. The uncertainty of each term in the above equation can now be determined.

(1) Metering method uncertainty, $\Delta M/M$ — the uncertainty is obtained from Table 4.1, Item (c):

$$\Delta M/M = \pm 0.5\%$$

(2) Disc revolution uncertainty, $\Delta R/R$ — assume that 50 disc revolutions were counted and timed. There is a chance for miscount, but this should be readily apparent by comparison of the timed interval with adjacent timings of the same run and should be eliminated; hence:

$$\Delta R/R = 0$$

(3) Meter constant uncertainty, $\Delta K_h/K_h$ — the meter constant uncertainty is taken as the watthour meter uncertainty and shown in Table 4.3, Item (c) (for watthour meters with three-phase calibration)

$$\Delta K_h/K_h = \pm 0.25\%$$

(4) Potential transformer uncertainty, $\Delta PTR/PTR$ — the potential transformer uncertainty is obtained from Table 4.4, Item (b), and is 0.3%. However, the number of potential transformers used in the metering circuit must also be considered. This information is obtained from Table 4.1, Item (c), and is 2. The effect of potential transformer uncertainty on power uncertainty will be:

$$\Delta PTR/PTR = \pm 0.3/\sqrt{2}$$

(5) Current transformer uncertainty $\Delta CTR/CTR$ — the current transformer uncertainty is obtained from Table 4.5, Item (b), and is $\pm 0.10\%$. The number of current transformers used in the metering circuit is obtained from Table 4.1, Item (c), and is 3. The effect of current transformer uncertainty on power uncertainty will be:

$$\Delta CTR/CTR = \pm 0.10/\sqrt{3}$$

(6) Timing uncertainty $\Delta t/t$ — the time interval for 50 meter revolutions is approximately 8 min and the smallest time increment of the clock is 1 sec; therefore, the minimum uncertainty is the smallest timing increment and equals 1 sec. The uncertainty during the 8 min interval is:

$$\frac{\Delta t}{t} = \frac{1}{8 \times 60} \times 100 = \pm 0.21\%$$

(7) Overall power uncertainty $\Delta P_T/P_T$ — the overall power uncertainty is the square root of the sum of the squares of the individual uncertainties previously described:

$$\Delta P_T/P_T = \sqrt{(0.50)^2 + (0.25)^2 + \left(\frac{0.30}{\sqrt{2}}\right)^2 + \left(\frac{0.10}{\sqrt{3}}\right)^2 + (0.21)^2} = \pm 0.64\%$$

Net effect on heat rate uncertainty = −1% per percent (Table 5.3, Column B, line 2).

Heat rate uncertainty = $1.0 \times \pm 0.64 = \pm 0.64\%$ (Column D).

(f) The primary flow is measured in the boiler feedwater line downstream of the top heater using a flow nozzle with pipe wall taps and a β ratio of 0.6. The nozzle was calibrated prior to installation. A 20 section flow straightener is installed 16 pipe diameters upstream of the nozzle and an inspection port allows before and after test inspections. The equation for flow is:

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$$w = Cd^2 KF_a \sqrt{\Delta p \rho}$$

where

w = flow
C = a constant
d = nozzle throat diameter
K = flow coefficient
F_a = thermal expansion factor
Δp = pressure drop across nozzle
ρ = specific weight

Following the procedure in Par. 5.08, rewrite the flow equation in logarithmic form:

$$\ln w = \ln C + 2(\ln d) + \ln K + \ln F_a + \tfrac{1}{2}[\ln(\Delta p) + \ln \rho]$$

Differentiating, noting $d(\ln u) = \frac{du}{u}$ and substituting Δ for d:

$$\frac{\Delta w}{w} = 2\frac{(\Delta d)}{(d)} + \frac{(\Delta K)}{(K)} + \frac{(\Delta F_a)}{(F_a)} + \tfrac{1}{2}\frac{[\Delta(\Delta p)]}{\Delta p} + \tfrac{1}{2}\frac{(\Delta \rho)}{(\rho)}$$

the uncertainty of each component can be determined as follows.

(1) The throat diameter is measured at 2.300 in. using a micrometer with an uncertainty of ±0.001 in.

$$2\frac{(\Delta d)}{(d)} = 2 \times \frac{\pm 0.001}{2.300} \times 100 = \pm 0.09\%$$

(2) The uncertainty in flow coefficient is composed of four components as discussed in Section 4:

Base uncertainty (Table 4.10, item C), $u_B = 0.6$
Uncertainty due to high β ratio (Fig. 4.6), $U_\beta = 0.2$
Uncertainty due to short distance between flow straightener and nozzle (Fig. 4.7), $U_{LS1} = 0.0$
Uncertainty due to small number of sections in flow straightener (Fig. 4.8), $U_{LS2} = 0.6$

$$\frac{(\Delta K)}{(K)} = \sqrt{(0.6)^2 + (0.2)^2 + (0.0)^2 + (0.6)^2} = \pm 0.87\%$$

(3) The flow uncertainty due to thermal expansion factor uncertainty is negligible:

$$\frac{(\Delta F_a)}{(F_a)} = 0.0$$

(4) About 8 in. nozzle pressure drop is expected, and measured by a commercial grade, compensated scale manometer without reading aid. The instrument uncertainty is ±0.10 in. (Table 4.13, item 3):

$$\tfrac{1}{2}\frac{[\Delta(\Delta p)]}{p} = \tfrac{1}{2} \times \frac{\pm 0.10}{8} \times 100 = \pm 0.62\%$$

(5) The specific weight is a function of temperature and pressure (measured upstream of the flow section). Hence:

$$\frac{(\Delta \rho)}{(\rho)} = \frac{(\partial \rho)}{(\partial p)_T} \times \Delta p + \frac{(\partial \rho)}{(\partial T)_p} \times \Delta T$$

where $(\partial \rho)/(\partial p)_T$ and $(\partial \rho)/(\partial T)_p$ are the effects of changes in pressure and temperature, respectively, on specific weight as obtained from the ASME Steam Tables [Appendix III, Ref. (76)]. Δp and ΔT are the uncertainties in the fluid pressure and temperature measurements.

Uncertainty in the pressure measurement is negligible, since for compressed water:

$$\frac{(\partial \rho)}{(\partial p)_T} = 0$$

Feedwater temperature is measured using a single test thermocouple with separate test leads and an instrument uncertainty of ±3.0°F (Table 4.18). From the ASME Steam Tables:

$$\frac{(\partial \rho)}{(\partial T)_p} = -0.07\%/^\circ\text{F}$$

Hence, the specific weight uncertainty is:

$$\tfrac{1}{2}\frac{(\Delta \rho)}{(\rho)} = \tfrac{1}{2} \times (-0.07) \times \pm 3.0 = \pm 0.10\%$$

(6) Combining the five uncertainty components, the total flow uncertainty is:

$$\sqrt{(0.09)^2 + (0.87)^2 + (0.0)^2 + (0.62)^2 + (0.10)^2} = \pm 1.08\%$$

Net effect on heat rate uncertainty = 1% per percent (Table 5.3, Column B).

Heat rate uncertainty = ±1.08 × 1 = ±1.08% (Column D, Line 1).

(g) Combining the uncertainties of items (a) through (f) produces the pretest instrumentation uncertainty in corrected heat rate:

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TABLE 5.3
HEAT RATE UNCERTAINTY DUE TO INSTRUMENTATION

Test Measurement A	Effect on Heat Rate, θ B	Instrumentation Uncertainty, U_I C	Component Heat Rate Uncertainty, UHR_i D
Throttle flow	+1%/%	1.08%	1.08%
Power	−1%/%	0.64%	−0.64%
Throttle pressure [Note (1)]	+0.010 − 0.003 = +0.007%/psi	10 psi	0.07%
Throttle temperature [Note (1)]	+0.030 + 0.050 = + 0.080%/°F	1.73°F	0.14%
Exhaust pressure	−2%/in. Hg	0.025 in. Hg	−0.05%
Extraction pressure	−0.05%/psi	3 psi	−0.15%
	$U_{HRi} = \theta U_I$	$U_{HR} = \pm 1.27\%$	
	$U_{HR} = \sqrt{\sum_{i=1}^{6} U_{HRi}^2}$		

NOTE:
(1) The same measurements of throttle pressure and temperature are used in determining the throttle enthalpy and the corresponding correction factors. Hence, their effects are combined algebraically to determine the net effect on heat rate uncertainty.

$$U_{HR} = \sqrt{(0.07)^2 + (0.14)^2 + (0.05)^2 + (0.15)^2 + (0.64)^2 + (1.08\%)^2}$$

$$U_{HR} = \pm 1.27\%$$

These figures are summarized in Table 5.3.

5.10 After test completion, the time uncertainty for the multiple-reading measurements and the spatial variability for the multilocation measurements (in this example, the latter affects only turbine throttle temperature and turbine exhaust pressure), were estimated using the procedures described in Par. 5.02. The results are summarized in Tables 5.4A and 5.4B. The calculations for the time and spatial uncertainty for throttle temperature and exhaust pressure are shown in Par. 5.02. Although not shown, similar calculations are done for the other variables including the effect of sample size (denoted by the variables N and L in Tables 5.4A and 5.4B) in determining the appropriate estimate of variability (standard deviation of range) and using an average estimate of the standard deviation, or range, if more than one instrument (denoted by M) was used.

5.11 The effect of uncertainty due to instrumentation, time, and space variability are combined in Table 5.5 to yield the overall heat rate uncertainty for the test. It is noteworthy that the effect of time and space variability had only a small effect on the overall uncertainty, as should be expected for a well-planned and executed test.

5.12 Example in the Use of Figs. 3.1 and 3.2. Figures 3.1 and 3.2 are intended for use by the engineer directing the test to determine the effect of time uncertainty on test results, and should be used as the test progresses. An example for the use of these figures follows.

(*a*) Table 5.3 indicates that the expected uncertainty in the test will be ±1.27%. At 1.27%, Fig. 3.1 indicates that U_T, the allowable effect due to scatter, is 0.12%.

(*b*) After 50 min of a planned 1 hr test, the Engineer directing the test determines by scanning the differential pressure readings for the 10 samples of five readings that the average range is 0.17 and the scanned average reading is 8.0.

(*c*) θ from Table 3.1 = 0.5 for flow, by flow nozzle differential. $\overline{Z}$ for Fig. 3.2 can now be calculated as follows:

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TABLE 5.4A
HEAT RATE UNCERTAINTY DUE TO VARIABILITY WITH TIME

Test Measurement	No. of Readings Per Instrument N	No. of Instruments M	Estimate of Time Variability S or R	Degrees of Freedom ν	Statistical Distribution t_ν or t_ν'	Uncertainty-Time Variability U_t
Throttle flow	61	1	0.47%	60	2.000	0.12%
Power	6	1	0.12%	5	2.571	0.13%
Throttle pressure	13	1	3.10 psi	12	2.179	1.87 psi
Throttle temperature	10	3	3.180°F	27	2.052	1.19°F
Exhaust pressure	13	4	0.01 in.	48	2.010	0.002 in.
Extraction pressure	13	1	0.5 psi	12	2.179	0.3 psi

GENERAL NOTES:
(a) If N > 10, use standard deviation S to estimate time variability and Student's t-distribution.

If $M = 1$	If $M > 1$
$\nu = N - 1$	$\nu = M(N - 1)$
$S = \sqrt{\dfrac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N - 1}}$	$S = \sqrt{\dfrac{\sum_{i=1}^{M} S_i^2}{M}}$
$U_T = t_\nu \dfrac{S}{\sqrt{N}}$	$U_t = t_\nu \dfrac{\bar{S}}{\sqrt{NM}}$

(b) If N < 10, use range R to estimate time variability and substitute t-distribution.

If $M = 1$	If $M > 1$
$\nu = N$	$\nu = M$
$R = X_{max} - X_{min}$	$\bar{R} = \dfrac{\sum_{i=1}^{M} R_i}{N}$
$U_t = t_\nu' R$	$U_t = t_\nu' \dfrac{\bar{R}}{\sqrt{M}}$

$$\bar{Z} = \frac{100 \times 0.5 \times 0.17}{8.0} = 1.06\%$$

$$\bar{Z}/U_T = 1.06/0.12 = 8.83$$

(*d*) Entering Fig. 3.2 at 8.83, the number of readings required is approximately 57 as read from the ordinate at the intersection of the 8 or more samples line. Thus, there will be sufficient readings at the conclusion of the planned duration of the test that time variability has minimal effect. Had the calculations shown that more than 61 readings are required, a test extension would be necessary to obtain the required number of readings.

NOTE:
The number of readings can also be calculated by:

$$N_R = [(\bar{Z} \times t_{95})/(U_T \times d_2^*)]^2$$

where $\bar{Z}$ is calculated as in (c) above and U_T is determined as in (a) above. Degrees of freedom and d_2^* for determining t_{95} are from Appendix II, Table II-1.

For 10 samples of size 5, $d_2^* = 2.34$ and $\nu = 36.5$ t_{95} for ν of $36.5 = 2$

$$N_R = \left(\frac{1.06 \times 2}{0.12 \times 2.34}\right)^2 = 57$$

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TABLE 5.4B
HEAT RATE UNCERTAINTY DUE TO VARIABILITY WITH SPACE

Test Measurements	No. of Sampling Locations L	No. of Instruments Per Location M	Estimate of Space Variability S or R	Degrees of Freedom ν	Statistical Distribution t_ν or t_ν'	Uncertainty-Space Variability U_S
Throttle flow	1	1	...	...	...	...
Power	1	1	...	...	...	...
Throttle pressure	1	1	...	...	...	...
Throttle temperature	3	1	1.00	3	1.304	1.304°F
Exhaust pressure	4	1	0.12	4	0.717	0.09 in.
Extraction pressure	1	1	...	...	...	...

GENERAL NOTES:

(a) If $L > 10$, use standard deviation S to estimate time variability and Student's t-distribution.

If $M = 1$	If $M > 1$
$\nu = L$	$\nu = L$
$S = \sqrt{\dfrac{\sum_{i=1}^{L} (x_i - \bar{x})^2}{L - 1}}$	$\bar{S} = \sqrt{\dfrac{\sum_{i=1}^{M} S_i^2}{M}}$
$U_S = t_\nu \dfrac{S}{\sqrt{L}}$	$U_S = t_\nu \dfrac{\bar{S}}{\sqrt{LM}}$

(b) If $L < 10$, use range R to estimate time variability and substitute t-distribution.

If $M = 1$	If $M > 1$
$\nu = L$	$\nu = L$
$R = x_{max} - x_{min}$	$\bar{R} = \dfrac{\sum_{i=1}^{N} R_i}{M}$
$U_S = t_\nu' R$	$U_S = t_\nu' \dfrac{\bar{R}}{\sqrt{M}}$

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TABLE 5.5
OVERALL HEAT RATE UNCERTAINTY

Test Measurement	Effect on Heat Rate Uncertainty θ	Sources of Uncertainty: Instrument U_I	Sources of Uncertainty: Time Variability U_t	Sources of Uncertainty: Space Variability U_S	Overall Measurement Uncertainty U_T	Component Heat Rate Uncertainty U_{HRi}
Throttle flow	1.0%/%	1.08%	0.12%	...	1.09%	±1.09%
Power	1.0%/%	0.64%	0.13%	...	0.65%	±0.65%
Throttle pressure	0.007%/psi	10 psi	1.87 psi	...	10.17 psi	±0.07%
Throttle temperature	0.080%/°F	1.73°F	1.17°F	1.304°F	2.09°F	±0.17%
Exhaust pressure	2.0%/in. Hg	0.025 in. Hg	0.002 in. Hg	0.09 in. Hg	0.09 in. Hg	±0.18%
Extraction pressure	0.050%/psi	3 psi	0.3 psi	...	3.01 psi	±0.15%

Overall heat rate uncertainty = ±1.30%

$$U_T = \sqrt{(U_I \text{ or } U_S)^2 + U_t^2}$$

$$U_{HRi} = \theta \times U_T$$

$$\text{Overall } U_{HR} = \sqrt{\sum_{i=1}^{6} U_{HRi}^2}$$

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APPENDIX I
COMPUTATION OF MEASUREMENT UNCERTAINTY IN PERFORMANCE TEST FOR A REHEAT TURBINE CYCLE

I.00 INTRODUCTION

The uncertainty of an overall test result for a reheat turbine is dependent upon the collective influence of the uncertainties of the data used in determining the test result. Since various combinations of instruments may be selected for any given test, a method is given for determining how individual uncertainties in test data may be combined into an uncertainty for the overall test result. This can be done in three steps, as follows.

(*a*) Determine the uncertainty of each of the several individual measurements. Component uncertainties of variables that require more than one type of test measurement, such as flow and power, should be combined as the square root of the sum of the squares of the individual measurements.

(*b*) Express the uncertainty of each individual measurement of Step (a) in terms of its effect on the overall test result.

(*c*) Compute the overall uncertainty for the test. This is the square root of the sum of the squares of the values obtained in Step (b).

Certain test variables, such as flow and power, affect the overall test result on a 1:1 ratio; i.e., a 1% uncertainty in flow or power causes a 1% uncertainty in steam rate or heat rate. Other test variables, such as pressures, temperatures, and secondary flows, affect the overall test results on less than a 1:1 ratio.

The reader is cautioned against the inappropriate use of the familiar correction-factor curves for throttle and reheat steam conditions to determine the effect on heat rate. Since errors in these steam conditions affect steam enthalpies which appear in the heat-rate equation, these curves do not show the total effect of the measurement errors. Therefore, the effect of an actual change in these variables is not the same as the effect of an error of the same magnitude in that variable when applied in the analysis of specific test results. However, the exhaust pressure correction to heat rate for a condensing unit can be correctly used to determine the effect of an error in exhaust pressure, since there is no effect on values in the heat rate equation.

The effect of the individual measurement on the overall result can be determined by one of the following appropriate calculation procedures. One procedure evaluates the test twice, using each of the two values of a particular variable and noting the effect of the difference. Since this must be done for each variable of significance, it is best to use a high-speed computer. An alternative approach involves an analysis which is outlined in the following paragraph and is better suited for the less complex cases.

This alternative approach to evaluating the effects of uncertainties in test measurements upon the overall uncertainty employs analytical or numerical differentiation. The method is outlined as follows.

I.01 Nomenclature and Definitions

For a reheat turbine cycle, the corrected heat rate is defined as:

$$HR_c = \frac{w_{lt}(H_{lt} - H_{11}) + w_{RH}(H_{HRH} - H_{CRH})}{P_g \times CF_{P1} \times CF_{T1} \times CF_{P6} \times CF_{THRH} \times CF_{\Delta P}} \quad (1)$$

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where

HR_c = test heat rate corrected for steam conditions
w_{lt} = calculated test value for throttle flow
w_{RH} = calculated test value for reheat flow
H_{lt} = test value for throttle enthalpy
H_{11} = test value of final-feed enthalpy
H_{HRH} = test value for hot reheat enthalpy
H_{CRH} = test value for cold reheat enthalpy
P_g = value of generator output at specified generator conditions
CF_{P1} = heat-rate divisor correction factor for throttle pressure
CF_{T1} = heat-rate divisor correction factor for throttle temperature
CF_{P6} = heat-rate divisor correction factor for exhaust pressure
CF_{THRH} = heat-rate divisor correction factor for hot reheat temperature
$CF_{\Delta P}$ = heat-rate divisor correction factor for reheater pressure drop

I.02 Expression of Individual Measurements in Terms of Their Effects on Overall Test Result

Now determine the effect that a change in each variable in the right-hand side of Eq. (1) will have upon the overall test result. This may be readily done by inspection for flow, power, and each of the correction factors, but a general approach is as follows.

(a) *Derive General Mathematical Expression.* For simplicity, rewrite above equation as

$$HR_c = \frac{A \times B + C \times D}{E} \tag{2}$$

where

$$A = w_{lt} \tag{3}$$
$$B = (H_{lt} - H_{11}) \tag{4}$$
$$C = w_{RH} \tag{5}$$
$$D = (H_{HRH} - H_{CRH}) \tag{6}$$
$$E = P_g \times CF_{P1} \times CF_{T1} \times CF_{P6} \times CF_{THRH} \times CF_{\Delta P} \tag{7}$$

Take the natural logarithm ln of both sides

$$\ln(HR_c) = \ln\left(\frac{A \times B + C \times D}{E}\right) = \ln(A \times B + C \times D) - \ln E \tag{8}$$

This equation can be written in differential form, and since $d(\ln U) = \frac{du}{u}$,

$$d\ln(HR_c) = d[\ln(A \times B + C \times D)] - d(\ln E) \tag{9}$$

$$\frac{d(HR_c)}{HR_c} = \frac{d(A \times B + C \times D)}{A \times B + C \times D} - \frac{d(E)}{E} \tag{10}$$

$$= \frac{A \times dB + B \times dA + C \times dD + D \times dC}{A \times B + C \times D} - \frac{dE}{E} \tag{11}$$

Based on the previous definitions, the differentials in Eq. (11) can be expressed as follows:

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$$dA = d\,w_t \tag{12}$$

$$dB = \left(\frac{\partial H_{lt}}{\partial P_{lt}}\right)_{T_{lt}} dp_{lt} + \left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{p_{lt}} dT_{lt} - \left(\frac{\partial H_{11}}{\partial p_{11}}\right)_{T_{11}} dp_{11} - \left(\frac{\partial H_{11}}{\partial T_{11}}\right)_{p_{11}} dT_{11} \tag{13}$$

$$dC = d\,w_{RH} \tag{14}$$

$$dD = \left(\frac{\partial H_{HRH}}{\partial p_{HRH}}\right)_{T_{HRH}} dp_{HRH} + \left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}} dT_{HRH} - \left(\frac{\partial H_{CRH}}{\partial p_{CRH}}\right)_{T_{CRH}} dp_{CRH} - \left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}} dT_{CRH} \tag{15}$$

and

$$\frac{dE}{E} = \frac{dP_g}{P_g} + \frac{dCF_{p1}}{CF_{p1}} + \frac{dCF_{T1}}{CF_{T1}} + \frac{dCF_{p6}}{CF_{p6}} + \frac{dCF_{HRH}}{CF_{HRH}} + \frac{dCF_{\Delta p}}{CF_{\Delta p}} \tag{16}$$

Now, substituting these values in Eq. (11) and replacing the differentials d by the differences Δ,

$$\frac{\Delta HR_c}{HR_c} = \frac{w_{lt}\left[\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}} \Delta p_{lt} + \left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{p_{lt}} \Delta T_{lt} - \left(\frac{\partial H_{11}}{\partial p_{11}}\right)_{T_{11}} \Delta p_{11} - \left(\frac{\partial H_{11}}{\partial T_{11}}\right)_{p_{11}} \Delta T_{11}\right]}{w_{lt}(H_{lt} - H_{11}) + w_{RH}(H_{HRH} - H_{CRH})}$$

$$+ \frac{(H_{lt} - H_{11})\,\Delta w_{lt}}{w_{lt}(H_{lt} - H_{11}) + w_{RH}(H_{HRH} - H_{CRH})}$$

$$+ \frac{w_{RH}\left[\left(\frac{\partial H_{HRH}}{\partial p_{HRH}}\right)_{T_{HRH}} \Delta p_{HRH} + \left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}} \Delta T_{HRH} - \left(\frac{\partial H_{CRH}}{\partial p_{CRH}}\right)_{T_{CRH}} \Delta p_{CRH} - \left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}} \Delta T_{CRH}\right]}{w_{lt}(H_{lt} - H_{11}) + w_{RH}(H_{HRH} - H_{CRH})}$$

$$+ \frac{(H_{HRH} - H_{CRH})\,\Delta w_{RH}}{w_{lt}(H_{lt} - H_{11}) + w_{RH}(H_{HRH} - H_{CRH})}$$

$$- \frac{\Delta p_g}{p_g} - \frac{\Delta CF_{p1}}{CF_{p1}} - \frac{\Delta CF_{T1}}{CF_{T1}} - \frac{\Delta CF_{p6}}{CF_{p6}} - \frac{\Delta CF_{THRH}}{CF_{THRH}} - \frac{\Delta CF_{\Delta p}}{CF_{\Delta p}} \tag{17}$$

For convenience, let

$$\text{DENOM} = w_{lt}(H_{lt} - H_{11}) + w_{RH}(H_{HRH} - H_{CRH}) = A \times B + C \times D \tag{18}$$

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Equation (17) can thus be rewritten

$$\frac{\Delta HR_c}{HR_c} = \left[\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}} p_{lt}}{\text{DENOM}}\right]\frac{\Delta p_{lt}}{p_{lt}} + \left[\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{p_{lt}} T_{lt}}{\text{DENOM}}\right]\frac{\Delta T_{lt}}{T_{lt}} - \left[\frac{w_{lt}\left(\frac{\partial H_{11}}{\partial p_{11}}\right)_{T_{11}} p_{11}}{\text{DENOM}}\right]\frac{\Delta p_{11}}{p_{11}}$$

$$- w_{lt}\left[\frac{\left(\frac{\partial H_{11}}{\partial T_{11}}\right)_{p_{11}} T_{11}}{\text{DENOM}}\right]\frac{\Delta T_{11}}{T_{11}} + \left[\frac{(H_{lt} - H_{11})\, w_{lt}}{\text{DENOM}}\right]\frac{\Delta w_{lt}}{w_{lt}}$$

$$+ \left[\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial p_{HRH}}\right)_{T_{HRH}} p_{HRH}}{\text{DENOM}}\right]\frac{\Delta p_{HRH}}{p_{HRH}} + \left[\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}} T_{HRH}}{\text{DENOM}}\right]\frac{\Delta T_{HRH}}{T_{HRH}}$$

$$- \left[\frac{w_{RH}\left(\frac{\partial H_{CRH}}{\partial H_{CRH}}\right)_{T_{CRH}} p_{CRH}}{\text{DENOM}}\right]\frac{\Delta p_{CRH}}{p_{CRH}} - \left[\frac{w_{RH}\left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}} T_{CRH}}{\text{DENOM}}\right]\frac{\Delta T_{CRH}}{T_{CRH}}$$

$$+ \left[\frac{(H_{HRH} - H_{CRH})\, w_{RH}}{\text{DENOM}}\right]\frac{\Delta w_{RH}}{w_{RH}} - \frac{\Delta p_g}{p_g} - \frac{\Delta CF_{p1}}{CF_{p1}}$$

$$- \frac{\Delta CF_{T1}}{CF_{T1}} - \frac{\Delta CF_{p6}}{CF_{p6}} - \frac{\Delta CF_{THRH}}{CF_{THRH}} - \frac{\Delta CF_{\Delta p}}{CF_{\Delta p}} \qquad (19)$$

Since the correction factors are calculated in terms of measured quantities, the uncertainty in those factors can be evaluated in terms of the errors in the relevant measured quantities. For example, the initial pressure correction factor can be written as follows:

$$\frac{\Delta CF_{p1}}{CF_{p1}} = \frac{\Delta CF_{p1}/\Delta p_1}{\Delta p_1/CF_{p1}} = \left(\frac{\Delta CF_{p1}/CF_{p1}}{\Delta p_1/p_1}\right) \times \frac{\Delta p_1}{p_1} \qquad (20)$$

Similarly, the other correction factor terms can be rewritten

$$\frac{\Delta CF_{T1}}{CF_{T1}} = \left(\frac{\Delta CF_{T1}/CF_{T1}}{\Delta T_1/T_1}\right) \times \frac{\Delta T_1}{T_1} \qquad (21)$$

$$\frac{\Delta CF_{p6}}{CF_{p6}} = \left(\frac{\Delta CF_{p6}/CF_{p6}}{\Delta p_6/p_6}\right) \times \frac{\Delta p_6}{p_6} \qquad (22)$$

$$\frac{\Delta CF_{THRH}}{CF_{THRH}} = \left(\frac{\Delta CF_{THRH}/CF_{THRH}}{\Delta T_{HRH}/T_{HRH}}\right) \times \frac{\Delta T_{HRH}}{T_{HRH}} \qquad (23)$$

Also, since the reheater pressure drop is a function of the hot and cold reheat pressures

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$$\frac{\Delta CF_{\Delta p}}{CF_{\Delta p}} = \frac{(\Delta CF_{\Delta p})_{p_{CRH}}/\Delta p_{HRH}}{CF_{\Delta p}/\Delta p_{HRH}} + \frac{(\Delta CF_{\Delta p})_{p_{HRH}}/\Delta p_{CRH}}{CF_{\Delta p}/\Delta p_{CRH}} \tag{24}$$

$$= \left[\frac{(\Delta CF_{\Delta p})_{p_{CRH}}/CF_{\Delta p}}{\Delta p_{HRH}/p_{HRH}}\right]\frac{\Delta p_{HRH}}{p_{HRH}} + \left[\frac{(\Delta CF_{\Delta p})_{p_{HRH}}/CF_{\Delta p}}{\Delta p_{CRH}/p_{CRH}}\right]\frac{\Delta p_{CRH}}{p_{CRH}} \tag{25}$$

where $(\Delta CF_{\Delta p})_{pCHR}$ is the change in reheater pressure drop correction factor when p_{HRH} is allowed to change and p_{CRH} = constant, and conversely, where $(\Delta CF_{\Delta p})_{pHRH}$ is the change in reheater pressure drop correction factor when p_{CRH} is allowed to change and p_{HRH} is constant.

The values for the uncertainties in the correction factors can thus be substituted in Eq. (19):

$$\frac{\Delta HR_c}{HR_c} = \left[\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}}}{\text{DENOM}}\,p_{lt}\right]\frac{\Delta p_{lt}}{p_{lt}} + \left[\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{p_{lt}}}{\text{DENOM}}\,T_{lt}\right]\frac{\Delta T_{lt}}{T_{lt}} - \left[\frac{w_{lt}\left(\frac{\partial H_{11}}{\partial p_{11}}\right)_{T_{11}}}{\text{DENOM}}\,p_{11}\right]\frac{\Delta p_{11}}{p_{11}}$$

$$- \left[\frac{w_{lt}\left(\frac{\partial H_{11}}{\partial T_{11}}\right)_{p_{11}}}{\text{DENOM}}\,T_{11}\right]\frac{\Delta T_{11}}{T_{11}} + \left[\frac{(H_{lt} - H_{11})\,w_{lt}}{\text{DENOM}}\right]\frac{\Delta w_{lt}}{w_{lt}}$$

$$+ \left[\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial p_{HRH}}\right)_{T_{HRH}}}{\text{DENOM}}\,p_{HRH}\right]\frac{\Delta p_{HRH}}{p_{HRH}} + \left[\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}}}{\text{DENOM}}\,T_{HRH}\right]\frac{\Delta T_{HRH}}{T_{HRH}}$$

$$- \frac{w_{RH}\left(\frac{\partial H_{CRH}}{\partial p_{CRH}}\right)_{T_{CRH}}}{\text{DENOM}}\,p_{CRH}\frac{\Delta p_{CRH}}{p_{CRH}} - \frac{w_{RH}\left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}}}{\text{DENOM}}\,T_{CRH}\frac{\Delta T_{CRH}}{T_{CRH}}$$

$$+ \left[\frac{(H_{HRH} - H_{CRH})\,w_{RH}}{\text{DENOM}}\right]\frac{\Delta w_{RH}}{w_{RH}} - \frac{\Delta P_g}{P_g}$$

$$- \left[\frac{\Delta CF_{p1}/CF_{p1}}{\Delta p_1/p_1}\right]\frac{\Delta p_1}{p_1} - \left[\frac{\Delta CF_{T1}/CF_{T1}}{\Delta T_1/T_1}\right]\frac{\Delta T_1}{T_1}$$

$$- \left[\frac{\Delta CF_{p6}/CF_{p6}}{\Delta p_6/p_6}\right]\frac{\Delta p_6}{p_6} - \left[\frac{\Delta CF_{THRH}/CF_{THRH}}{\Delta T_{HRH}/T_{HRH}}\right]\frac{\Delta T_{HRH}}{T_{HRH}}$$

$$- \left[\frac{(\Delta CF_{\Delta p})_{p_{CRH}}/CF_{\Delta p}}{\Delta p_{HRH}/p_{HRH}}\right]\frac{\Delta p_{HRH}}{p_{HRH}} - \left[\frac{(\Delta CF_{\Delta p})_{p_{HRH}}/CF_{\Delta p}}{\Delta p_{CRH}/p_{CRH}}\right]\frac{\Delta p_{CRH}}{p_{CRH}} \tag{26}$$

We have thus obtained a general expression for the uncertainty in calculated heat rate as a function of the error in individual measurements.

If the terms for each independent measurement are grouped, Eq. (26) can be rewritten:

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$$\frac{\Delta HR_c}{HR_c} = \left\{\left[\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}}}{\text{DENOM}}\, p_{lt}\right] - \left[\frac{\Delta CF_{p1}/CF_{p1}}{\Delta p_1/p_1}\right]\right\}\frac{\Delta p_1}{p_1}$$

$$+\left\{\left[\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{p_{lt}}}{\text{DENOM}}\, T_{lt}\right] - \left[\frac{\Delta CF_{T1}/CF_{T1}}{\Delta T_1/T_1}\right]\right\}\frac{\Delta T_1}{T_1}$$

$$-\left[\frac{w_{lt}\left(\frac{\partial H_{11}}{\partial p_{11}}\right)_{T_{11}}}{\text{DENOM}}\, p_{11}\right]\frac{\Delta p_{11}}{p_{11}} - \left[\frac{w_{lt}\left(\frac{\partial H_{11}}{\partial T_{11}}\right)_{p_{11}}}{\text{DENOM}}\, T_{11}\right]\frac{\Delta T_{11}}{T_{11}}$$

$$+\left[\frac{(H_{lt} - H_{11})\,(w_{lt})}{\text{DENOM}}\right]\frac{\Delta w_{lt}}{w_{lt}} + \left[\frac{(H_{HRH} - H_{CRH})\, w_{RH}}{\text{DENOM}}\right]\frac{\Delta w_{RH}}{w_{RH}}$$

$$+\left\{\left[\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial p_{HRH}}\right)_{T_{HRH}}}{\text{DENOM}}\, p_{HRH}\right] - \left[\frac{(\Delta CF_{\Delta p})_{p_{CRH}}/CF_{\Delta p}}{\Delta p_{HRH}/p_{HRH}}\right]\right\}\frac{\Delta p_{HRH}}{p_{HRH}}$$

$$+\left\{\left[\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}}}{\text{DENOM}}\, T_{HRH}\right] - \left[\frac{\Delta CF_{THRH}/CF_{THRH}}{\Delta T_{HRH}/T_{HRH}}\right]\right\}\frac{\Delta T_{HRH}}{T_{HRH}}$$

$$-\left\{\left[\frac{w_{RH}\left(\frac{\partial H_{CRH}}{\partial p_{CRH}}\right)_{T_{CRH}}}{\text{DENOM}}\, p_{CRH}\right] + \left[\frac{(\Delta CF_{\Delta p})_{p_{HRH}}/CF_{\Delta p}}{\Delta p_{CRH}/p_{CRH}}\right]\right\}\frac{\Delta p_{CRH}}{p_{CRH}}$$

$$-\left[\frac{w_{RH}\left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}}}{\text{DENOM}}\, T_{CRH}\right]\frac{\Delta T_{CRH}}{T_{CRH}} - \frac{\Delta P_g}{P_g}$$

$$-\left[\frac{\Delta CF_{p6}/CF_{p6}}{\Delta p_6/p_6}\right]\frac{\Delta p_6}{p_6} \qquad (27)$$

Each of the terms in Eq. (27) represents the fractional change for a specific measured variable multiplied by a weighting factor between brackets (this factor is referred to as sensitivity ratio). In the context of this analysis, they represent the percentage of error in that variable and its effect on the uncertainty in calculated heat rate.

These terms are individually calculated for this example in the following paragraphs.

(*b*) *Apply Results.* The parameters in Eq. (27) can be calculated for the unit. A heat balance diagram for this unit is shown in Fig. I.1. From this heat balance,

$$w_{lt} = 5{,}958{,}707 \text{ lbm/h} \qquad (28)$$
$$H_{lt} = 1460.5 \text{ Btu/lbm} \qquad (29)$$
$$H_{11} = 536.7 \text{ Btu/lbm} \qquad (30)$$
$$w_{RH} = 4{,}819{,}165 \text{ lbm/h} \qquad (31)$$
$$H_{HRH} = 1520.5 \text{ Btu/lbm} \qquad (32)$$
$$H_{CRH} = 1306.1 \text{ Btu/lbm} \qquad (33)$$

The parameter DENOM can thus be calculated

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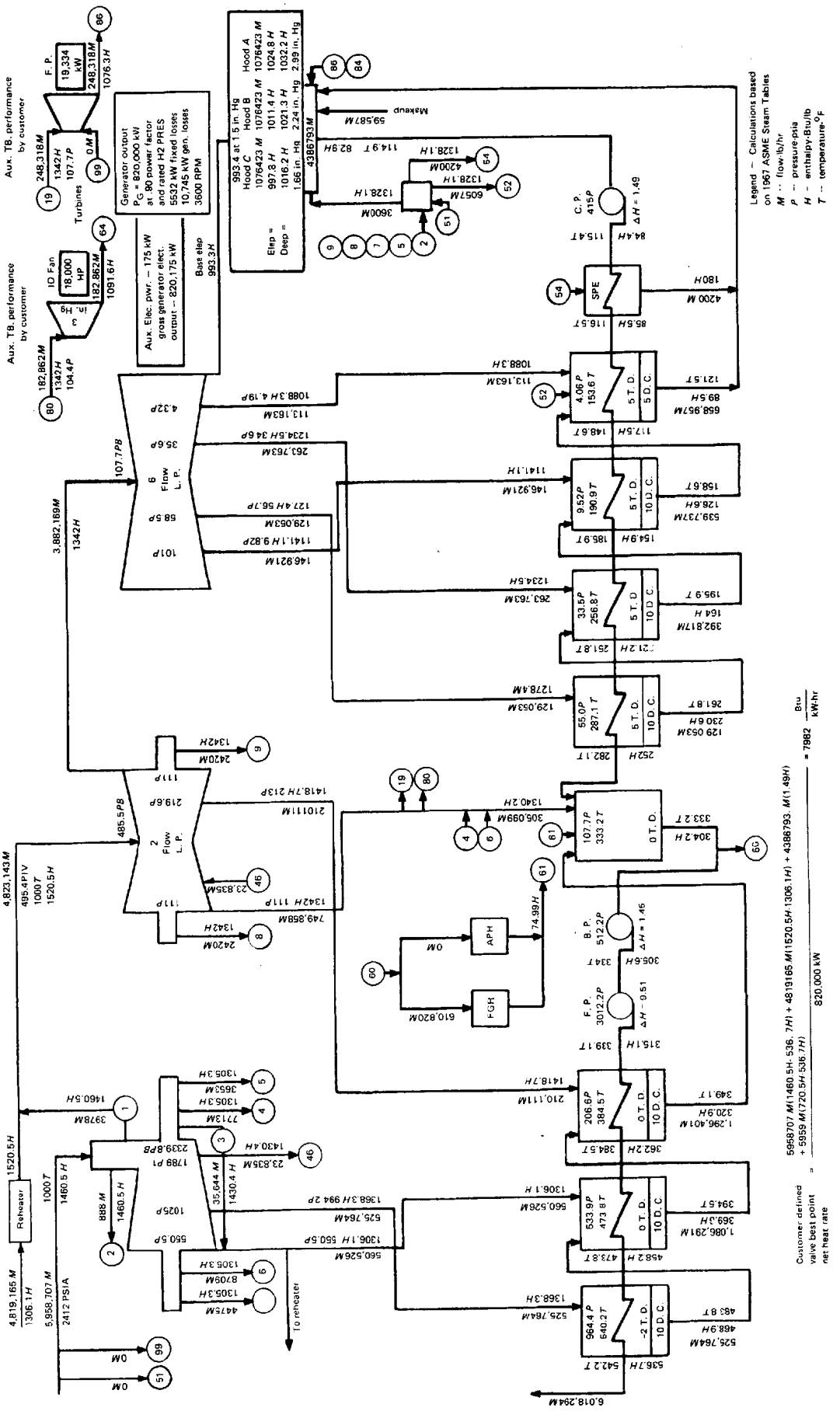


FIG. I.1 HEAT BALANCE

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$$\text{DENOM} = w_{lt}(H_{lt} - H_{11}) + w_{RH}(H_{HRH} - H_{CRH}) \tag{18}$$

$$= 5{,}958{,}707(1460.5 - 536.7) + 4{,}819{,}165(1520.5 - 1306.1)$$

$$= 6.53788 \times 10^9 \tag{34}$$

The effect of each measured quantity on heat rate can thus be calculated.

(1) *Throttle Pressure.* The uncertainty in heat rate caused by a 1% error in throttle pressure or the sensitivity ratio for throttle pressure (SR_{Pt}) can be written from Eq. (27).

$$SR_{pt} = \frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}}}{\text{DENOM}} p_{lt} - \frac{\Delta CF_{p1}/CF_{p1}}{\Delta p_1/p_1} \tag{35}$$

The term $\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}}$ is the slope of the superheated steam enthalpy vs pressure curve at constant temperature. This slope is given in Fig. 5.4. For this case,

$$\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}} = \left[\frac{\partial H}{\partial p}(p = 2412, T = 1000)\right]_T = -0.035 \tag{36}$$

The heat balance throttle pressure and temperature have been substituted in Eq. (35). Therefore,

$$\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial p_{lt}}\right)_{T_{lt}}}{\text{DENOM}} p_{lt} = \frac{5{,}958{,}707 \times (-0.035) \times (2412)}{6.53788 \times 10^9} = -0.0769 \tag{37}$$

The second right-hand side term in Eq. (35) is the uncertainty due to the correction factor. The term $\frac{\Delta CF_{p1}/CF_{p1}}{\Delta p_1/p_1}$ is the slope of the throttle pressure correction factor curve. This slope can be found by graphical differentiation as shown in Fig. I.2.

$$\frac{\Delta CF_{p1}/CF_{p1}}{\Delta p_1/p_1} = -\frac{0.3\%}{4.8\%} = -0.0625\%/\% \tag{38}$$

The total effect on corrected heat rate can be thus calculated

$$= -0.0769 - (-0.0625) = -0.014 \tag{39}$$

(2) *Throttle Temperature.* The uncertainty in heat rate caused by a 1% error in throttle temperature or the sensitivity ratio of throttle temperature (SR_{Tt}) can be written from Eq. (27):

$$SR_{T1} = \frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{p_{lt}}}{\text{DENOM}} T_{lt} - \frac{\Delta CF_{T1}/CF_{T1}}{\Delta T_1/T_1} \tag{40}$$

The term $\left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{p_{lt}}$ is the slope of the superheated steam enthalpy vs temperature curve at constant pressure. This slope is given in Fig. 5.5. For this case,

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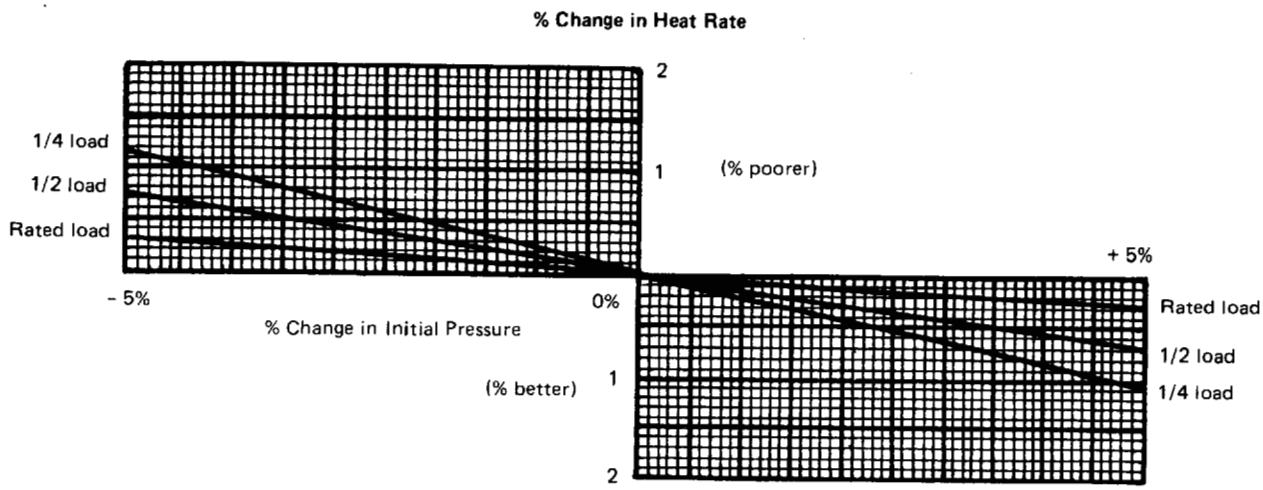


FIG. I.2 INITIAL PRESSURE CORRECTION FACTOR FOR SINGLE REHEAT TURBINES WITH SUPERHEATED INITIAL STEAM CONDITIONS

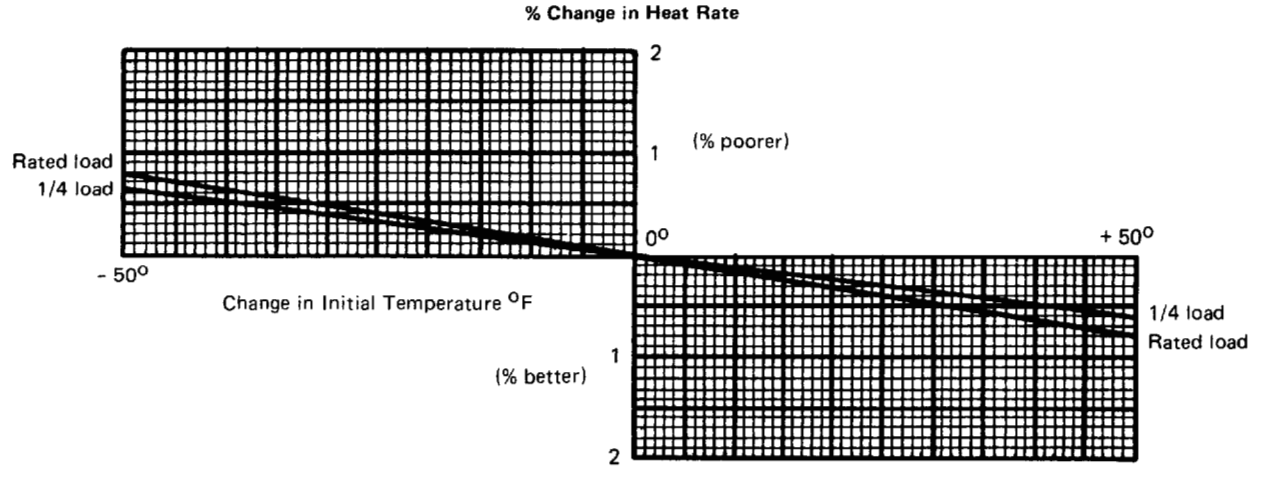


FIG. I.3 INITIAL TEMPERATURE CORRECTION FACTOR FOR TURBINES WITH SUPERHEATED INITIAL STEAM CONDITIONS

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$$\left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{P_{lt}} = \left[\frac{\partial H}{\partial T}\,(p = 2412,\ T = 1000)\right]_p = 0.665 \tag{41}$$

The information on the heat balance allows the calculation of the first right-hand side term in Eq. (39).

$$\frac{w_{lt}\left(\frac{\partial H_{lt}}{\partial T_{lt}}\right)_{P_{lt}}}{\text{DENOM}}\,T_{lt} = \frac{5{,}958{,}707\ (0.665)\ (1000)}{6.53788 \times 10^9} = 0.606 \tag{42}$$

The second right-hand side term in Eq. (39) is the uncertainty due to the correction factor. It is the slope of the throttle temperature correction factor curve found in Fig. I.3.

$$\text{The term } \frac{\Delta CF_{T1}/CF_{T1}}{\Delta T_1/T_1} = \frac{-0.7}{45.7} = -0.0153\%/°\text{F} \tag{43}$$

At 1000°F, 1% = 10°F.

For a 10°F error in throttle temperature, the effect of the throttle temperature correction factor is

$$-0.0153 \times 10 = -0.153\%/\% \tag{44}$$

The uncertainty in corrected heat rate due to 1% error in throttle temperature is thus

$$= 0.606 - (-0.153) = 0.76\%/\% \tag{45}$$

(3) *Final Feedwater Pressure.* The term $(\partial H_{11}/\partial p_{11})_{T_{11}}$ is the slope of the compressed water enthalpy vs pressure at constant temperature. Since enthalpy hardly changes in the compressed liquid range if the temperature is left constant, for the practical range of error in pressure measurement,

$$\left(\frac{\partial H_{11}}{\partial p_{11}}\right)_{T_{11}} = 0 \tag{46}$$

(4) *Final Feedwater Temperature.* The fourth term in Eq. (27) is an expression of the uncertainty in heat rate caused by an error in the final feedwater temperature measurement. Since in the compressed liquid region, enthalpy does not change for the pressure errors being considered, the partial derivative $(\partial H_{11}/\partial T_{11})_p$ can be written as a total derivative

$$\left(\frac{\partial H_{11}}{\partial T_{11}}\right)_{p_{11}} = \left(\frac{dH_{SL}}{dT_{SL}}\right)_{T_{11}} \tag{47}$$

where dH_{SL}/dT_{SL} is the slope of the saturated enthalpy vs saturated temperature curve. This slope is given in Fig. 5.7.

$$\frac{dH_{SL}}{dT_{SL}}\,(T = 542) = 1.26 \tag{48}$$

The fourth term in Eq. (27) can thus be calculated

$$\frac{-w_{lt}\left(\frac{\partial H_{11}}{\partial T_{11}}\right)_{P_{11}}}{\text{DENOM}}\,T_{11} = \frac{-5{,}958{,}707(1.26)\ (542)}{6.53788 \times 10^9} = -0.622 \tag{49}$$

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(5) *Throttle Flow.* The throttle flow term is calculated as follows:

$$\frac{w_{It}(H_{It} - H_{11})}{\text{DENOM}} = \frac{5{,}958{,}707(1460.5 - 536.7)}{6.53788 \times 10^9} = 0.842 \tag{50}$$

(6) *Reheat Flow.* The reheat flow term is calculated as follows:

$$\frac{w_{RH}(H_{HRH} - H_{CRH})}{\text{DENOM}} = \frac{4{,}819{,}165(1520.5 - 1306.1)}{6.53788 \times 10^9} = 0.158 \tag{51}$$

(7) *Hot Reheat Pressure.* The uncertainty in heat rate caused by a 1% error in hot reheat pressure or the sensitivity ratio for reheat pressure (SR_{PHRH}) can be written from Eq. (27).

$$SR_{PHRH} = \frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial p_{HRH}}\right)_{T_{HRH}}}{\text{DENOM}} p_{HRH} - \frac{(\Delta CF_{\Delta p})_{p_{CRH}}/CF_{\Delta p}}{\Delta p_{HRH}/p_{HRH}} \tag{52}$$

The term $(\partial H_{HRH}/\partial p_{HRH})_{T_{HRH}}$ is given in Fig. 5.4. It is

$$\left[\frac{\partial H}{\partial p}(p = 495, T = 1000)\right]_T = -0.03 \tag{53}$$

The first term of Eq. (52) can thus be calculated

$$\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial p_{HRH}}\right)_{T_{HRH}}}{\text{DENOM}} p_{HRH} = \frac{4{,}819{,}165(-0.03)\ (495)}{6.53788 \times 10^9} = -0.011 \tag{54}$$

The term $[(\Delta CF_{\Delta p})_{pCRH}/CF_{\Delta p}]/(\Delta p_{HRH}/p_{HRH})$ is the slope of the reheater pressure drop correction curve, Fig. I.4.

$$\frac{(\Delta CF_{\Delta p})_{p_{CRH}}/CF_{\Delta p}}{\Delta p_{HRH}/p_{HRH}} = 0.100\%/\% \tag{55}$$

The uncertainty in corrected heat rate is then

$$= -0.011 - 0.100 = -0.111 \tag{56}$$

(8) *Hot Reheat Temperature.* The uncertainty in heat rate caused by a 1% error in hot reheat temperature (SR_{THRH}) is found from Eq. (27).

$$SR_{THRH} = \frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}}}{\text{DENOM}} T_{HRH} - \frac{\Delta CF_{THRH}/CF_{THRH}}{\Delta T_{HRH}/T_{HRH}} \tag{57}$$

The term $(\partial H_{HRH}/\partial T_{HRH})_{pHRH}$ is again calculated from Fig. 5.5; it is

$$\left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}} = \left[\frac{\partial H}{\partial T}(p = 495, T = 1000)\right]_p = 0.54 \tag{58}$$

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The first term in Eq. (55) is thus

$$\frac{w_{RH}\left(\frac{\partial H_{HRH}}{\partial T_{HRH}}\right)_{p_{HRH}}}{\text{DENOM}} T_{HRH} = \frac{4{,}819{,}165(0.54)\ (1000)}{6.53788 \times 10^9} = 0.398 \tag{59}$$

The second term is the slope of the hot reheat temperature correction factor. It is found from Fig. I.5.

$$\frac{\Delta CF_{THRH}/CF_{THRH}}{\Delta T_{HRH}/T_{HRH}} = \frac{-0.70}{(50/1000) \times 100} = -0.14\%/\% \tag{60}$$

The uncertainty in corrected heat rate is

$$= 0.398 - (-0.14) = 0.54 \tag{61}$$

(*9*) *Cold Reheat Pressure.* The uncertainty in heat rate caused by a 1% error in cold reheat pressure (SR_{PCRH}) is

$$SR_{PCRH} = \frac{-w_{RH}\left(\frac{\partial H_{CRH}}{\partial p_{CRH}}\right)_{T_{CRH}}}{\text{DENOM}} p_{CRH} - \frac{(\Delta CF_{\Delta p})_{p_{HRH}}/CF_{\Delta p}}{\Delta p_{CRH}/p_{CRH}} \tag{62}$$

The term $(\partial H_{CRH}/\partial p_{CRH})_{T_{CRH}}$ is calculated from Fig. 5.4.

$$\left(\frac{\partial H_{CRH}}{\partial p_{CRH}}\right)_{T_{CRH}} = \left[\frac{\partial H}{\partial p}\,(p = 550,\ T = 620)\right]_T = -0.078 \tag{63}$$

The first term is thus

$$\frac{-w_{RH}\left(\frac{\partial H_{CRH}}{\partial p_{CRH}}\right)_{T_{CRH}}}{\text{DENOM}} p_{CRH} = \frac{-4{,}819{,}165(-0.078)}{6.53788 \times 10^9} 550 = +0.0316 \tag{64}$$

The second term $(\Delta CF_{\Delta p_{PHRH}}/CF_{\Delta p})/(\Delta p_{CRH}/p_{CRH})$ is the slope of the reheater pressure drop correction factor, Fig. I.4.

$$\frac{\Delta CF_{\Delta p_{HRH}}/CF_{\Delta p}}{\Delta p_{CRH}/p_{CRH}} = 0.10\%/\% \tag{65}$$

The uncertainty in corrected heat rate is

$$+0.032 - 0.10 = -0.07 \tag{66}$$

(*10*) *Cold Reheat Temperature.* The sensitivity ratio ($SR_{T_{CRH}}$) for the cold reheat temperature measurement is

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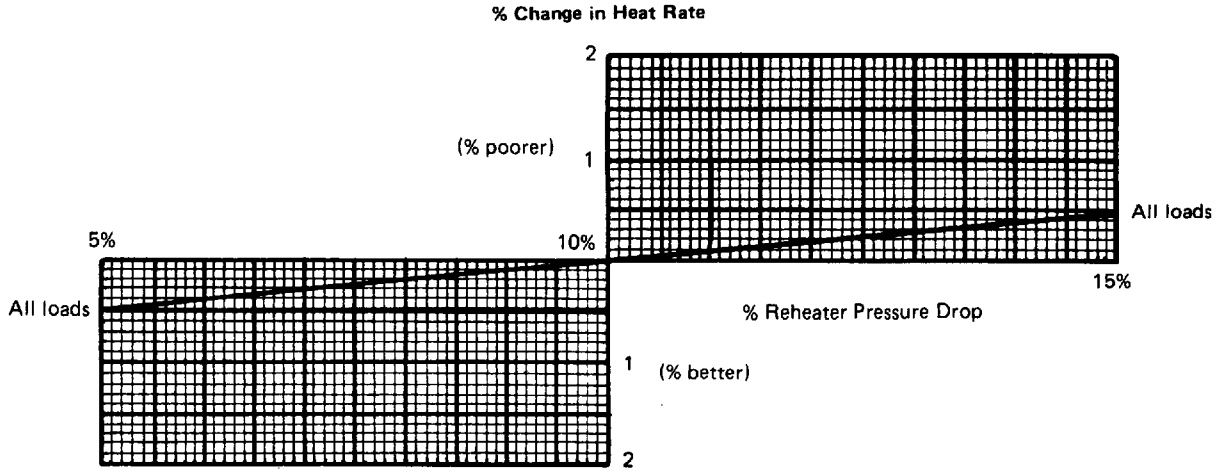


FIG. I.4 REHEATER PRESSURE DROP CORRECTION FACTOR FOR TURBINES WITH SUPERHEATED INITIAL STEAM CONDITIONS

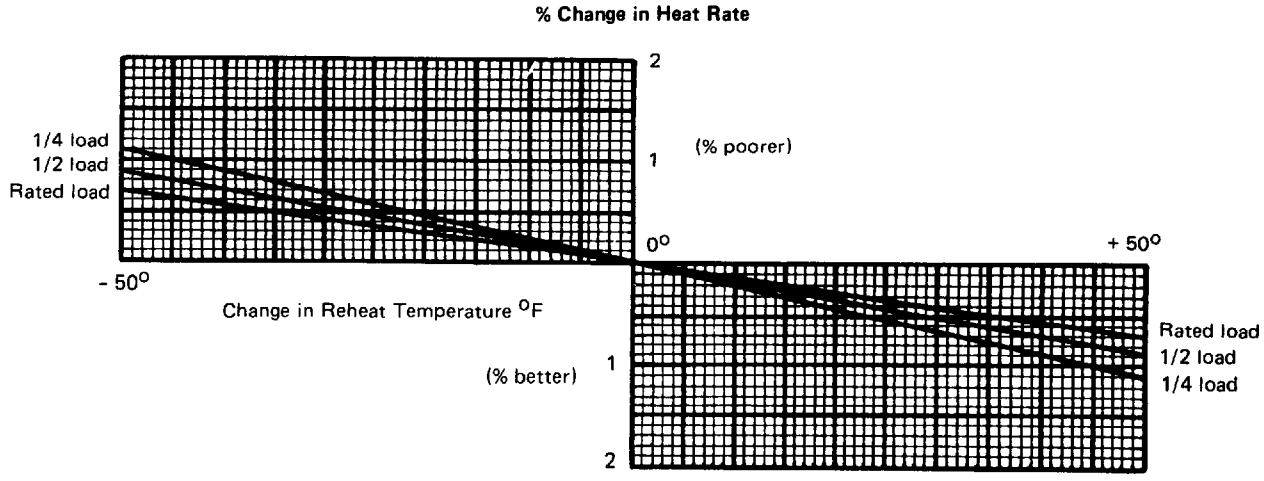


FIG. I.5 REHEATER TEMPERATURE CORRECTION FACTOR FOR TURBINES WITH SUPERHEATED INITIAL STEAM CONDITIONS

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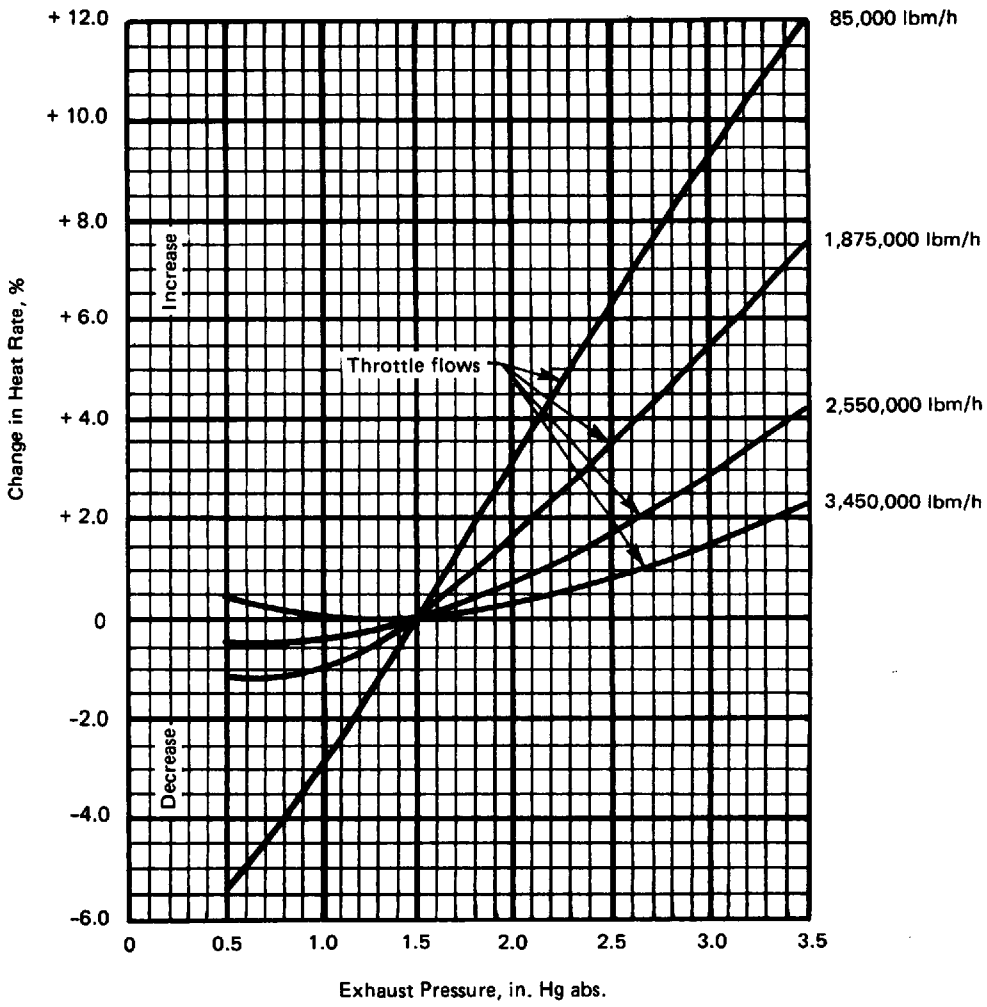


FIG. I.6 EXHAUST PRESSURE CORRECTION FACTOR FOR TURBINES WITH SUPERHEATED INITIAL STEAM CONDITIONS

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TABLE I.1
ERRORS IN CALCULATED HEAT RATE DUE TO ERRORS IN INDIVIDUAL MEASUREMENTS

Test Measurement A	Effect on Heat Rate Uncertainty (per %) B	Additional Effect Due to Correction Factor C	Effect on Heat Rate D = B + C	Assumed Uncertainty of Measurement E (%)	Heat Rate Uncertainty F = D × E	F^2
Throttle flow [Note (1)]	0.84	0.16 [Note (2)]	1.0	±0.15	±0.15	0.0225
Power	−1.0	—	−1.0	±0.10	±0.10	0.0100
Throttle pressure	−0.077	0.0625	−0.014	±0.85	±0.0119	0.000142
Throttle temperature	0.606	0.153	0.76	±0.10	±0.076	0.005783
Final feed pressure	0	—	0	±1.00	±0.00	0.000
Final feed temperature	−0.62	—	0.62	±0.18	±0.112	0.0125
Hot reheat pressure	−0.011	−0.10	0.111	±0.45	±0.050	0.0025
Hot reheat temperature	0.398	0.14	0.54	±0.10	±0.0540	0.00292
Cold reheat pressure	0.0316	−0.10	−0.068	±1.34	±0.0911	0.0083
Cold reheat temperature	−0.279	—	−0.28	±0.16	±0.0448	0.002
Exhaust pressure	—	−0.044	−0.044	±1.0	±0.044	0.00194

σ^2 = Sum of the squares = 0.06858
$\sigma = \sqrt{\text{Sum of squares}} = 0.26$

NOTES:
(1) The uncertainty in throttle flow is not the same as condensate flow uncertainty; it must be calculated from the heat balance around the heaters.
(2) The reheat flow uncertainty depends on throttle flow uncertainty. A 1% uncertainty in throttle flow is assumed to cause 1% uncertainty in the calculated reheat flow.

$$SR_{TCRH} = \frac{-w_{RH}\left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}}}{\text{DENOM}} T_{CRH} \tag{67}$$

The partial derivative term can be evaluated from Fig. 5.5.

$$\left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}} = \left[\frac{\partial H}{\partial T}(p = 550, T = 620)\right]_p = 0.61 \tag{68}$$

Therefore,

$$SR_{TCRH} = \frac{-w_{RH}\left(\frac{\partial H_{CRH}}{\partial T_{CRH}}\right)_{p_{CRH}}}{\text{DENOM}} T_{CRH} = \frac{-4{,}819{,}165(0.61)\ (620)}{6.53788 \times 10^9} = -0.279 \tag{69}$$

(11) *Exhaust Pressure.* The sensitivity ratio for exhaust pressure is

$$SR_{p6} = \frac{\Delta CF_{p6}/CF_{p6}}{\Delta p_6/p_6} \tag{70}$$

This expression can be calculated by graphical differentiation of Fig. I.6.

The slope of the exhaust pressure correction curve at design exhaust pressure of 3 in. Hg and at full load flow is 1.47% per in. Hg. For a 1% change in exhaust pressure, the correction becomes 1.47 × 0.03 or 0.044% per percent.

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In the foregoing analysis, the uncertainty in calculated heat rate resulting from a 1% error in each independent measurement was calculated. An additional uncertainty term was introduced when the test heat rate was corrected to design conditions. These uncertainties are listed in Table I.1 under Columns B and C, respectively. The number in Column D is thus the uncertainty in heat rate.

$$D = B + C \tag{71}$$

Column E contains the assumed uncertainty for each of the measurements on the unit. Thus, the uncertainty in heat rate caused by each of the measurements is given by the following formula.

$$F = D \times E \tag{72}$$

The total uncertainty (σ) in the result (corrected heat rate) caused by these combined measurement uncertainties can thus be calculated

$$\sigma^2 = \text{sum of squares} = \Sigma F^2 = 0.06858 \tag{73}$$

$$\sigma = \sqrt{0.06858} = \pm 0.26\% \tag{74}$$

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APPENDIX II
DERIVATION OF FIG. 3.2

This Appendix presents the method used for developing Fig. 3.2, required number of readings for a test.

U_T on Fig. 3.1 is defined as

$$U_T = \theta_1(t_{95}S_{\bar{x}})\ 100/\bar{x} \text{ or } \theta_2(t_{95}S_{\bar{x}}) \quad (1)$$

In this equation, θ_1 is the ratio of the percentage change in heat rate or steam rate to the percentage change in readings, and θ_2 is the percentage change in heat rate or steam rate per unit of reading (such as °F). Values of θ_1 and θ_2 applicable to steam turbine tests are given in Table 3.1. $S_{\bar{x}}$ is the estimated standard deviation for the average of the readings, t_{95} is the Student's t-distribution for N-1 degrees of freedom from Table 5.1, and $\bar{x}$ is the average of N number of readings.

Substituting $\dfrac{t_{95}S_x}{\sqrt{N}}$ for $t_{95}S_{\bar{x}}$ in Eq. (1) results in:

$$U_T = \frac{\theta_1(t_{95}S_x)\ 100}{\sqrt{N}\ (\bar{x})} \text{ or } \frac{\theta_2(t_{95}S_x)}{\sqrt{N}} \quad (2)$$

In Eq. (2), S_x is the estimated standard deviation of N number of readings.

Solving Eq. (2) for N

$$N = \left[\frac{\theta_1(t_{95}S_x)\ 100}{U_T(\bar{x})}\right]^2 \text{ or } \left[\frac{\theta_2(t_{95}S_x)}{U_T}\right]^2 \quad (3)$$

Where computers are available in an automated data logging system, Eq. (3) can be used to predict the number of readings required by calculating a running standard deviation and running average during the progress of a test. Where computers are not available and for sample sizes of 10 or less, the range (maximum reading-minimum reading) for identical sample sizes may be used to estimate S_x.

$$S_x = \bar{R}/d_2^* \quad (4)$$

Where $\bar{R}$ is the average range for the number of samples being considered (each sample containing the same number of readings) and d_2^* is from Table II.1.

Substituting Eq. (4) for S_x in Eq. (3) results in

$$N = \left[\frac{\theta_1(t_{95}\bar{R})\ 100}{(U_T)(\bar{x})\ d_2^*}\right]^2 \text{ or } \left[\frac{\theta_2(t_{95}\bar{R})}{(U_T)\ d_2^*}\right]^2 \quad (5)$$

t_{95} in this equation is the Student's t-distribution for the degrees of freedom ν given in Table II.1 for the M number of samples of sample size N used to establish $\bar{R}$.

The Fig. 3.2 family of curves, which were developed using Eq. (4) as a basis, can be used for manually establishing the number of readings required for a test. The term $\bar{Z}$ in the calculation for entry into the abscissa of this curve is equal to $\theta_1(\bar{R})$ $100/\bar{x}$ or $\theta_2 \times R$ in Eq. (4). $\bar{Z}$ for calculating $\bar{Z}/U_T$ for entry into Fig. 3.1 is calculated by using the average of the maximum-minimum readings in all the samples M of size N considered for $\bar{R}$, and an average for $\bar{x}$. An approximate average for $\bar{x}$ based on a scanned average or from the term 0.5 (maximum plus minimum readings) can be used (see nomenclature in Par. 3.05).

Sample sizes of five readings were selected for developing Fig. 3.2. The test engineer scanning the data available should be able to readily pick out the high and low readings from batches of five consecutive readings. The sample size of five readings was, therefore, selected as a convenience. A curve similar to Fig. 3.2 can be developed for any sample sizes from 5 to 10 using Table II.1 and the above equations.

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TABLE II.1
VALUES ASSOCIATED WITH THE DISTRIBUTION OF THE AVERAGE RANGE[1]

Number Of Sets	Number of Observations Per Set N											
	5		6		7		8		9		10	
M	ν	d_2^*	ν	d_2^*	ν	d_2^*	ν	d_2^*	ν	d_2^*	ν	d_2^*
1	3.8	2.48	4.7	2.67	5.5	2.83	6.3	2.96	7.0	3.08	7.7	3.18
2	7.5	2.40	9.2	2.60	10.8	2.77	12.3	2.91	13.8	3.02	15.1	3.13
3	11.1	2.38	13.6	2.58	16.0	2.75	18.3	2.89	20.5	3.01	22.6	3.11
4	14.7	2.37	18.1	2.57	21.3	2.74	24.4	2.88	27.3	3.00	30.1	3.10
5	18.4	2.36	22.6	2.56	26.6	2.73	30.4	2.87	34.0	2.99	37.5	3.10
6	22.0	2.35	27.1	2.56	31.8	2.73	36.4	2.87	40.8	2.99	45.0	3.10
7	25.6	2.35	31.5	2.55	37.1	2.72	42.5	2.87	47.5	2.99	52.4	3.10
8	29.3	2.35	36.0	2.55	42.4	2.72	48.5	2.87	54.3	2.98	59.9	3.09
9	32.9	2.34	40.5	2.55	47.7	2.72	54.5	2.86	61.0	2.98	67.3	3.09
10	36.5	2.34	44.9	2.55	52.9	2.72	60.6	2.86	67.8	2.98	74.8	3.09

NOTE:
(1) Adapted with permission from Ref. (69) of Appendix III.

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PERFORMANCE TEST CODES

While providing for exhaustive tests, these Codes are so drawn that selected parts may be used for tests of limited scope.

PERFORMANCE TEST CODES NOW AVAILABLE

PTC 1 — General Instructions 1980 (R1985)
PTC 2 — Definitions and Values 1980 (R1985)
PTC 6 — Steam Turbines 1976 (R1982)
PTC 6.1 — Interim Test Code for an Alternative Procedure for Testing Steam Turbines 1984
PTC 6A — Appendix A to Test Code for Steam Turbines (With 1958 Addenda) 1982
PTC 7 — Reciprocating Steam-Driven Displacement Pumps 1949 (R1969
PTC 7.1 — Displacement Pumps 196: (R1969)
PTC 8.2 — Centrifugal Pumps (With 1973 Addenda) 1965
PTC 18 — Hydraulic Prime Movers 1949
PTC 18.1 — Pumping Mode of Pump/Turbines 1978

PTC 6 Report — Guidance for Evaluation of Measurement Uncertainty in Performance Tests of Steam Turbines 1974 (R1985)
PTC 6S Report — Simplified Procedures for Routine Performance Test of Steam Turbines 1974 (R1985)

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