AN AMERICAN NATIONAL STANDARD

ASME
PTC 12.1-2000
[Revision of ANSI/ASME
PTC 12.1-1978 (R 1987)]

Closed Feedwater Heaters

PERFORMANCE TEST CODES

The American Society of
Mechanical Engineers

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FOREWORD

The Performance Test Code Committee 12.1 was assembled to review, edit, and update the existing 1978 Code edition. The Code has been extensively revised to comply with the latest requirements in the PTC 1–1991, General Instructions, including the required uncertainty analysis. This Code incorporates a revised calculation procedure, including examples. The calculation method requires iterations and can be performed manually but is best done by using a computer program. The Code also incorporates an alternative for using ultrasonic flow measurement techniques to test individual or split-string feedwater heaters, when flow nozzles are not available. This edition of the Code provides a relatively simple but accurate method of calculating the performance of a heater utilizing the Code procedure with a minimum knowledge of the design characteristics of the heater.

This version was approved by the Board on Performance Test Codes on February 23, 2000 and as an American National Standard by the ANSI Board of Standards Review on May 23, 2000.

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NOTICE

All Performance Test Codes **MUST** adhere to the requirements of **PTC 1, GENERAL INSTRUCTIONS**. The following information is based on that document and is included here for emphasis and for the convenience of the user of this Code. It is expected that the Code user is fully cognizant of Parts I and III of PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures which yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests. They specify procedures, instrumentation, equipment operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do **not** specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree **before starting the test and preferably before signing the contract** on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

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CONTENTS

Foreword iii
Committee Roster v
Board Roster vi

Section

0 Introduction 1
1 Object and Scope 3
2 Definitions and Description of Terms 5
3 Guiding Principles 17
4 Instruments and Methods of Measurement 27
5 Computation of Results 33
6 Report of Results 55
7 References 57

Figures

3.3.1 Typical DCA and TTD versus Internal Liquid Level 19
3.8.1 Desuperheating, Condensing, and Drain Cooling Zones 22
3.8.2 Desuperheating and Condensing Zones 23
3.8.3 Condensing and Drain Cooling Zones 24
3.8.4 Condensing Zone 25
3.8.5 External Drain Cooler 26
4.4.1 Typical Transducer Installation 29

Tables

3.3.1 Deviation Limits of Parameters 18
4.6 Maximum Uncertainty Values 31
5.1.1 Three-Zone Heater 34
5.1.2 Two-Zone Heater Desuperheating and Condensing 36
5.1.3 Two-Zone Heater Condensing and Drain Cooling 38
5.1.4 Condensing Only Heater 40
5.1.5 External Drain Cooler 42
5.1.6 PTC 12.1 Heater Test Report Form 44

Nonmandatory Appendices

A Basic Heat Transfer Equations 59
B Heater Performance Calculation Examples 61
C Uncertainty Considerations 73
D Principal Quantities and Commonly Used Conversion Factors In Heat Transfer (SI Units) 81

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SECTION 0 — INTRODUCTION

0.1

For the purposes of this Code, a closed feedwater heater is a power plant component designed to heat a given quantity of feedwater through a specified temperature range. The heating medium is steam or condensate at a specified enthalpy and pressure. In such heaters, the feedwater and heating medium typically are routed through the tubes and shell, respectively. Feedwater heaters are designed to be configured in one of the following ways:

(a) horizontal
(b) vertical channel down
(c) vertical channel up
(d) duplex (two separate tube bundles in a single divided shell)

In some cases, more than one feedwater heater is required for a given feedwater flow and heat source. In such instances, the feedwater heater is divided into two or three parallel heaters which constitute a multiple string arrangement. Depending on the design conditions, the heat transfer surface area within the feedwater heater may be configured as follows:

(a) desuperheating zone
(b) condensing zone
(c) drain cooling zone

Steam is the heating medium in the condensing and desuperheating zones. Condensate is the heating medium in the drain cooling zone.

0.2

This Code is written in accordance with the PTC-1, General Instructions. PTC-2, Definitions and Values defines certain technical terms and numerical constants which are used in this Code with the significance and value therein established. The PTC-19 series Supplements on Instruments and Apparatus, covering the instruments prescribed in this Code, should be used for reference.

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SECTION 1 — OBJECT AND SCOPE

1.1 OBJECT

The object of this Code is to provide the procedures, direction, and guidance for determining the performance of a closed feedwater heater with regard to the following:

(a) Terminal Temperature Difference (*TTD*), which is the difference between the saturation temperature corresponding to the steam inlet pressure and the feedwater outlet temperature;

(b) Drain Cooler Approach (*DCA*), which is the difference between drain outlet temperature and feedwater inlet temperature;

(c) tube side (feedwater) pressure loss through the heater; and

(d) shell side pressure loss through the desuperheating zone, and through the drain cooling zone.

1.2 SCOPE

This Code applies to all horizontal and vertical heaters except those with partial pass drain cooling zones. Designs with partial pass drain cooling zones are horizontal heaters with submerged drain cooling zones, and vertical channel-up heaters with drain cooling zones. In those designs, only a portion of the feedwater passes through the drain cooling zones; therefore, there are two feedwater flow streams with different temperature profiles.

A feedwater heater is designed to accomplish heat transfer between fluids. The heater design is based on a specific operating condition that includes flow, temperature, and pressure. This specific condition constitutes the design point that is found on the manufacturer's feedwater heater specification sheet.

It is not feasible to expect that the test will be conducted at the design point. Therefore, it is necessary to predict the heater performance by adjusting the design parameters for the test conditions. Methods of calculating the predicted heater performance are presented in the Code. These predicted values shall then be compared to corresponding measured test values.

1.3 UNCERTAINTY

This Code provides recommendations on instrumentation, procedures, and accuracies required for data collection. An example of an uncertainty analysis is provided in Appendix C. When the recommended instrumentation accuracies are employed as described in Section 4, and the method of calculation described in Section 5 is used, the expected total uncertainties in the test results will be as follows:

- Difference between predicted *TTD* and measured *TTD*: ±0.36°F
- Difference between predicted *DCA* and measured *DCA*: ±0.32°F
- Difference between predicted and measured tube side pressure loss (percent of predicted): ±3.1%
- Difference between predicted and measured shell side pressure loss through the desuperheating zone (percent of predicted): ±2.2%
- Difference between predicted and measured shell side pressure loss through the drain cooling zone (percent of predicted): ±1.8%

These uncertainties are provided as typical values using the instrumentation accuracies, locations, and techniques recommended by this Code. The uncertainties may be reduced through careful placement of alternative or redundant instrumentation. The total uncertainties presented above were calculated using the procedure described in Subsection 5.3. The bias uncertainties were determined by the judgment of this committee for a test adhering to the procedures of this Code.

A post-test uncertainty analysis is recommended. However, a post-test uncertainty analysis is optional if parties to the test agree that the test adhered to all instrumentation requirements and procedures contained in this Code.

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SECTION 2 — DEFINITIONS AND DESCRIPTION OF TERMS

2.1 SYMBOLS

Symbol	Term	Description	Units	
			U.S. Customary	SI
A_1'	Drain cooling zone or external drain cooler heat transfer surface area (design)	Based on outside of tubes in drain cooling zone or external drain cooler (effective surface only), provided by heater designer	sq ft	m^2
A_2'	Condensing zone heat transfer surface area (design)	Based on outside of tubes in condensing zone (effective surface only), provided by heater designer	sq ft	m^2
A_3'	Desuperheating zone heat transfer surface area (design)	Based on outside of tubes in desuperheating zone (effective surface only), provided by heater designer	sq ft	m^2
C_1*	Hourly heat capacity flow rate of steam condensate in drain cooling zone or external drain cooler (computed)	By computation	Btu/(hr-°F)	W/C
C_3*	Hourly heat capacity flow rate of steam in desuperheating zone (computed)	By computation	Btu/(hr-°F)	W/C
c_1*	Hourly heat capacity flow rate of feedwater in drain cooling zone or external drain cooler (computed)	By computation	Btu/(hr-°F)	W/C

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Symbol	Term	Description	Units	
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c_2*	Hourly heat capacity flow rate of feedwater in condensing zone (computed)	By computation	Btu/(hr-°F)	W/C
c_3*	Hourly heat capacity flow rate of feedwater in desuperheating zone (computed)	By computation	Btu/(hr-°F)	W/C
DCA	Drain cooler approach (actual)	T_1-t_1 (measured values)	°F	°C
DCA'	Drain cooler approach (design)	Provided by heater designer	°F	°C
*DCA**	Predicted drain cooler approach (computed)	T_1*-t_1	°F	°C
H_d	Drains inlet enthalpy (computed)	From ASME Steam Tables at T_d for each saturated liquid	Btu/lbm	kJ/kg
H_1*	Drain outlet enthalpy (computed)	From ASME Steam Tables at P_1 and T_{1a}* for compressed liquid	Btu/lbm	kJ/kg
H_3	Steam inlet enthalpy (computed)	From ASME Steam Tables at P_3 and T_3 for dry or superheated steam. Otherwise from steam quality measurement, if possible, or from performing a turbine heat balance.	Btu/lbm	kJ/kg
h_1	Feedwater inlet enthalpy (computed)	From ASME Steam Tables at p_1 and t_1 for compressed liquid	Btu/lbm	kJ/kg
h_4*	Feedwater outlet enthalpy (computed)	From ASME Steam Tables at p_4 and t_{4a}* for compressed liquid	Btu/lbm	kJ/kg
$(NTU)_1$*	Number of transfer units, drain cooling zone or external drain cooler (computed)	By computation	—	—

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Symbol	Term	Description	Units	
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$(NTU)_2$*	Number of transfer units, condensing zone (computed)	By computation	—	—
$(NTU)_3$*	Number of transfer units, desuperheating zone (computed)	By computation	—	—
ΔP_{dc}	Drain cooling zone or external drain cooler pressure loss due to friction (actual)	Measured value of the differential pressure	psi	Pa
$\Delta P_{dc}'$	Drain cooling zone or external drain cooler pressure loss due to friction (design)	Provided by heater designer	psi	Pa
ΔP_{dc}*	Predicted drain cooling zone or external drain cooler pressure loss due to friction (computed)	By computation	psi	Pa
ΔP_{ds}	Desuperheating zone pressure loss due to friction (actual)	Measured value of the differential pressure	psi	Pa
$\Delta P_{ds}'$	Desuperheating zone pressure loss due to friction (design)	Provided by heater designer	psi	Pa
ΔP_{ds}*	Predicted desuperheater pressure loss due to friction (computed)	By computation	psi	Pa
P_1	Drain outlet pressure (actual)	Measured value	psia or in. Hga	Pa
P_2	Steam pressure in condensing zone, drain cooling zone inlet pressure or external drain cooler inlet pressure (actual)	Measured value	psia or in. Hga	Pa
P_3	Steam inlet pressure (actual)	Measured value	psia or in. Hga	Pa
P_2'*	Steam pressure in condensing zone (feedwater heaters only) (computed)	By computation	psia or in. Hga	Pa

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Symbol	Term	Description	Units	
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P_3'	Steam inlet pressure (design)	From design heat balance	psia or in. Hga	Pa
p_1	Feedwater inlet pressure (actual)	Measured value	psia	Pa
p_4	Feedwater outlet pressure (actual)	Measured value	psia	Pa
Δp_t	Feedwater pressure loss due to friction (actual)	Measured value of the differential pressure	psi	Pa
$\Delta p_t'$	Feedwater pressure loss due to friction (design)	Provided by heater designer	psi	Pa
Δp_t^*	Predicted feedwater pressure loss due to friction (computed)	By computation	psi	Pa
Q^*	Total heat transferred (computed)	By computation	Btu/hr	W
Q_1'	Drain cooling zone or external drain cooler heat transferred (design)	Rate of heat transfer to feedwater, provided by heater designer	Btu/hr	W
Q_2'	Condensing zone heat transferred (design)	Rate of heat transfer to feedwater, provided by heater designer	Btu/hr	W
Q_3'	Desuperheating zone heat transferred (design)	Rate of heat transfer to feedwater, provided by heater designer	Btu/hr	W
R_1^*	Heat capacity ratio, drain cooling zone or external drain cooler (computed)	By computation	—	—
R_3^*	Heat-capacity ratio, desuperheating zone (computed)	By computation	—	—
r_{fs1}	Condensate fouling resistance, drain cooling zone or external drain cooler (assumed)	By agreement	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{fs1}'	Condensate fouling resistance, drain cooling zone or external drain cooler (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W

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Symbol	Term	Description	Units	
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r_{fs2}	Steam fouling resistance, condensing zone (assumed)	By agreement	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{fs2}'	Steam fouling resistance, condensing zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{fs3}	Steam fouling resistance, desuperheating zone (assumed)	By agreement	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{fs3}'	Steam fouling resistance, desuperheating zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{ft1}	Feedwater fouling resistance, drain cooling zone or external drain cooler (assumed)	By agreement	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{ft1}'	Feedwater fouling resistance, drain cooling zone or external drain cooler (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{ft2}	Feedwater fouling resistance, condensing zone (assumed)	By agreement	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{ft2}'	Feedwater fouling resistance, condensing zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W

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Symbol	Term	Description	Units	
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r_{f3}	Feedwater fouling resistance, desuperheating zone (assumed)	By agreement	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{f3}'	Feedwater fouling resistance, desuperheating zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{m1}'	Tube metal resistance, drain cooling zone or external drain cooler (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{m2}'	Tube metal resistance, condensing zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{m3}'	Tube metal resistance, desuperheating zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{s1}*	Condensate film resistance, drain cooling zone or external drain cooler (computed)	By computation	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{s1}'	Condensate film resistance corrected for reheat, drain cooling zone or external drain cooler (no correction required for external drain cooler) (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{s2}'	Steam film resistance, condensing zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{s3}*	Steam film resistance, desuperheating zone (computed)	By computation	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{s3}'	Steam film resistance, desuperheating zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W

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Symbol	Term	Description	Units	
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r_{f1}*	Feedwater film resistance, drain cooling zone or external drain cooler (computed)	By computation	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{f1}'	Feedwater film resistance, drain cooling zone or external drain cooler (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{f2}*	Feedwater film resistance, condensing zone (computed)	By computation	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{f2}'	Feedwater film resistance, condensing zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{f3}*	Feedwater film resistance, desuperheating zone (computed)	By computation	hr-ft^2-°F/Btu	[m^2-°C]/W
r_{f3}'	Feedwater film resistance, desuperheating zone (design)	Provided by heater designer	hr-ft^2-°F/Btu	[m^2-°C]/W
T_d	Drains inlet temperature (actual)	Measured value upstream of control valve	°F	°C
T_{ds}	Steam temperature at desuperheating zone exit (actual)	Not required for calculation	°F	°C
T_{ds}'	Steam temperature at desuperheating zone exit (design)	Provided by heater designer	°F	°C
T_s*	Saturated steam temperature corresponding to steam inlet pressure (computed)	From ASME Steam Tables, corresponding to P_3	°F	°C
T_1	Drain cooling zone or external drain cooler outlet temperature (actual)	Measured value	°F	°C
T_1*	Drain cooling zone or external drain cooler outlet temperature (computed)	By computation	°F	°C

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Symbol	Term	Description	Units	
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T_{1a}*	Drain cooling zone outlet temperature (computed)	By computation (using t_1 + *DCA*′)	°F	°C
T_1′	Drain cooling zone or external drain cooler outlet temperature (design)	From design heat balance	°F	°C
T_2	Drain cooling zone or external drain cooler condensate inlet temperature (actual)	Measured value	°F	°C
T_2*	Saturated steam temperature in condensing zone (feedwater heaters only) (computed)	From ASME Steam Tables corresponding to P_2*	°F	°C
T_2′	Drain cooling zone or external drain cooler condensate liquid inlet temperature and saturated steam temperature in condensing zone (design)	Provided by heater designer	°F	°C
T_3	Steam inlet temperature (actual)	Measured value	°F	°C
T_3′	Steam inlet temperature (design)	From design heat balance	°F	°C
TTD	Terminal temperature difference (actual)	$T_s - t_4$ (except for external drain cooler only, $T_2 - t_4$)	°F	°C
*TTD**	Predicted terminal temperature difference (computed)	$T_s - t_4$* (except for external drain cooler only, $T_2 - t_4$*)	°F	°C
TTD′	Terminal temperature difference (design)	Provided by heater designer	°F	°C
t_1	Feedwater inlet temperature (actual)	Measured value	°F	°C
t_1′	Feedwater inlet temperature (design)	From design heat balance	°F	°C

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Symbol	Term	Description	Units	
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t_2*	Feedwater temperature leaving the drain cooling zone and entering the condensing zone (computed)	By computation (for external drain cooler only, use t_4*)	°F	°C
t_2'	Feedwater temperature leaving the drain cooling zone and entering the condensing zone (design)	Provided by heater designer (for external drain cooler only, use t_4')	°F	°C
t_3*	Feedwater temperature leaving the condensing zone and entering the desuperheating zone (computed)	By computation	°F	°C
t_3'	Feedwater temperature leaving the condensing zone and entering the desuperheating zone (design)	Provided by heater designer	°F	°C
t_4	Feedwater outlet temperature (actual)	Measured value	°F	°C
t_4*	Feedwater outlet temperature (computed)	By computation	°F	°C
t_4'	Feedwater outlet temperature (design)	From design heat balance	°F	°C
t_{4a}*	Feedwater outlet temperature (computed)	By computation (using $T_s - TTR'$)	°F	°C
U_1*	Overall heat transfer coefficient, drain cooling zone or external drain cooler (computed)	Reciprocal of the summation of resistance for the drain cooling zone or the external drain cooler	Btu/hr-ft^2-°F	W/[m^2-°C]
U_2*	Overall heat transfer coefficient, condensing zone (computed)	Reciprocal of the summation of condensing zone resistances	Btu/hr-ft^2-°F	W/[m^2-°C]
U_3*	Overall heat transfer coefficient, desuperheating zone (computed)	Reciprocal of the summation of desuperheating zone resistances	Btu/hr-ft^2-°F	W/[m^2-°C]
v	Average feedwater velocity	Velocity at the average feedwater temperature	ft/sec	m/s

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Symbol	Term	Description	Units	
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W_d	Drains inlet flow rate to heater (actual or computed)	Either by flow meter (meter to be upstream of flash point) or calculated by performing heat balances on the heaters cascading to the heater being tested	lbm/hr	kg/s
W_s	Steam flow rate (actual)	By computation	lbm/hr	kg/s
W_s'	Steam flow rate (design)	From design heat balance	lbm/hr	kg/s
W_1	Drain outlet flow rate from heater or external drain cooler (actual)	Measured value	lbm/hr	kg/s
W_1*	Drain outlet flow rate from heater or external drain cooler (computed)	Either calculated from heat balance or by flow meter (meter to be upstream of flash point)	lbm/hr	kg/s
W_1'	Drain outlet flow rate from heater or external drain cooler (design)	From design heat balance	lbm/hr	kg/s
w	Feedwater flow rate to heater or external drain cooler (actual)	Measured value	lbm/hr	kg/s
w'	Feedwater flow rate to heater or external drain cooler (design)	From design heat balance	lbm/hr	kg/s
ϵ_1*	Effectiveness, drain cooling zone or external drain cooler (computed)	By computation	—	—
ϵ_2*	Effectiveness, condensing zone (computed)	By computation	—	—
ϵ_3*	Effectiveness, desuperheating zone (computed)	By computation	—	—

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2.2 NOMENCLATURE

Symbol	Term
A	Heat transfer surface area
C	Shell side hourly heat capacity flow rate
c	Feedwater hourly heat capacity flow rate
DCA	Drain cooler approach
H	Shell side enthalpy
h	Feedwater enthalpy
k	Thermal conductivity
NTU	Number of transfer units
P	Shell side pressure
p	Feedwater pressure
Q	Heat transferred
R	Heat capacity ratio
r	Heat transfer resistance (corrected to the outside tube surface)
T	Shell side temperature
TTD	Terminal temperature difference
t	Feedwater temperature
U	Overall heat transfer coefficient
v	Feedwater velocity
W	Shell side flow rate
w	Feedwater flow rate

2.3 SUBSCRIPTS

Numerical subscripts (1, 2, 3, 4) represent points as identified on the thermal profile in Figs. 3.8.1 through 3.8.5.

Symbol	Description
a	Assumed
d	Drains
dc	Drain cooling zone
ds	Desuperheating zone
fs	Shell side fouling
ft	Tube side fouling
m	Metal (wall)
s	Shell side
t	Tube side

2.4 SUPERSCRIPTS

Symbol	Description
′(prime)	Represents either design data or values computed with data obtained from the heater manufacturer
*(asterisk)	Represents computed values associated with the predicted performance
no superscript	Represents test data or data computed from test results

2.5 GREEK LETTERS

Symbol	Description
Δ	change in parameter
ϵ	effectiveness

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SECTION 3 — GUIDING PRINCIPLES

3.1 ITEMS FOR AGREEMENT

The parties to the test shall reach a definite agreement regarding the specific test objectives in Section 1. As a minimum, the following items shall be agreed upon prior to the test:

(a) unit operating conditions during the test; specifically on the means to secure consistent inlet steam conditions and feedwater flow and the method of determining drain flow;

(b) method of recording data, number, and frequency of observations and duration of the run;

(c) instrumentation to be used and any permitted alternatives;

(d) instrumentation accuracy and methods and frequency of calibration;

(e) the location of all instrumentation, taking into consideration the internal design of the heater and the external piping configuration;

(f) determination of parameters not directly measured;

(g) fouling resistance to be used in computing design-adjusted *TTD* and *DCA*;

(h) method of testing and determining performance of multiple-string feedwater heaters; and

(i) identification of any known damage or deficiency, e.g., plugged tubes.

3.2 PARAMETERS AFFECTING FEEDWATER HEATER PERFORMANCE

In a feedwater heater, the *TTD* and the *DCA* are indications of the ability of the heater to transfer heat under a given set of conditions, i.e., the design point. This ability is represented by the overall heat transfer coefficient for each zone, the log mean temperature difference *(LMTD)* and the available heat transfer surface area. The principal items affecting the heater's ability to transfer heat are:

(a) tube material, diameter, thickness, length, and arrangement;

(b) tube cleanliness;

(c) noncondensable gases in the steam or water spaces of the heater;

(d) shell liquid level;

(e) feedwater inlet temperature, pressure, and flow;

(f) steam inlet pressure and temperature;

(g) drains inlet enthalpy and flow; and

(h) unbalanced feedwater flow with multiple string arrangements.

Heater performance (as defined in Subsection 1.1) is affected by the heater design, tube cleanliness, and the operating conditions during the test. Operation at conditions other than the design point will result in changed performance. This means that heater performance cannot be determined simply by comparison of measured *TTD* and *DCA* with their guaranteed values. Therefore, it is necessary to predict the heater performance by adjusting the design parameters for the test conditions. These predicted values shall then be compared to the corresponding measured test values.

3.3 METHODS OF OPERATION DURING THE TEST

3.3.1 General. The feedwater heater and other components in the turbine cycle shall be operated in steady state as close to design parameters as possible during the test unless specified otherwise by this Code.

The heater must be properly operated to ensure optimum performance. The heater shall be operated with the proper level and vented of noncondensible gases. Improper venting or water level may significantly affect the performance of the heater.

The test runs should be conducted as close to the design conditions as possible. The deviation limits from the design conditions for each test parameter have been established and are given in Table 3.3.1. If these limits are exceeded, the run shall be rejected. If unacceptable deviations are discovered during computation of results from a completed test run, that run shall be rejected.

3.3.2 Heater. It is recommended that any external sources of noncondensible gases such as vents from other apparatus be diverted from the tested heaters during the run. All heater bypass valves or emergency drain valves on the tested heaters immediately up-

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TABLE 3.3.1
DEVIATION LIMITS OF PARAMETERS

Parameters	Limits of Deviation for the Test Conditions from Design Conditions	Steady State Limits [Note (2)]
Feedwater flow	±10.0%	±3%
Feedwater inlet temperature [Note (1)]	±10.0°F	±2°F
Feedwater inlet pressure	±10.0% of absolute pressure	—
Extraction pressure	±10.0% of absolute pressure	±1%
Extraction temperature	±20.0°F	±4°F
Drains flow in	±10.0%	—

NOTES:
(1) Large temperature variations may occur at the inlet to the lowest pressure heater due to condenser backpressure changes caused by seasonal differences in cooling water temperature. Inlet temperature changes from 20 to 30°F are common on some units for winter versus summer performance. Testing under these conditions is by mutual agreement.
(2) See Subsection 3.6.

stream or downstream of the tested heaters should be checked to ensure that no excessive leakage exists. Temporary modifications, such as the installation of various required instruments, are acceptable, provided their installation has no effect on the operation or performance of the heater.

(a) Venting. Noncondensible gas accumulation in both the condensing and drain cooling zones of the heater will degrade the performance of the heater by blanketing some heat transfer surface area. It may also lead to corrosion of heater internals. If a heater is not performing properly, the venting system design and operation should be checked.

Troubleshooting the entire venting system design is beyond the scope of this Code; however, a simple test to determine whether the vent orifice is properly sized and free of obstruction can be performed as follows. With the heater venting normally, and the cycle at steady state conditions, make a preliminary run. When this is complete, open the heater vent flow orifice bypass valve to ensure increased vent flow. This mode should be maintained for approximately $^1/_2$ hr to sufficiently purge the heater of noncondensibles. Once this purging is complete, repeat the run. Comparison of the feedwater outlet temperatures of these two runs should yield close agreement. If there is a significant difference, an improperly sized or obstructed orifice should be suspected and corrective actions taken.

When venting the recommended 0.5% of steam flow, it will add heat input in the desuperheating zone; however, the amount of contribution is insignificant. For heaters without a desuperheating zone, the vented flow will only be a pass through.

(b) Water Level. It is important that the water level at the drain cooling zone inlet is maintained as close as possible to design normal water level specified by the manufacturer. If the water level is higher than design, some additional heat transfer surface in the condensing zone may be flooded; this may reduce the heat transfer capability, and may, in turn, cause the *TTD* to be adversely affected. If the water level in the heater is lower than specified, steam may enter the drain cooling zone. The steam entering the drain cooling zone will significantly increase the *DCA,* and may cause drain cooler damage.

Assuming the *DCA* is operating close to the design point, the normal water level shall be verified before beginning the test. The following method shall be used to set the internal water level for horizontal- and vertical-channel heaters. Vertical-channel-down heaters shall be set at the manufacturer's recommended normal liquid level.

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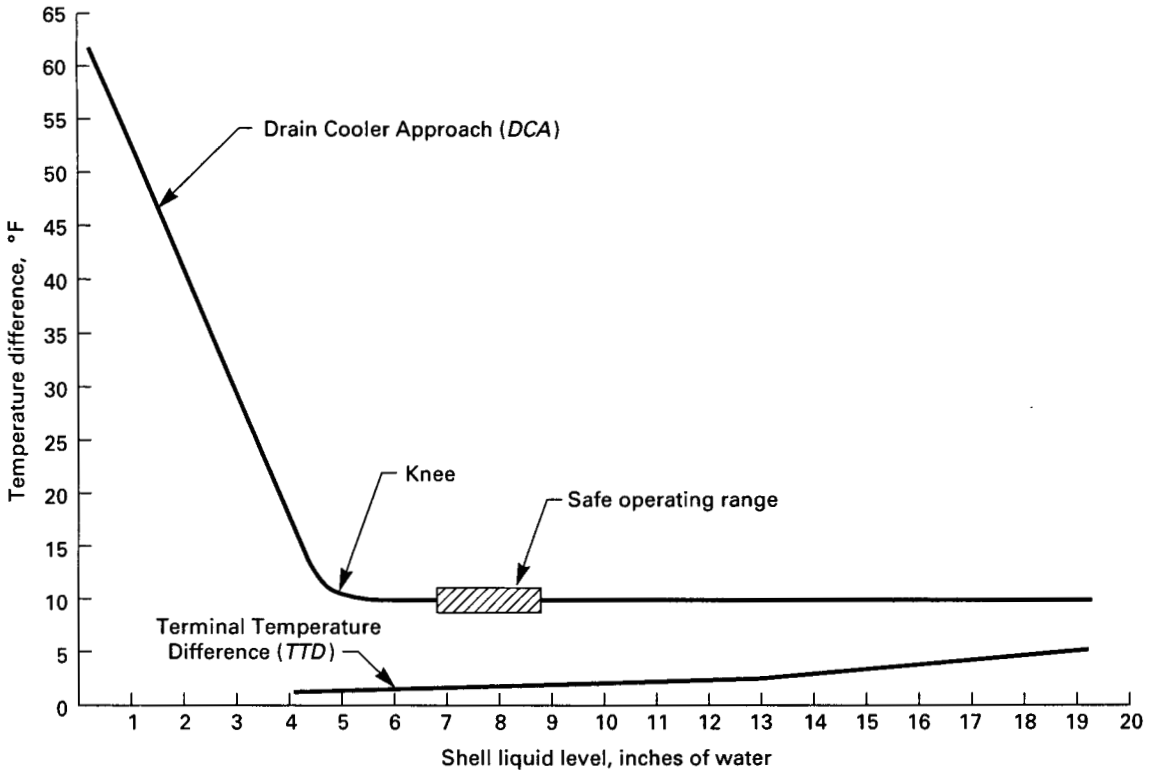


FIG. 3.3.1 TYPICAL DCA AND TTD VERSUS INTERNAL LIQUID LEVEL

The liquid level controller set point shall be lowered in step increments of approximately one inch until the drain outlet temperature increases noticeably. Each step increment shall be held for five minutes or until the drain temperature is stabilized prior to recording the heater drain outlet temperature. The *DCA* is then calculated and plotted as a function of the internal liquid level. This procedure is repeated until the *DCA* shows a sharp upward break with a rapid increase in drain outlet temperature.

Conversely, if the *DCA* is noticeably high prior to starting the test, the opposite approach is taken. The water level is increased in one inch increments, drain outlet temperature is allowed to stabilize, and the "*DCA* vs internal heater liquid level" curve is once again plotted.

The overall plot of "*DCA* vs internal heater liquid level" should resemble the shape of the curve depicted in Fig. 3.3.1. The optimum liquid level is determined by finding the "knee break" of the curve and adding an appropriate safety factor (2.0 in.) of liquid in order to determine a safe operating level. If the optimum level plus the safety factor (2.0 in.) is lower than the manufacturer's level mark, further evaluation of the level to be set during the test should be made, including discussing the discrepancy with the manufacturer's representative. In any case, the final level set point must be agreed upon by all parties to the test.

This margin above the minimum level controller set point provides an internal liquid level that can withstand some fluctuations while still properly sealing the drain cooler. This final liquid level controller set point shall be constant throughout the duration of the test.

3.4 PREPARATION FOR THE TEST

3.4.1 General. The test preparation shall include examination and familiarization with the apparatus by all involved parties. If the physical state of the equipment and operating conditions depart from prior agreement, a new agreement shall be reached.

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3.4.2 Preliminary Runs. A preliminary run should be conducted for the purpose of:

(a) checking all instruments;

(b) training personnel;

(c) checking for adequate venting and proper water level;

(d) making necessary instrument and equipment adjustments; and

(e) familiarizing with the computational procedure.

3.5 DURATION OF RUNS AND FREQUENCY OF READINGS

The test shall consist of three runs. During each run, all data shall be recorded at least 40 times over a minimum time period of 30 min at steady state conditions.

3.6 STEADY STATE LIMITS

The feedwater heater shall be brought to the steady state condition prior to initiating a run, and shall be maintained throughout the run. The steady state limits are defined in Table 3.3.1. If these limits are exceeded, the run shall be rejected.

Any condition whose variation may affect the test results shall be made as constant as possible before the test run begins and shall be maintained as constant as possible throughout the run. It is desirable to observe and record all readings for a brief period after the unit has attained steady conditions but before the formal readings are taken (see Table 3.3.1).

If inconsistencies are observed for a test run, the run shall be rejected in whole or in part (by agreement among parties to the test), and shall be repeated if necessary to attain the object of the test.

3.7 MEASUREMENT UNCERTAINTY

3.7.1 Introduction. Measurements collected during a test are only representations of a physical process which allows judgments regarding the given process. The value of the resulting judgment is dependent on how well the measurements represent reality. Measurements that have a large uncertainty (see PTC 19.1-1998 for details) can lead to faulty decisions which may result in a large effort to resolve problems which may not in fact exist or, conversely, the data may mask problems that should be taken into consideration.

Errors associated with measured data can generally be described by two primary components: (1) precision error and (2) bias error. Precision error refers to the ability to repeat a measurement given similar test conditions. Bias error refers to consistent systematic errors that result primarily from the test setup and calibration of instrumentation.

3.7.2 Precision Error. Precision error can be reduced by taking many repeated measurements over a period of time or by using redundant instrumentation.

For example, the temperature of a static fluid is more accurately determined by using four thermocouples instead of one. Or, if only one thermocouple is available, the average of four separate readings taken at different times would be more representative of the true temperature than would a single reading. In fact, in some processes where steady state is represented by a cyclic oscillation of a measured parameter, it is essential to take many readings at various times to get a true representation of the process. In general, precision error is inversely proportional to the square root of the number of measurements or readings taken.

3.7.3 Bias Error. Bias error is more difficult to control. This type of error will show up consistently regardless of the number of readings. It can result, for example, from the placement of a thermocouple into a fluid stream whose temperature is highly stratified. The thermocouple will read only the local temperature which may or may not be representative of the average fluid temperature. This is true for pressure, flow, and any other type of measurement. Placement of instrumentation makes the bias error unique for each installation.

Bias error is reduced primarily by good judgment and experience regarding the test equipment and the scope of the test. Since most instruments make local measurements, bias error can sometimes be reduced by making many measurements over the geometry of the test equipment. For example, a traverse over a cross section or an array of instruments provides more information from which good judgment may be made. Careful calibration of instrumentation is another example of reducing bias error.

In general, accurate test results are obtained through careful placement of reliable instrumentation and by taking many repeated measurements from a steady state condition. A more thorough discussion of measurement and measurement uncertainty is provided in ASME PTC 19.1-1998, Test Uncertainty.

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3.7.4 Combination of Precision and Bias Uncertainties (Total Uncertainty). Subsection 5.3 of this Code provides the method of combining precision and bias uncertainties based on PTC 19.1.

3.8 LOCATION OF TEST POINTS

The following five figures locate the required test points for the various heater configurations. These test points consist of temperature, pressure, and flow measurements. The temperature and pressure test locations are necessary for all testing, and the flow points are used when heater flow streams are directly measured instead of calculated by heat balance techniques. Use of these test points is mandatory to obtain the required data necessary to calculate heater performance.

The manufacturer of the heater normally provides taps for the temperature and pressure measurement points. However, the vendor only supplies the feedwater heater and the nozzle connections. Therefore, the potential test point locations are limited to these areas.

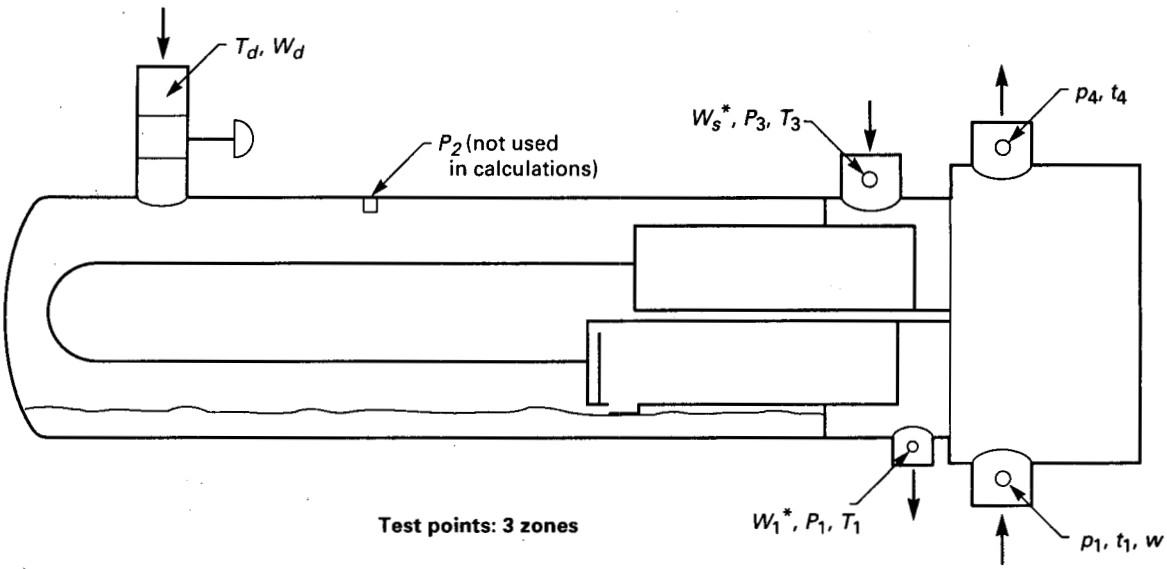
A potential for thermally stratified flow exists in both the drain outlet and feedwater flow streams. Recommendations for ideal temperature measurements on these points are as follows.

(a) Feedwater outlet temperatures should be measured at a point that allows thorough mixing of the flow stream. This is generally ten to fifteen pipe diameters after the heater outlet or after a valve or elbow that promotes turbulent flow and/or mixing.

(b) Drain outlet temperatures should be as far from the outlet as practical. The suggested location is just prior to the valve that controls drain outlet flow to the next heater.

All of the other test points indicated on the sketches are generally considered to be adequate for measurement of thermal performance parameters. However, it is the responsibility of the parties to the test to adequately locate proper performance test measurement points.

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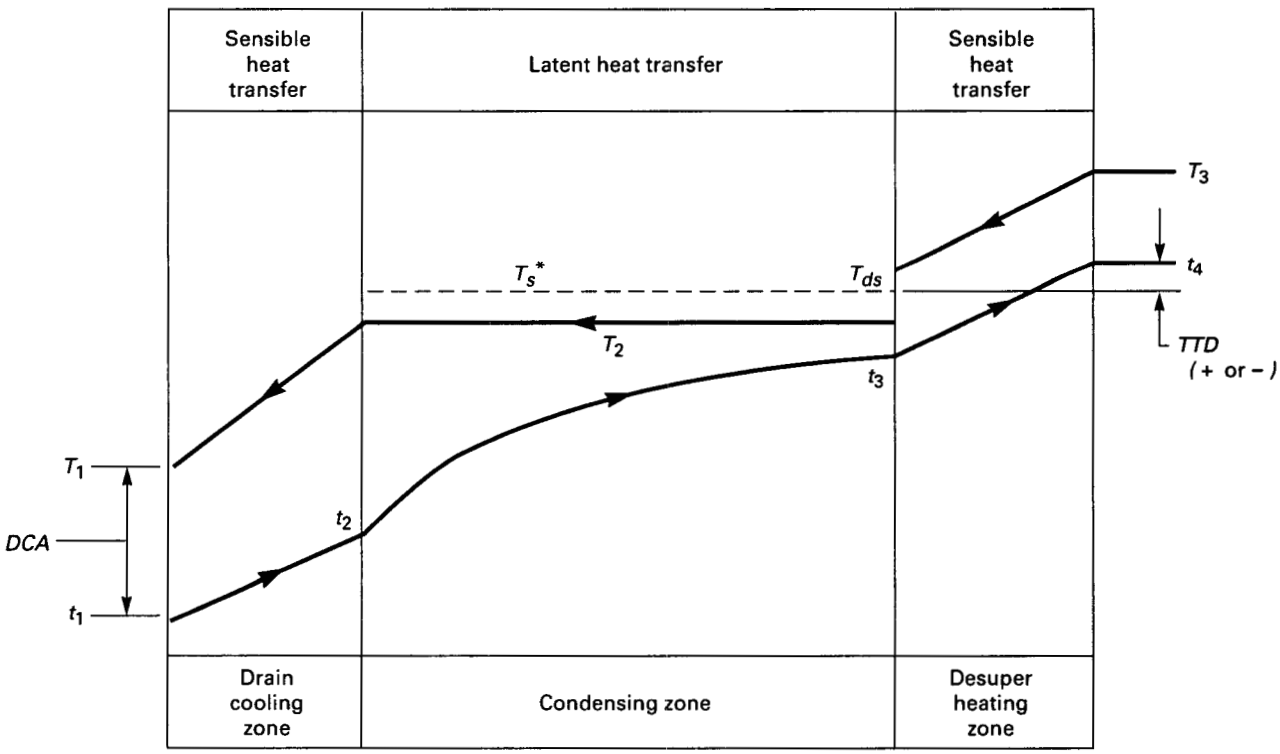
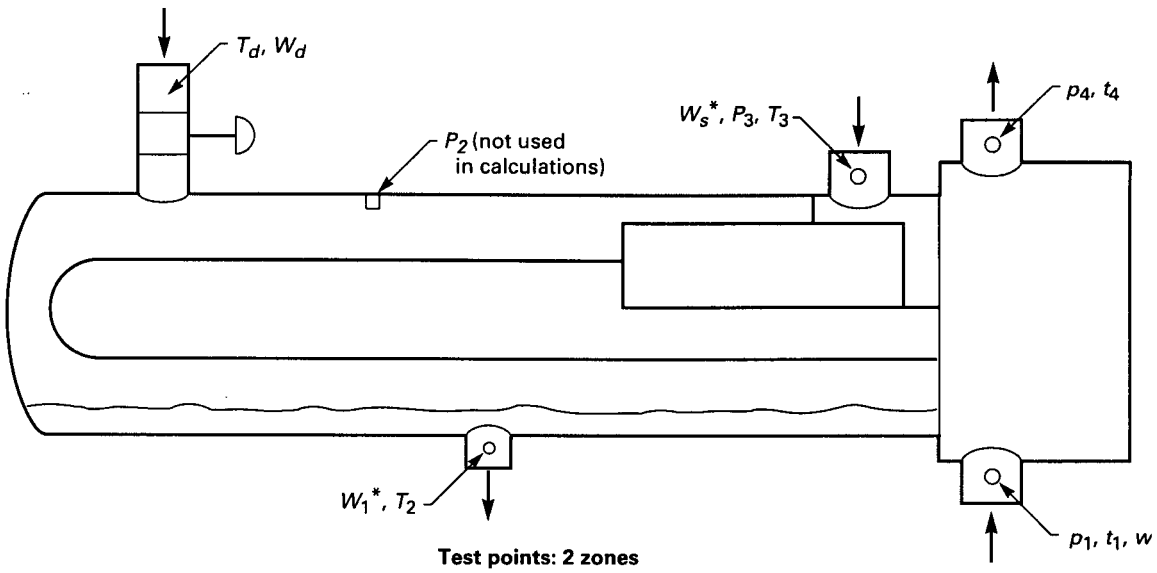
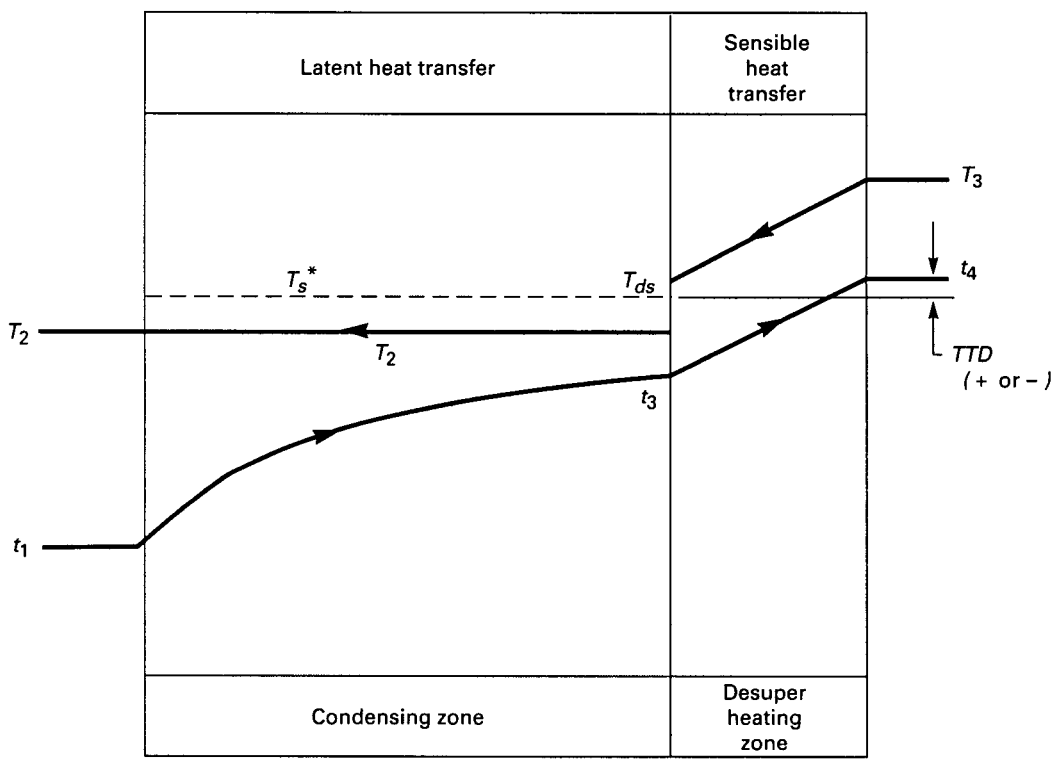


FIG. 3.8.1 DESUPERHEATING, CONDENSING, AND DRAIN COOLING ZONES

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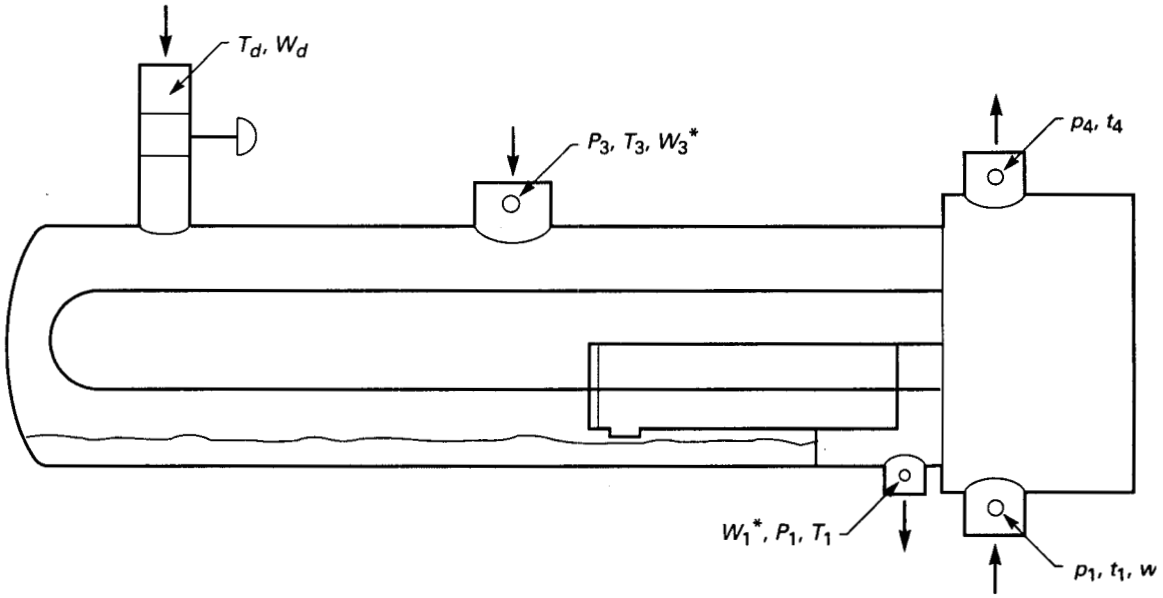
Test points: 2 zones



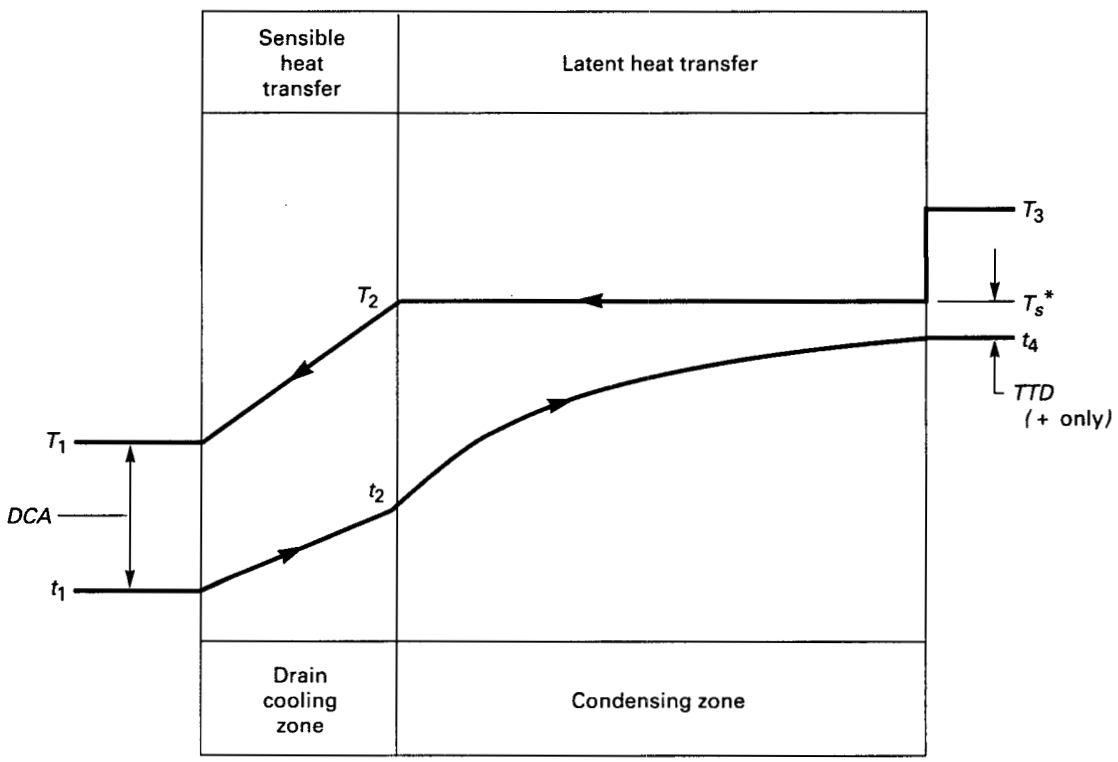
Thermal profile

FIG. 3.8.2 DESUPERHEATING AND CONDENSING ZONES

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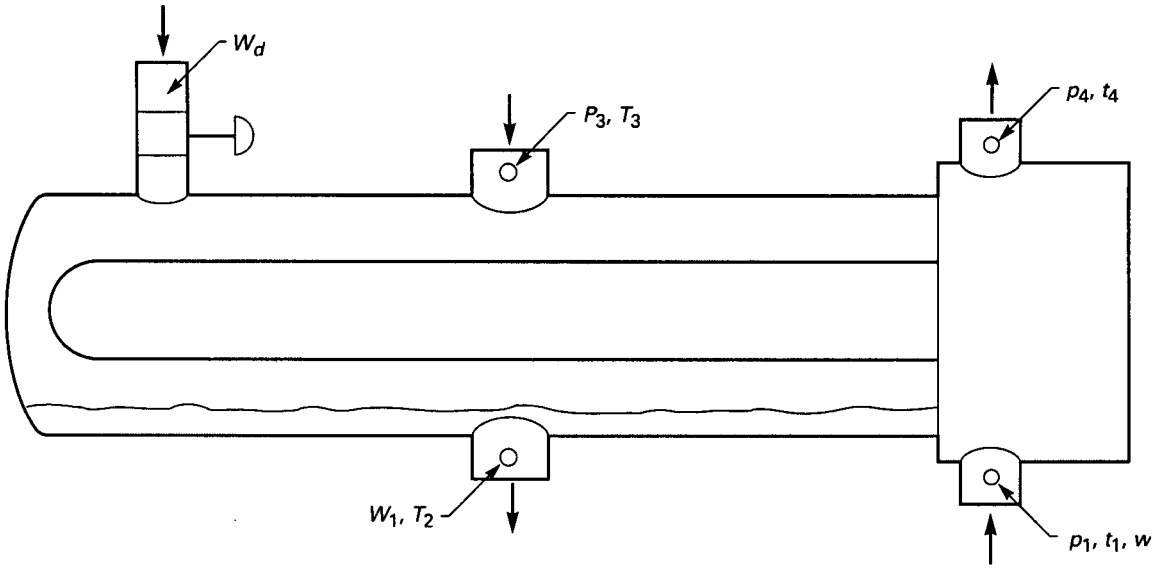
Test points: 2 zones



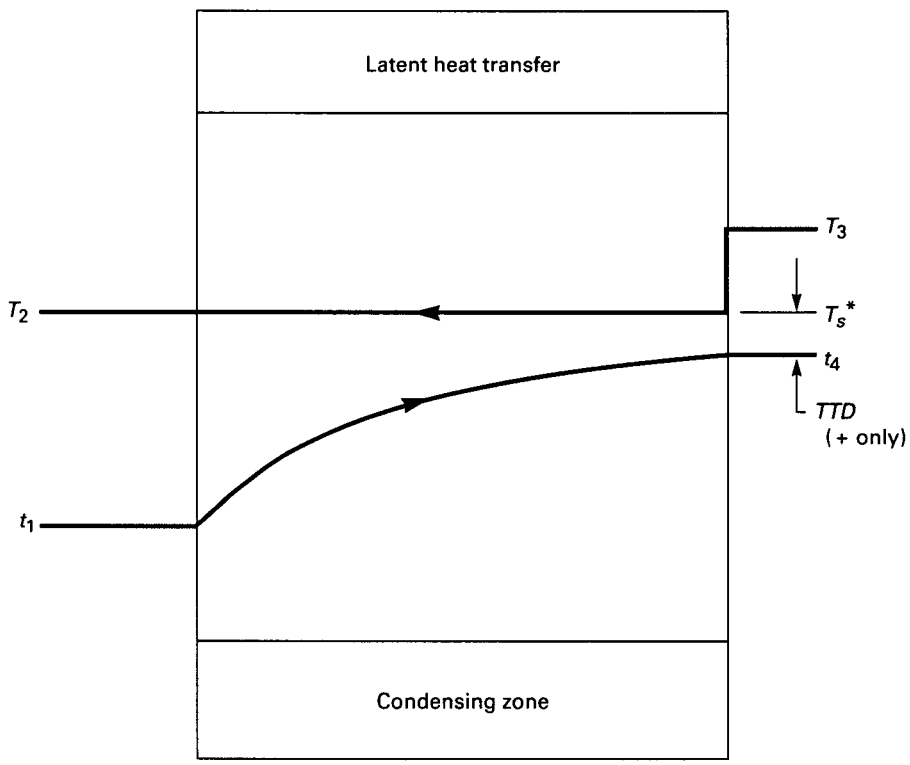
Thermal profile

FIG. 3.8.3 CONDENSING AND DRAIN COOLING ZONES

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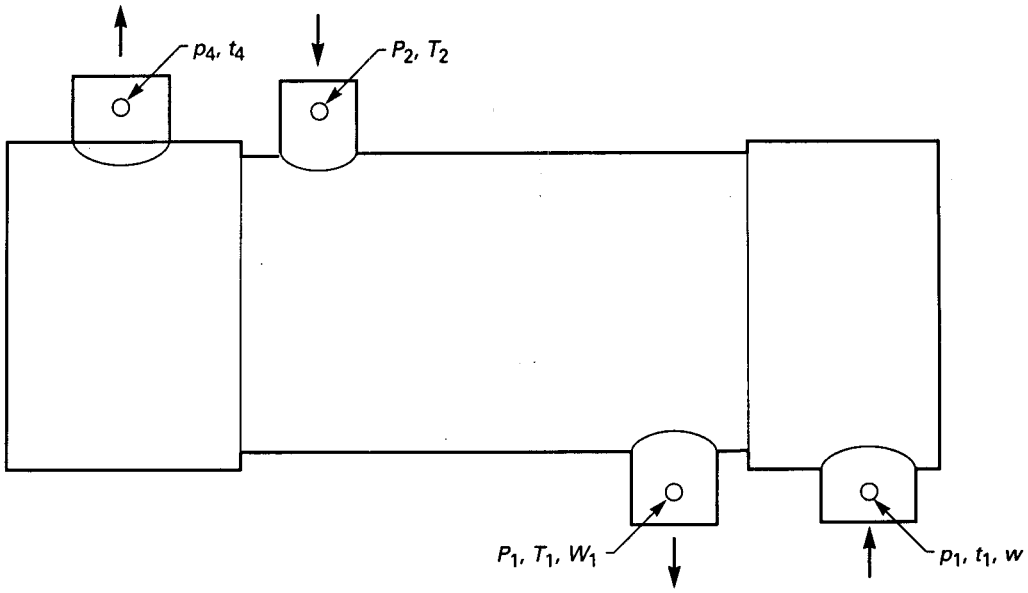
Test points: 1 zone



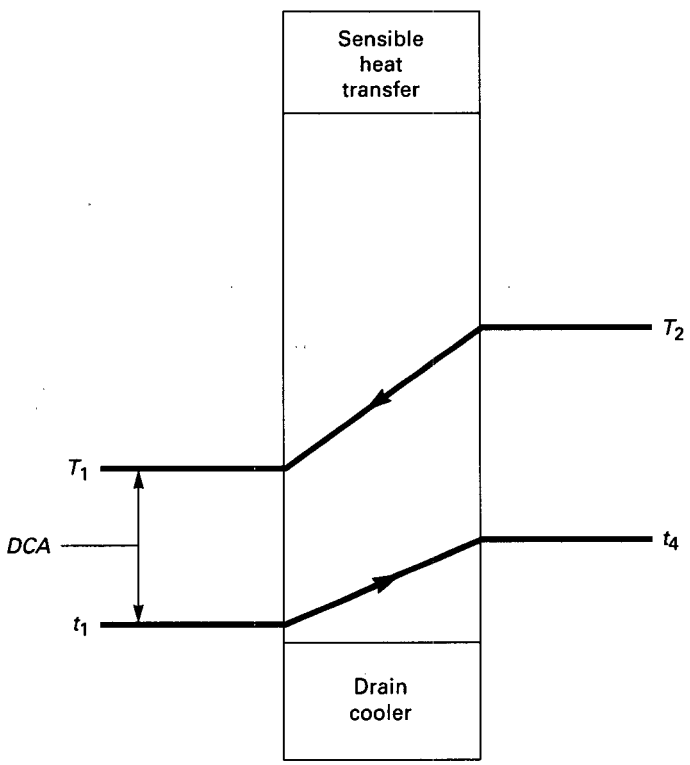
Thermal profile

FIG. 3.8.4 CONDENSING ZONE

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Test points: Drain cooler



Thermal profile

FIG. 3.8.5 EXTERNAL DRAIN COOLER

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SECTION 4 — INSTRUMENTS AND METHODS OF MEASUREMENT

4.1 GENERAL

This Code presents the requirements for instruments and methods that shall be used. It emphasizes the use of "state of the art" instrumentation. General guidance on the selection and use of temperature, pressure, and flow instrumentation can be found in the PTC 19 series, Supplements on Instruments and Apparatus.

The instruments described in this Section are required for performance tests on feedwater heaters. Temperature and pressure measurements around a feedwater heater can be straightforward. Flow measurement, however, can be quite complex. In some configurations, it may be necessary to perform a heat balance or to collect data from several heaters in order to resolve feedwater, shell, and drains flows to the tested heater.

4.2 PRESSURE MEASUREMENT

Pressure measurements shall be taken at the locations shown in Figs. 3.8.1 through 3.8.5. These pressures may range from the highest pressure in the cycle to below atmospheric pressure. This wide range of pressure measurements makes instrument selection heater dependent. Absolute pressures are needed for steam calculations. If gage transmitters are used, it is necessary to convert the pressures to absolute values prior to using the test data in calculations. Outlet pressure measurements indicated in Figs. 3.8.1 through 3.8.5 are needed to determine pressure loss through the feedwater side or shell side of the heater. The feedwater pressure loss should be measured with a differential pressure device connected between feedwater inlet and outlet. (Warning: If the pressure taps are at unequal elevations, a differential water leg correction is required to account for the static head). Other means of pressure testing of similar or higher accuracy and reliability may also be used, if the specific instruments are agreed to prior to the test. An example would be deadweight gage (see PTC 19.2, Pressure Measurement).

Regardless of the pressure measurement instrument selected, attention must be given to how the instrument is installed and operated. Particular attention must be paid to elevation differences in the source of the pressure and the instrument. The line connecting the pressure-sensing instrument is usually filled with fluid, causing the instrument to read high or low depending on the relative location of the instrument to the source. In instances where the instrument is below the source, the correction (known as a water leg correction) is subtracted from the reading. The water leg correction is added if the instrument is above the source, provided the existence of a full water leg is determined. In general, liquid-filled lines should be routed from the source to the instrument in a manner such that the line continuously slopes downward and a low point drain should be available for purging the line. The opposite is true for vapor-filled lines with a vent located near the top of the line, just before the instrument. Some vapor legs will collect condensate and may require low-volume flow, continuous venting to stay dry. If the venting method is utilized, the flow rate must be kept low [approximately 0.5 ft^3/hr ($0.014 m^3/hr$)] enough to have an undetectable effect on pressure measurement. All pressure measuring devices shall be calibrated before and after the test to verify that the instruments meet the requirements of Subsection 4.6. If the instrumentation does not satisfy these requirements, the test shall be rejected.

4.3 TEMPERATURE MEASUREMENT

Temperature measurement shall be taken at the locations shown in Figs. 3.8.1 through 3.8.5. Test grade temperature measuring devices shall be used (see PTC 19.3, Temperature Measurement).

The location of these devices is important. Temperature measuring devices shall be located at a point

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where the most uniform temperatures are found. They must not be installed where there may be an air pocket or where they may be near a cold-water manifold. When they are located near a large, uninsulated heat source, they must be shielded from radiation. Elements that are too long for the thermowell or exposed thermowells should be insulated (see PTC 19.3).

All temperature measuring instruments shall be calibrated before and after the test. Calibrations should be performed around the range of expected use and should include hysteresis checks.

At least five calibration temperatures should be used. Mid-span temperature should be replicated in both heating and cooling runs. The total uncertainty, including the standard error of estimate (SEE), shall be less than or equal to the requirements of Subsection 4.6. If this level of accuracy cannot be demonstrated, an agreement among the parties to the test is required prior to the test in order to use the instrumentation. If the post-test calibration does not meet the requirements of Subsection 4.6, the test results shall be rejected.

4.4 WATER FLOW MEASUREMENT

Laboratory-calibrated flowmeters, which may include ultrasonic transit-time flowmeters, shall be used for feedwater. For drain flow measurements calibrated or uncalibrated flowmeters may be used or drain flow rates may be calculated by a heat balance. For proper use of nozzles, orifice meters, and venturi meters, see PTC 19.5. This Section includes guidance for the use of ultrasonic transit-time flowmeters.

The accurate determination of flow is one of the most difficult field measurements. Flow measurements are affected by irregularities in the pipe wall, calibration of instrumentation, and the location of suitable runs of piping in which to install fluid meters.

There are two acceptable methods of testing feedwater heaters. The first method uses the existing plant flow nozzle that satisfies ASME PTC 19.5, Section II, quality requirements, and utilizes temperature and pressure instrumentation required by this Code on the entire string of feedwater heaters. Use of a known feedwater flow and heat balance techniques allows the calculation of drain flows which then can be cascaded throughout the system. However, the following restrictions apply.

- Due to unknown flow distribution resulting from differences in piping, valves, and percentage of tubes plugged, this method cannot be utilized where a split-string feedwater heater setup exists unless each string has its own flow nozzle that meets the appropriate requirements.
- When using this method of calculating drain flows that cascade to the last feedwater heater, the uncertainty increases. The uncertainty calculations specified in Appendix C must be performed to determine if this method meets the requirements of this Code.

The second method incorporates direct flow measurements utilizing ultrasonic technology. These devices are generally nonintrusive with respect to the piping systems and have the potential to be moved from one location to another with relative ease. Calibrated meters using the transit-time principle and transducers designed for high temperature have demonstrated Code-required accuracies consistent with other plant flow nozzles. A typical nonintrusive transducer installation on a pipe is illustrated in Fig. 4.4.1.

In order to achieve the best possible accuracy using ultrasonic flow measuring equipment, several parameters must be considered and some operational precautions must be observed.

The most critical steps when installing the transducer array are proper alignment and selection of the couplant that bonds the transducers to the piping. Multiple couplant compounds are available and should be selected based on the temperature range expected for the process fluid. Templates or precise measurements shall be utilized to ensure good alignment of the transducers with respect to the piping.

Separate flow calibrations should be used for each different pipe size and the flow rate should cover the range expected for the process fluid in the field.

With the proper use of ultrasonic flow-measuring equipment, it is possible to measure the actual feedwater and drain flows in real time. The feedwater and drain flows must be monitored simultaneously at all times during the test.

Periodic equipment maintenance and recalibration of the flow transducer pairs may be necessary. Users will have to establish their own calibration cycles based on the temperatures, equipment usage, and brand.

Properly trained operators are required and site selection for the transducer location is critical. There are several known factors which can influence flow

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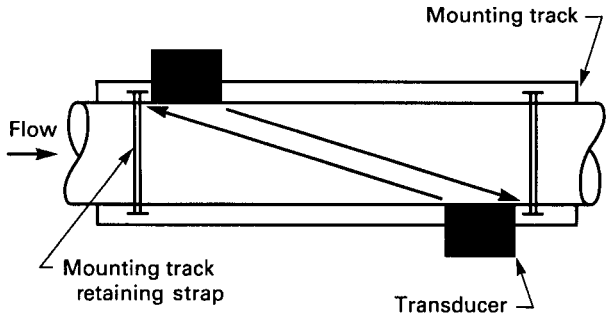


FIG. 4.4.1 TYPICAL TRANSDUCER INSTALLATION

measurement under field conditions using ultrasonic equipment. The major factors are listed below.

(a) Piping configuration is critical when measuring flows. Most equipment vendors recommend that transducers be located in a straight length of pipe of at least 15 pipe diameters with at least 10 pipe diameters upstream and 5 pipe diameters downstream from any bends, elbows, valves, joint weld seams, points of aeration, and other items which could distort the flow profile. Field measurements should duplicate or exceed this piping criteria for maximum accuracy.

Flow measurement using ultrasonics is possible with less than an ideal number of pipe diameters, but the accuracy has the potential to be reduced by an unknown factor. One technique which has proven useful in compensating for nonsymmetrical flow profiles, when less than an ideal number of pipe diameters is available, is transducer rotation. Using this technique, the transducers are installed in one location and a flow reading is obtained. The transducers are then rotated around the circumference of the pipe and additional flow measurements are made.

The final location of the transducers is determined by averaging the indicated flows and selecting the location closest to the calculated average flow value. A typical rotation is 120 deg, but accuracy has the potential to be increased with a smaller angle of rotation. This procedure is somewhat cumbersome but it can improve the accuracy of flow measurement if the required straight length of unobstructed piping is not available. Multiple-path flow measurement is more accurate than single-path measurement under this condition.

(b) It is necessary to both stop the flow and maintain a full pipe in the section under consideration in order to set an appropriate zero offset compensation factor. Without this ability, flow will be offset by some constant amount. Bypasses and emergency drain lines can usually be utilized to stop the flow.

(c) The zeroing of the flow measuring equipment must be done as close to normal operating temperature as possible. Otherwise, this procedure will not produce an appropriate zero offset.

(d) If pressure regimes within the piping are such that flashing occurs or excessive aeration is present, ultrasonic equipment will receive a signal too weak to function. This may be a continuous process, occur only under certain conditions, or intermittently.

(e) Internal/external pipe scale and unbonded pipe liners can cause ultrasonic flow detection equipment to be unusable or to give false flow indications.

(f) Operation of ultrasonic equipment in the proximity of other ultrasonic flow measuring equipment can cause crosstalk and inaccurate readings. Likewise, both electrical and radio interferences can invalidate flow readings. These problems are generally solved by shielding the electrical components and routing flow meter transducer cables away from high voltage lines and other instrumentation cables.

(g) Most ultrasonic flow-measuring devices require that the pipe material, outside dimensions, and exact wall thickness be known in order to correct the indicated flows to actual ones. Digital thickness gages based on ultrasonic technology are generally used to provide wall thickness information. Other information is usually obtained from drawings and piping specifications. The following equation can be used to correct mathematically for different pipe wall thicknesses if the appropriate data from the flow meter calibration runs is available.

To correct for different thicknesses, multiply measured flow rate by

$$[d_A/d_N]^2$$

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where

d_A = actual pipe internal diameter

d_N = nominal pipe internal diameter

(h) Sources of Error. The four main contributions to error when using ultrasonic flow meters are: uncertainty of the pipe dimensions, coupling of the transducers, uneven velocity profiles of the flow, and "drift" of the electronics during the period of the test.

To reduce the first, careful measurements of the pipe dimensions, including wall thickness, at the point of flow measurement must be made. Using electronic ultrasonic technology to make several of these measurements around the axis of the pipe is recommended.

To reduce the second, trained, experienced technicians should install the transducers securely on the pipe according to the manufacturer's instructions. If the coupling is completely inadequate, such a loss of signal will occur that many meters have warning signals incorporated in their design to alert the operators.

The effect of uneven velocity profiles, which may be expected downstream from convoluted piping typically found in feedwater heaters, can best be reduced by measuring flow across several axial planes dissecting the pipe. Therefore, it is recommended to record flow measurements after transducers are rotated about the pipe axis, to as many positions as seem practical or necessary depending on the variation of flow indications. A comparison of the flow indications at these different planes will provide a practical indication of the effect of nonuniformity of the velocity profile. The difference between the indications at different planes should be treated as a systematic uncertainty.

The maximum straight length of piping ahead of the meter should be utilized, which is recommended to be at least 10 diameters. There should be at least 5 diameters remaining downstream of the flow meter before any fittings or obstructions.

To measure the drift of the sensor system over time and ensure a reliable zero, a pipe of nearly identical material, temperature, and dimensions, full of standing water is required. Before and after each test, or at the beginning and end of each day, the ultrasonic meter should be installed on this section and the flow indication observed. This value should be treated as a systematic uncertainty in accordance with PTC 19.1. After recording the zero offset, the indicator may be readjusted to indicate zero flow for the next test period.

4.5 SPLIT-STREAM FEEDWATER HEATER TESTING

Due to economic considerations, most plants have only one final feedwater flow nozzle measuring the combined flow from all heaters that are operating in parallel. This causes uncertainty in the actual flow distribution through each heater. Uncertainty in the feedwater flow also directly affects the calculation of the drain flow for that particular feedwater heater.

Since flow inequalities may exist due to differences in valve coefficients, piping configuration, and number of tubes plugged in each heater, split-stream feedwater heaters cannot be tested according to this Code unless at least one of the following conditions exists.

- Each heater has its own flow element to measure feedwater flow which meets the requirements of this Code, and the calculated values for the cascaded drains using the heat balance method meet the uncertainty limitations imposed by Subsection 4.6.
- Flow instrumentation can be installed to measure directly both the feedwater and drain flow(s) simultaneously for each feedwater heater to be tested. Overall uncertainty calculations referenced in Subsection 3.7 must be made to ensure that the final results are within the required limitations.

4.6 INSTRUMENT UNCERTAINTIES

Primary instruments selected for the test shall have total uncertainties equal to or less than the following values.

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TABLE 4.6 MAXIMUM UNCERTAINTY VALUES

Flow Rates		Pressure		Temperature	
Feedwater at heater	±1%	Desuperheater pressure loss	±1%	Steam inlet	±1.00°F
Drains	±1%	Steam inlet	±0.25%	Drains inlet	±0.25°F
		Feedwater inlet	±2%	Drain outlet	±0.25°F
		Feedwater pressure loss	±1%	Feedwater inlet	±0.25°F
		Drain cooler pressure loss	±1%	Feedwater outlet	±0.25°F

GENERAL NOTE: Uncertainties expressed in terms of percentage are based on measured values.

The use of instrumentation providing total uncertainties exceeding the limits indicated above shall be subject to mutual agreement by the parties to the test.

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SECTION 5 — COMPUTATION OF RESULTS

5.1 INTRODUCTION

The feedwater heater performance test is to be conducted under the conditions specified in Section 3. The following points are important to the accuracy and documentation of the test.

(a) Design, test, and computed data shall be tabulated on the data sheet (see Tables 5.1.1 through 5.1.5) or a similar type of form used to compute and document the test results.

(b) Compressed water enthalpies shall be used in the calculations for feedwater.

(c) The latest edition of the ASME Steam Tables shall be used in the calculations of the test results.

(d) The calculation procedure shall be based on all resistances to heat transfer being corrected to the outside diameter of the tube.

(e) The calculation procedure shall be based on the reheat factor being applied by the manufacturer to the condensate film resistance of the drain cooling zone r'_{s1}.

Tables 5.1.1 through 5.1.5 provide a convenient means for recording the design data, computed data, and the test data. The heater manufacturer shall supply the design data for the heater. Table 5.1.6 provides a form for recording data during the test if using manual readings. Similar forms may be used or, preferentially, the data can be recorded with a data acquisition system.

Since steam surrounds the drain cooler shrouds, drain coolers are subject to reheat (horizontal heaters with short type drain coolers or vertical channel up heaters). Therefore, steam condenses on the lower temperature drain cooler shrouds injecting heat back into the condensate inside the drain cooler. In order to compensate for this condition, the heater manufacturer applies a reheat factor to either the shell-side heat transfer coefficient or to the *LMTD*. Since most heater manufacturers use the true *LMTD* and modify the shell-side heat transfer coefficient, this Code will use this method. The user of this Code should make certain that the shell side film resistance provided by the manufacturer includes the reheat factor. A separate reheat factor is not required. When the shell-side film resistance is back-calculated from the overall drain cooling zone heat transfer coefficient, the reheat factor is included.

The terms and symbols shown in the following tables and data sheets are defined in Section 2. The performance calculation procedures are given in para. 5.2. The results of these calculations are the basis for the evaluations of the performance of the heater being tested.

5.2 PERFORMANCE CALCULATION PROCEDURES

This subsection contains five paragraphs covering performance calculation procedures for feedwater heaters with various configurations. Calculations shall be performed for each of the test runs. Paragraph 5.2.1 covers a three-zone feedwater heater with integral desuperheating zone, condensing zone, and drain cooling zone. Paragraph 5.2.2 covers a two-zone feedwater heater with desuperheating zone and condensing zone. Paragraph 5.2.3 covers a two-zone feedwater heater with condensing zone and drain cooling zone. Paragraph 5.2.4 covers a feedwater heater with condensing zone only. Paragraph 5.2.5 covers an external drain cooler.

It is not feasible to expect that the test will be conducted at the design point. In addition, it is not possible to measure the internal shell side or tube side temperatures at the transitions between zones (drain cooling zone to condensing zone and/or condensing zone to desuperheating zone), because there is insufficient test data to adjust the test results to design conditions. Therefore, performance comparisons are made by predicting the heater performance by adjusting the design parameters (including the internal transition temperatures) to the test conditions. The predicted values for *TTD, DCA,* tube side Δp, drain cooling zone Δp, and desuperheating zone Δp, shall be compared to the measured test values.

The calculation determines the feedwater outlet temperature and the drain cooling zone outlet temperature by iteration. These iterations should continue until the old and new computed values of

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TABLE 5.1.1
THREE-ZONE HEATER

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Design Data (supplied by manufacturer)						
1	Feedwater flow rate	w'		w'		w'	
2	Steam flow rate	W'_s		W'_s			
3	Drains flow rate			W'_d		W'_1	
4	Steam inlet pressure	P'_3					
5	Shell side pressure loss	$\Delta P'_{ds}$				$\Delta P'_{dc}$	
6	Shell side temperature in	T'_3		T'_2		T'_2	
7	Shell side temperature out	T'_{ds}		T'_2		T'_1	
8	Feedwater temperature in	t'_3		t'_2		t'_1	
9	Feedwater temperature out	t'_4		t'_3		t'_2	
10	Feedwater pressure loss			$\Delta p'_t$			
11	Heat transferred	Q'_3		Q'_2		Q'_1	
12	Heat transfer area	A'_3		A'_2		A'_1	
13	Feedwater film resistance	r'_{f3}		r'_{f2}		r'_{f1}	
14	Feedwater fouling resistance	r'_{ft3}		r'_{ft2}		r'_{ft1}	
15	Tube material resistance	r'_{m3}		r'_{m2}		r'_{m1}	
16	Shell side fouling resistance	r'_{fs3}		r'_{fs2}		r'_{fs1}	
17	Shell side film resistance (r'_{s1} corrected for reheat by the manufacturer)	r'_{s3}		r'_{s2}		r'_{s1}	
18	Terminal temperature difference *and* Drain cooler approach	TTD'				DCA'	

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Test Data						
19	Actual feedwater flow rate	w		w		w	
20	Actual drains flow rate in			W_d			
21	Actual shell side temperature in	T_3					
22	Actual shell side temperature out			T_2		T_1	
23	Actual drains temperature in			T_d			
24	Actual feedwater outlet temperature	t_4					
25	Actual feedwater inlet temperature					t_1	
26	Actual shell side pressure loss	ΔP_{ds}					
27	Actual feedwater pressure loss			Δp_t			
28	Actual steam pressure in	P_3					
29	Actual feedwater pressure in					p_1	

(continued)

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TABLE 5.1.1 (CONT'D)
THREE-ZONE HEATER

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Computed Data						
30	Steam flow rate	W_s^*		W_s^*			
31	Feedwater enthalpy in					h_1	
32	Feedwater enthalpy out	h_4^*					
33	Steam enthalpy in	H_3					
34	Drains enthalpy in			H_d			
35	Drain enthalpy out					H_1^*	
36	Assumed feedwater outlet temperature	t_{4a}^*					
37	Total heat load			Q^*			
38	Feedwater pressure loss			Δp_t^*			
39	Steam pressure in condensing zone			P_2^*			
40	Saturated steam temperature at steam inlet P_3	T_s					
41	Drains flow rate			W_d		W_1^*	
42	Shell side temperature in			T_2^*		T_2^*	
43	Shell side temperature out			T_2^*		T_1^*	
44	Feedwater film resistance	r_{t3}^*		r_{t2}^*		r_{t1}^*	
45	Feedwater fouling resistance (by agreement)	r_{ft3}		r_{ft2}		r_{ft1}	
46	Shell side fouling resistance (by agreement)	r_{fs3}		r_{fs2}		r_{fs1}	
47	Shell side film resistance	r_{s3}^*				r_{s1}^*	
48	Overall heat transfer coefficient	U_3^*		U_2^*		U_1^*	
49	Hourly heat capacity flow of shell side fluid	C_3^*				C_1^*	
50	Hourly heat capacity flow of feedwater fluid	c_3^*		c_2^*		c_1	
51	Hourly heat capacity ratio	R_3^*				R_1^*	
52	Number of transfer units	$(NTU)_3^*$		$(NTU)_2^*$		$(NTU)_1^*$	
53	Effectiveness	ϵ_3^*		ϵ_2^*		ϵ_1^*	
54	Feedwater outlet temperature	t_4^*		t_3^*		t_2^*	
55	Predicted terminal temperature difference	TTD^*					
56	Predicted drain cooler approach					DCA^*	
57	Shell side pressure loss	ΔP_{ds}^*				ΔP_{dc}^*	

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TABLE 5.1.2
TWO-ZONE HEATER DESUPERHEATING AND CONDENSING

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value
	Design Data (supplied by manufacturer)				
1	Feedwater flow rate	w'		w'	
2	Steam flow rate	W'_s		W'_s	
3	Drains flow rate			W'_d	
4	Inlet steam pressure	P'_3			
5	Shell side pressure loss	$\Delta P'_{ds}$			
6	Shell side temperature in	T'_3		T'_2	
7	Shell side temperature out	T'_{ds}		T'_2	
8	Feedwater temperature in	t'_3		t'_1	
9	Feedwater temperature out	t'_4		t'_3	
10	Feedwater pressure loss			$\Delta p'_t$	
11	Heat transferred	Q'_3		Q'_2	
12	Heat transfer area	A'_3		A'_2	
13	Feedwater film resistance	r'_{f3}		r'_{f2}	
14	Feedwater fouling resistance	r'_{ft3}		r'_{ft2}	
15	Tube material resistance	r'_{m3}		r'_{m2}	
16	Shell side fouling resistance	r'_{fs3}		r'_{fs2}	
17	Shell side film resistance	r'_{s3}		r'_{s2}	
18	Terminal temperature difference	TTD'			

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value
	Test Data				
19	Actual feedwater flow rate	w		w	
20	Actual drains flow rate in			W_d	
21	Actual shell side temperature out			T_2	
22	Actual drains temperature in			T_d	
23	Actual feedwater outlet temperature	t_4			
24	Actual feedwater inlet temperature			t_1	
25	Actual shell side pressure loss	ΔP_{ds}			
26	Actual feedwater pressure loss			Δp_t	

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TABLE 5.1.2 (CONT'D)
TWO-ZONE HEATER DESUPERHEATING AND CONDENSING

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value
	Computed Data				
27	Steam flow rate	W_s^*		W_s^*	
28	Feedwater enthalpy in			h_1	
29	Feedwater enthalpy out	h_4^*			
30	Steam enthalpy in	H_3			
31	Drains enthalpy in			H_d	
32	Drain enthalpy out			H_1^*	
33	Assumed feedwater outlet temperature	t_{4a}^*			
34	Total heat load			Q^*	
35	Feedwater pressure loss			Δp_t^*	
36	Steam pressure in condensing zone			P_2^*	
37	Saturated steam temperature at steam inlet P_3	T_s			
38	Drains flow rate			W_d	
39	Shell side temperature in			T_2^*	
40	Shell side temperature out			T_2^*	
41	Feedwater film resistance	r_{t3}^*		r_{t2}^*	
42	Feedwater fouling resistance (by agreement)	r_{ft3}		r_{ft2}	
43	Shell side fouling resistance (by agreement)	r_{fs3}		r_{fs2}	
44	Shell side film resistance	r_{s3}^*			
45	Overall heat transfer coefficient	U_3^*		U_2^*	
46	Hourly heat capacity flow rate of shell side fluid	C_3^*			
47	Hourly heat capacity flow rate of feedwater fluid	c_3^*		c_2^*	
48	Hourly heat capacity ratio	R_3^*			
49	Number of transfer units	$(NTU)_3^*$		$(NTU)_2^*$	
50	Effectiveness	ϵ_3^*		ϵ_2^*	
51	Feedwater outlet temperature	t_4^*		t_3^*	
52	Predicted terminal temperature difference	TTD^*			
53	Shell side pressure loss	ΔP_{ds}^*			

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TABLE 5.1.3
TWO-ZONE HEATER CONDENSING AND DRAIN COOLING

Line No.	Term	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Design Data (supplied by manufacturer)				
1	Feedwater flow rate	w'		w'	
2	Steam flow rate	W'_s			
3	Drains flow rate	W'_d		W'_1	
4	Inlet steam pressure	P'_3			
5	Shell side pressure loss			$\Delta P'_{dc}$	
6	Shell side temperature in	T'_3		T'_2	
7	Shell side temperature out	T'_2		T'_1	
8	Feedwater temperature in	t'_2		t'_1	
9	Feedwater temperature out	t'_4		t'_2	
10	Feedwater pressure loss	$\Delta p'_t$			
11	Heat transferred	Q'_2		Q'_1	
12	Heat transfer area	A'_2		A'_1	
13	Feedwater film resistance	r'_{f2}		r'_{f1}	
14	Feedwater fouling resistance	r'_{ft2}		r'_{ft1}	
15	Tube material resistance	r'_{m2}		r'_{m1}	
16	Shell side fouling resistance	r'_{fs2}		r'_{fs1}	
17	Shell side film resistance (r'_{s1} corrected for reheat by the manufacturer)	r'_{s2}		r'_{s1}	
18	Terminal temperature difference *and* Drain cooler approach	TTD'		DCA'	

Line No.	Term	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Test Data				
19	Actual feedwater flow rate	w		w	
20	Actual drains flow rate in	W_d			
21	Actual shell side temperature in	T_3			
22	Actual shell side temperature out	T_2		T_1	
23	Actual drains temperature in	T_d			
24	Actual feedwater outlet temperature	t_4			
25	Actual feedwater inlet temperature			t_1	
26	Actual shell side pressure loss			ΔP_{dc}	
27	Actual feedwater pressure loss	Δp_t			

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TABLE 5.1.3 (CONT'D)
TWO-ZONE HEATER CONDENSING AND DRAIN COOLING

Line No.	Term	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Computed Data				
28	Steam flow rate	W_s^*			
29	Feedwater enthalpy in			h_1	
30	Feedwater enthalpy out	h_4			
31	Steam enthalpy in	H_3			
32	Drains enthalpy in	H_d			
33	Drain enthalpy out			H_1^*	
34	Assumed feedwater outlet temperature	t_{4a}^*			
35	Total heat transferred	Q^*			
36	Feedwater pressure loss	Δp_t^*			
37	Saturated steam temperature at steam inlet P_3	T_s			
38	Drains flow rate	W_d		W_1^*	
39	Shell side temperature in			T_s	
40	Shell side temperature out			T_1^*	
41	Feedwater film resistance	r_{t2}^*		r_{t1}^*	
42	Feedwater fouling resistance (by agreement)	r_{ft2}		r_{ft1}	
43	Shell side fouling resistance (by agreement)	r_{fs2}		r_{fs1}	
44	Shell side film resistance			r_{s1}^*	
45	Overall heat transfer coefficient	U_2^*		U_1^*	
46	Hourly heat capacity flow rate of shell side fluid			C_1^*	
47	Hourly heat capacity of flow rate of feedwater fluid	c_2^*		c_1^*	
48	Hourly heat capacity ratio			R_1^*	
49	Number of transfer units	$(NTU)_2^*$		$(NTU)_1^*$	
50	Effectiveness	ϵ_2^*		ϵ_1^*	
51	Feedwater outlet temperature	t_4^*		t_2^*	
52	Predicted terminal temperature difference	TTD^*			
53	Predicted drain cooler approach			DCA^*	
54	Shell side pressure loss			ΔP_{dc}^*	

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TABLE 5.1.4
CONDENSING ONLY HEATER

Line No.	Term	Condensing Symbol	Condensing Value
	Design Data (supplied by manufacturer)		
1	Feedwater flow rate	w'	
2	Steam flow rate	W'_s	
3	Drains flow rate	W'_d	
4	Inlet steam pressure	P'_3	
5	Shell side temperature in	T'_3	
6	Shell side temperature out	T'_2	
7	Feedwater temperature in	t'_1	
8	Feedwater temperature out	t'_4	
9	Feedwater pressure loss	$\Delta p'_t$	
10	Heat transferred	Q'_2	
11	Heat transfer area	A'_2	
12	Feedwater film resistance	r'_{f2}	
13	Feedwater fouling resistance	r'_{ft2}	
14	Tube material resistance	r'_{m2}	
15	Shell side fouling resistance	r'_{fs2}	
16	Shell side film resistance	r'_{s2}	
17	Terminal temperature difference	TTD'	

Line No.	Term	Condensing Symbol	Condensing Value
	Test Data		
18	Actual feedwater flow rate	w	
19	Actual drains flow rate in	W_d	
20	Actual shell side temperature in	T_3	
21	Actual shell side temperature out	T_2	
22	Actual drains temperature in	T_d	
23	Actual feedwater outlet temperature	t_4	
24	Actual feedwater inlet temperature	t_1	
25	Actual feedwater pressure loss	Δp_t	
26	Actual steam pressure in	P_3	
27	Actual feedwater pressure in	p_1	

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TABLE 5.1.4 (CONT'D)
CONDENSING ONLY HEATER

Line No.	Term	Condensing Symbol	Condensing Value
	Computed Data		
28	Feedwater pressure loss	Δ^*_{pt}	
29	Saturated steam temperature at steam inlet P_3	T_s	
30	Feedwater film resistance	r^*_{t2}	
31	Feedwater fouling resistance (by agreement)	r_{ft2}	
32	Shell side fouling resistance (by agreement)	r_{fs2}	
33	Overall heat transfer coefficient	U^*_2	
34	Hourly heat capacity flow rate of feedwater fluid	c^*_2	
35	Number of transfer units	$(NTU)^*_2$	
36	Effectiveness	ϵ^*_2	
37	Feedwater outlet temperature	t^*_4	
38	Predicted terminal temperature difference	TTD^*	

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TABLE 5.1.5
EXTERNAL DRAIN COOLER

Line No.	Term	Drain Cooler Symbol	Drain Cooler Value
	Design Data (supplied by manufacturer)		
1	Feedwater flow rate	w'	
2	Drain flow rate	W'_1	
3	Shell side pressure loss	$\Delta P'_{dc}$	
4	Shell side temperature in	T'_2	
5	Shell side temperature out	T'_1	
6	Feedwater temperature in	t'_1	
7	Feedwater temperature out	t'_4	
8	Feedwater pressure loss	$\Delta P'_t$	
9	Heat transferred	Q'_1	
10	Heat transfer area	A'_1	
11	Feedwater film resistance	r'_{f1}	
12	Feedwater fouling resistance	r'_{ft1}	
13	Tube material resistance	r'_{m1}	
14	Shell side fouling resistance	r'_{fs1}	
15	Shell side film resistance	r'_{s1}	
16	Drain cooler approach	DCA'	

Line No.	Term	Drain Cooler Symbol	Drain Cooler Value
	Test Data		
17	Actual feedwater flow rate	w	
18	Actual drain flow rate out	W_1	
19	Actual drain temperature out	T_1	
20	Actual drains temperature in	T_2	
21	Actual feedwater outlet temperature	t_4	
22	Actual feedwater inlet temperature	t_1	
23	Actual drain pressure loss	ΔP_{dc}	
24	Actual feedwater pressure loss	Δp_t	
25	Actual drains pressure in	P_2	
26	Actual feedwater pressure in	p_1	

(continued)

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TABLE 5.1.5 (CONT'D)
EXTERNAL DRAIN COOLER

Line No.	Term	Drain Cooler Symbol	Drain Cooler Value
	Computed Data		
27	Feedwater pressure loss	Δp_t^*	
28	Drain temperature out	T_1^*	
29	Feedwater film resistance	r_{ft1}^*	
30	Feedwater fouling resistance (by agreement)	r_{ft1}	
31	Shell side fouling resistance (by agreement)	r_{fs1}	
32	Shell side film resistance	r_{s1}^*	
33	Overall heat transfer coefficient	U_1^*	
34	Hourly heat capacity flow rate of shell side fluid	C_1^*	
35	Hourly heat capacity flow rate of feedwater fluid	c_1^*	
36	Hourly heat capacity ratio	R_1^*	
37	Number of transfer units	$(NTU)_1^*$	
38	Effectiveness	ϵ_1^*	
39	Feedwater outlet temperature	t_4^*	
40	Predicted terminal temperature difference	TTD^*	
41	Predicted drain cooler approach	DCA^*	
42	Drain pressure loss	ΔP_{dc}^*	

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TABLE 5.1.6
PTC 12.1 HEATER TEST REPORT FORM

HEATER INFORMATION

Name of Plant and Unit Number _____
Unit Guarantee Point (MW) _____
Unit Test Point (MW) _____
Test Engineer _____
Date of Test _____
Heater Designation _____
Heater Manufacturer _____
Heater Orientation Horizontal Vertical (Circle Applicable Orientation)
Heater Zones Desuperheating Condensing Drain Cooling (Circle Applicable Zones)

Channel Up _____
Channel Down _____

TUBE DATA

Material ____
Number of Tubes ____
Tube Diameter ____
Wall Thickness ____
Tube Pitch ____

TEST DATA

LOCATION	PARAMETER	SYMBOL	TEST RUN 1	2	3	4	5	6
	Time							
	Operating Liquid Level							
Feedwater Inlet	Pressure	p_1						
	Temperature	t_1						
	Flow Rate	w						
Feedwater Outlet	Pressure	p_4						
	Temperature	t_4						
	Feedwater Pressure Loss	Δ_{pf}						
Drains Inlet #1								
	Temperature	T_{d1}						
	Flow Rate	W_{d1}						
Drains Inlet #2								
	Temperature	T_{d2}						
	Flow Rate	W_{d2}						
Drains Inlet*								
	Temperature	T_2						
	Pressure	P_2						
Drain Outlet	Pressure	P_1						
	Temperature	T_1						
	Flow Rate	W_1						
Extraction Steam	Pressure	P_3						
	Temperature	T_3						
Heater Shell	Pressure	P_2						

* External drain cooler only

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feedwater outlet temperature differ by no more than 0.1°F.

The resistance summation and effectiveness-*NTU* methods are used in the calculation procedures. Individual resistance for each zone can be obtained from the heater manufacturer, or calculated based on the manufacturer's design specification data sheet. The basic heat transfer equations and examples on how to use the calculation procedures are included in the Appendices.

5.2.1 Three-Zone Heater (Integral Desuperheating Zone, Condensing Zone, and Drain Cooling Zone)

1. Calculate the assumed feedwater outlet temperature, and the assumed drain cooling zone outlet temperature. For the first iteration, let

$$t^*_{4a} = T_s - TTD'$$

and let

$$T^*_{1a} = t_1 + DCA'$$

In reiteration, if

$$| t^*_{4a} - t^*_4 | > 0.1,$$

let

$$t^*_{4a} = t^*_4$$

using T^*_4 as calculated in Step 30.

2. Calculate the feedwater outlet enthalpy h^*_4, and drain cooling zone outlet enthalpy H^*_1.

3. Calculate the total heat transferred.

$$Q^* = w\,(h^*_4 - h_1)$$

4. Calculate H_d from P_d and T_d for single drain stream or by flow weighted average of enthalpies for multiple inlet drain streams and calculate the steam flow rate.

$$W^*_s = \frac{Q^* - \Sigma W_d(H_d - H^*_1)}{H^*_3 - H^*_1}$$

5. Calculate the total condensate flow into the drain cooling zone.

$$W^*_1 = W^*_s + \Sigma W_d$$

6. Calculate the desuperheating zone pressure loss.

$$\Delta P^*_{ds} = \Delta P'_{ds}(W^*_s/W'_s)^{1.8}$$

7. Calculate the drain cooling zone pressure loss.

$$\Delta P^*_{dc} = \Delta P'_{dc}(W^*_1/W'_1)^{1.8}$$

8. Calculate the feedwater pressure loss.

$$\Delta p^*_t = \Delta p'_t(w/w')^{1.8}$$

9. Calculate the steam pressure inside the condensing zone.

$$P^*_2 = P_3 - \Delta P^*_{ds}$$

and determine the saturation temperature T^*_2 corresponding to this pressure.

10. Calculate the drain cooling zone, shell side heat transfer resistance.

$$r^*_{s1} = r'_{s1}(W'_1/W^*_1)^{0.6}$$

11. Calculate the drain cooling zone feedwater film resistance.

$$r^*_{t1} = r'_{t1}(w'/w)^{0.8}$$

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12. Calculate the condensing zone feedwater film resistance.

$$r^*_{t2} = r'_{t2}(w'/w)^{0.8}$$

13. Calculate the desuperheating zone steam film resistance.

$$r^*_{s3} = r'_{s3}(W'_s/W^*_s)^{0.6}$$

14. Calculate the desuperheating zone feedwater film resistance.

$$r^*_{t3} = r'_{t3}(w'/w)^{0.8}$$

15. Calculate the drain cooling zone overall heat transfer coefficient.

$$U^*_1 = \frac{1}{r^*_{s1} + r_{fs1} + r'_{m1} + r_{ft1} + r^*_{t1}}$$

16. Calculate the condensing zone overall heat transfer coefficient.

$$U^*_2 = \frac{1}{r'_{s2} + r_{fs2} + r'_{m2} + r_{ft2} + r^*_{t2}}$$

17. Calculate the desuperheating zone overall heat transfer coefficient.

$$U^*_3 = \frac{1}{r^*_{s3} + r_{fs3} + r'_{m3} + r_{ft3} + r^*_{t3}}$$

18. Calculate the drain cooling zone condensate hourly heat-capacity flow rate.

$$C^*_1 = \frac{W^*_1 Q'_1}{W'_1(T'_2 - T'_1)}$$

19. Calculate the drain cooling zone feedwater hourly heat-capacity flow rate.

$$c^*_1 = \frac{wQ'_1}{w'(t'_2 - t'_1)}$$

20. Calculate the drain cooling zone heat capacity ratio and $(NTU)^*_1$.

$$R^*_1 = c^*_1/C^*_1$$

$$(NTU)^*_1 = U^*_1 A'_1/c^*_1$$

21. Calculate the drain cooling zone effectiveness.

$$\epsilon^*_1 = \frac{1 - \exp\,[(NTU)^*_1(R^*_1 - 1)]}{1 - R^*_1 \exp\,[(NTU)^*_1(R^*_1 - 1)]}$$

22. Calculate the feedwater temperature leaving the drain cooling zone.

$$t^*_2 = \epsilon^*_1(T^*_2 - t_1) + t_1$$

23. Calculate the condensing zone feedwater hourly heat capacity flow rate and $(NTU)^*_2$.

$$c^*_2 = \frac{wQ'_2}{w'(t'_3 - t'_2)}$$

$$(NTU)^*_2 = U^*_2 A_2/c^*_2$$

24. Calculate the condensing zone effectiveness.

$$\epsilon^*_2 = 1 - \exp\,[-(NTU)^*_2]$$

25. Calculate the feedwater temperature leaving the condensing zone.

$$t^*_3 = \epsilon^*_2(T^*_2 - t^*_2) + t^*_2$$

26. Calculate the desuperheating zone steam hourly heat-capacity flow rate.

$$C^*_3 = \frac{W^*_s Q'_3}{W'_s(T'_3 - T'_{ds})}$$

27. Calculate the desuperheating zone feedwater hourly heat-capacity flow rate.

$$c^*_3 = \frac{wQ'_3}{w'(t'_4 - t'_3)}$$

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28. Calculate the desuperheating zone heat capacity ratio and $(NTU)_3^*$.

$$R_3^* = c_3^*/C_3^*$$

$$(NTU)_3^* = U_3^* A'_3/c_3^*$$

29. Calculate the desuperheating zone effectiveness.

$$\epsilon_3^* = \frac{1 - \exp\,[(NTU)_3^*(R_3^* - 1)]}{1 - R_3^* \exp\,[(NTU)_3^*(R_3^* - 1)]}$$

30. Calculate the final feedwater temperature leaving the desuperheating zone and check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new

$$t_4^* \text{ if } | t_4^* - t_{4a}^* | > 0.1$$

$$t_4^* = \epsilon_3^*(T_3 - t_3^*) + t_3^*$$

31. Calculate the drain outlet temperature.

$$T_1^* = T_2^* - R_1^* \epsilon_1^* (T_2^* - t_1)$$

32. Calculate the predicted terminal temperature difference.

$$TTD^* = T_s - t_4^*$$

33. Calculate the predicted drain cooler approach.

$$DCA^* = T_1^* - t_1$$

34. Calculate terminal temperature difference at the test point.

$$TTD = T_s - t_4$$

35. Calculate drain cooler approach temperature at the test point.

$$DCA = T_1 - t_1$$

36. If directly measured differential pressure is not available, calculate drain cooling zone pressure loss at the test point.

$$\Delta P_{dc} = P_2 - P_1$$

37. If directly measured differential pressure is not available, calculate desuperheating zone pressure loss at the test point.

$$\Delta P_{ds} = P_3 - P_2$$

38. If directly measured differential pressure is not available, calculate feedwater pressure loss at the test point.

$$\Delta p_t = p_1 - p_4$$

39. Compare TTD^*, DCA^*, ΔP_{dc}^*, ΔP_{ds}^*, Δp_t^* with TTD, DCA, ΔP_{dc}, ΔP_{ds}, and ΔP_t.

5.2.2 Two Zone Heater (Desuperheating and Condensing Heater)

1. Calculate the assumed feedwater outlet temperature. For the first iteration, let

$$t_{4a}^* = T_s^* - TTD'$$

In reiteration, if

$$| t_{4a}^* - t_4^* | > 0.1,$$

let

$$t_{4a}^* = t_4^*$$

using t_4^* as calculated in Step 20.

2. Calculate the feedwater outlet enthalpy h_4^*.
3. Calculate the total heat transferred.

$$Q^* = w(h_4^* - h_1)$$

4. Calculate H_d from P_d and T_d for single drain stream, or by flow weighted average of enthalpies for multiple inlet drain streams, and calculate the steam flow rate.

$$W_s^* = \frac{Q^* - \Sigma W_d(H_d - H_1^*)}{H_3 - H_1^*}$$

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5. Calculate the desuperheating zone pressure loss.

$$\Delta P^*_{ds} = \Delta P'_{ds}(W^*_s/W'_s)^{1.8}$$

6. Calculate the feedwater pressure loss.

$$\Delta p^*_t = \Delta p'_t(w/w')^{1.8}$$

7. Calculate the steam pressure inside the condensing zone,

$$P^*_2 = P_3 - \Delta P^*_{ds}$$

and determine the saturation temperature T^*_2 corresponding to this pressure.

8. Calculate the condensing zone feedwater film resistance.

$$r^*_{t2} = r'_{t2}(w'/w)^{0.8}$$

9. Calculate the desuperheating zone steam film resistance.

$$r^*_{s3} = r'_{s3}(W'_s/W^*_s)^{0.6}$$

10. Calculate the desuperheating zone feedwater film resistance.

$$r^*_{t3} = r'_{t3}(w'/w)^{0.8}$$

11. Calculate the condensing zone overall heat transfer coefficient.

$$U^*_2 = \frac{1}{r'_{s2} + r_{fs2} + r'_{m2} + r_{ft2} + r^*_{t2}}$$

12. Calculate the desuperheating zone overall heat transfer coefficient.

$$U^*_3 = \frac{1}{r^*_{s3} + r_{fs3} + r'_{m3} + r_{ft3} + r^*_{t3}}$$

13. Calculate the condensing zone feedwater hourly heat-capacity flow rate and $(NTU)^*_2$.

$$c^*_2 = \frac{wQ'_2}{w'(t'_3 - t'_1)}$$

$$(NTU)^*_2 = U^*_2 A'_2/c^*_2$$

14. Calculate the condensing zone effectiveness.

$$\epsilon^*_2 = 1 - \exp\,[-(NTU)^*_2]$$

15. Calculate the feedwater temperature leaving the condensing zone.

$$t^*_3 = \epsilon^*_2(T^*_2 - t_1) + t_1$$

16. Calculate the desuperheating zone steam hourly heat-capacity flow rate.

$$C^*_3 = \frac{W^*_s Q'_3}{W'_s(T'_3 - T'_{ds})}$$

17. Calculate the desuperheating zone feedwater hourly heat-capacity flow rate.

$$c^*_3 = \frac{wQ'_3}{w'(t'_4 - t'_3)}$$

18. Calculate the desuperheating zone heat-capacity flow rate and $(NTU)^*_3$.

$$R^*_3 = c^*_3/C^*_3$$

$$(NTU)^*_3 = U^*_3 A'_3/c^*_3$$

19. Calculate the desuperheating zone effectiveness.

$$\epsilon^*_3 = \frac{1 - \exp\,[(NTU)^*_3(R^*_3 - 1)]}{1 - R^*_3 \exp\,[(NTU)^*_3(R^*_3 - 1)]}$$

20. Calculate the final feedwater temperature leaving the desuperheating zone and check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new

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$$t_4^* \text{ if } | t_4^* - t_{4a}^* | > 0.1$$

$$t_4^* = \epsilon_3^*(T_3 - t_3^*) + t_3^*$$

21. Calculate the predicted terminal temperature difference.

$$TTD^* = T_s - t_4^*$$

22. Calculate terminal temperature difference at the test point.

$$TTD = T_s - t_4$$

23. If directly measured differential pressure is not available, calculate desuperheating zone pressure loss at the test point.

$$\Delta P_{ds} = P_3 - P_2$$

24. If directly measured differential pressure is not available, calculate feedwater pressure loss at the test point.

$$\Delta p_t = p_1 - p_4$$

25. Compare TTD^*, ΔP_{ds}^*, Δp_t^* with TTD, ΔP_{ds}, and Δp_t.

5.2.3 Two Zone Heater (Condensing and Drain Cooling)

1. Calculate the assumed feedwater outlet temperature and the assumed drain cooling zone outlet temperature. For the first iteration, let

$$t_{4a}^* = T_s - \text{TTD}'$$

and let

$$T_{1a}^* = t_1 + DCA'$$

In reiteration, if

$$| t_{4a}^* - t_4^* | > 0.1,$$

let

$$t_{4a}^* = t_4^*$$

using t_4^* as calculated in Step 21.

2. Calculate the feedwater outlet enthalpy h_4^*, and drain cooling zone outlet enthalpy H_1^*.

3. Calculate the total heat transferred.

$$Q^* = w(h_4^* - h_1^*)$$

4. Calculate H_d from P_d and T_d for single drain stream or by flow weighted average of enthalpies for multiple inlet drain streams and calculate the steam flow rate.

$$W_s^* = \frac{Q^* - \Sigma W_d(H_d - H_1^*)}{H_3 - H_1^*}$$

5. Calculate the total condensate flow into the drain cooling zone.

$$W_1^* = W_s^* + \Sigma W_d$$

6. Calculate the drain cooling zone pressure loss.

$$\Delta P_{dc}^* = \Delta P'_{dc}(W_1^*/W'_1)^{1.8}$$

7. Calculate the feedwater side pressure loss.

$$\Delta p_t^* = \Delta p'_t(w/w')^{1.8}$$

8. Determine the saturation temperature T_s corresponding to the steam pressure P_3.

9. Calculate the drain cooling zone condensate film resistance.

$$r_{s1}^* = r'_{s1}(W'_1/W_1^*)^{0.6}$$

10. Calculate the drain cooling zone feedwater film resistance.

$$r_{t1}^* = r'_{t1}(w'/w)^{0.8}$$

11. Calculate the condensing zone feedwater film resistance.

$$r_{t2}^* = r'_{t2}(w'/w)^{0.8}$$

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12. Calculate the drain cooling zone overall heat transfer coefficient.

$$U_1^* = \frac{1}{r_{s1}^* + r_{fs1} + r'_{m1} + r_{ft1} + r_{t1}^*}$$

13. Calculate the condensing zone overall heat transfer coefficient.

$$U_2^* = \frac{1}{r'_{s2} + r_{fs2} + r'_{m2} + r_{ft2} + r_{t2}^*}$$

14. Calculate the drain cooling zone condensate hourly heat-capacity flow rate.

$$C_1^* = \frac{W_1^* Q'_1}{W'_1(T'_2 - T'_1)}$$

15. Calculate the drain cooling zone feedwater hourly heat-capacity flow rate.

$$c_1^* = \frac{wQ'_1}{w'(t'_2 - t'_1)}$$

16. Calculate the drain cooling zone heat capacity ratio and $(NTU)_1^*$.

$$R_1^* = c_1^*/C_1^*$$

$$(NTU)_1^* = U_1^* A'_1/c_1^*$$

17. Calculate the drain cooling zone effectiveness.

$$\epsilon_1^* = \frac{1 - \exp\,[(NTU)_1^*(R_1^* - 1)]}{1 - R_1^* \exp\,[(NTU)_1^*(R_1^* - 1)]}$$

18. Calculate the feedwater temperature leaving the drain cooling zone.

$$t_2^* = \epsilon_1^*(T_s^* - t_1) + t_1$$

19. Calculate the condensing zone feedwater hourly heat-capacity flow rate and $(NTU)_2^*$.

$$c_2^* = \frac{wQ'_2}{w'(t'_4 - t'_2)}$$

$$(NTU)_2^* = U_2^* A'_2/c_2^*$$

20. Calculate the condensing zone effectiveness.

$$\epsilon_2^* = 1 - \exp\,[-(NTU)_2^*]$$

21. Calculate the final feedwater temperature leaving the condensing zone and check this temperature against the initially assumed temperature in Step 1. Repeat the calculation starting at Step 2 using the new t_4^* if $| t_4^* - t_{4a} | > 0.1$.

$$t_4^* = \epsilon_2^*(T_s - t_2^*) + t_2^*$$

22. Calculate the drain outlet temperature.

$$T_4^* = T_s - R_1^* \epsilon_1^*(T_s^* - t_1)$$

23. Calculate the predicted terminal temperature difference.

$$TTD^* = T_s - t_4^*$$

24. Calculate the predicted drain cooler approach.

$$DCA^* = T_1^* - t_1$$

25. Calculate terminal temperature difference at the test point.

$$TTD = T_s - t_4$$

26. Calculate drain cooler approach temperature at the test point.

$$DCA = T_1 - t_1$$

27. If directly measured differential pressure is not available, calculate drain cooling zone pressure loss at the test point.

$$\Delta P_{dc} = P_2 - P_1$$

28. If directly measured differential pressure is not

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available, calculate feedwater pressure loss at the test point.

$$\Delta p_t = p_1 - p_4$$

29. Compare TTD^*, DCA^*, ΔP^*_{dc}, Δp^*_t, with TTD, DCA, ΔP_{dc}, and Δp_t.

5.2.4 One Zone Heater (Condensing Only)

1. Calculate the feedwater side pressure loss.

$$\Delta p^*_t = \Delta p'_t(w/w')^{1.8}$$

2. Determine the saturation temperature T_s corresponding to the inlet steam pressure P_3.

3. Calculate the condensing zone feedwater film resistance.

$$r^*_{t2} = r'_{t2}(w'/w)^{0.8}$$

4. Calculate the condensing zone overall heat transfer coefficient.

$$U^*_2 = \frac{1}{r'_{s2} + r_{fs2} + r'_{m2} + r_{ft2} + r^*_{t2}}$$

5. Calculate the condensing zone feedwater hourly heat capacity flow rate and $(NTU)^*_2$.

$$C^*_2 = \frac{wQ'_2}{w'(t'_3 - t'_2)}$$

$$(NTU)^*_2 = U^*_2 A'_2/c^*_2$$

6. Calculate the condensing zone effectiveness.

$$\epsilon^*_2 = 1 - \exp\,[-(NTU)^*_2]$$

7. Calculate final feedwater temperature leaving the heater.

$$t^*_4 = \epsilon^*_2(T_s - t_1) + t_1$$

8. Calculate the predicted terminal temperature difference.

$$TTD^* = T_s - t^*_4$$

9. Calculate terminal temperature difference at the test point.

$$TTD = T_s - t_4$$

10. If directly measured differential pressure is not available, calculate feedwater pressure loss at the test point.

$$\Delta p_t = p_1 - p_4$$

11. Compare TTD^*, Δp^*_t with TTD, and Δp_t.

5.2.5 Drain Cooler Only

1. Calculate the shell side pressure loss.

$$\Delta P^*_{dc} = \Delta P'_{dc}(W_1/W'_1)^{1.8}$$

2. Calculate the feedwater side pressure loss.

$$\Delta p^*_t = \Delta p'_t(w/w')^{1.8}$$

3. Calculate the condensate film resistance.

$$r^*_{s1} = r'_{s1}(W'_1/W_1)^{0.6}$$

4. Calculate the feedwater film resistance.

$$r^*_{t1} = r'_{t1}(w'/w)^{0.8}$$

5. Calculate the overall heat transfer coefficient.

$$U^*_1 = \frac{1}{r^*_{s1} + r_{fs1} + r'_{m1} + r_{ft1} + r^*_{t1}}$$

6. Calculate the condensate hourly heat-capacity flow rate.

$$C^*_1 = \frac{W_1 Q'_1}{W'_1(T'_2 - T'_1)}$$

7. Calculate feedwater hourly heat-capacity flow rate.

$$c^*_1 = wQ'_1/w'(t'_4 - t'_1)$$

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8. Calculate heat capacity ratio and $(NTU)_1^*$.

$$R_1^* = c_1^*/C_1^*$$

$$(NTU)_1^* = U_1^* A_1'/c_1^*$$

9. Calculate effectiveness.

$$\epsilon_1^* = \frac{1 - \exp\,[(NTU)_1^*(R_1^* - 1)]}{1 - R_1^* \exp\,[(NTU)_1^*(R_1^* - 1)]}$$

10. Calculate feedwater temperature leaving the drain cooler.

$$t_4^* = \epsilon_1^*(T_2 - t_1) + t_1$$

11. Calculate the drain outlet temperature.

$$T_1^* = T_2 - R_1^* \epsilon_1^*(T_2 - t_1)$$

12. Calculate the predicted terminal temperature difference.

$$TTD^* = T_2 - t_4^*$$

13. Calculate the predicted drain cooler approach temperature.

$$DCA^* = T_1^* - t_1$$

14. Calculate terminal temperature difference at the test point.

$$TTD = T_2 - t_4$$

15. Calculate drain cooler approach temperature at the test point.

$$DCA = T_1 - t_1$$

16. If directly measured differential pressure is not available, calculate drain cooler pressure loss at the test point.

$$\Delta P_{dc} = P_2 - P_1$$

17. If directly measured differential pressure is not available, calculate feedwater pressure loss at the test point.

$$\Delta p_t = p_1 - p_4$$

18. Compare TTD^*, DCA^*, ΔP_{dc}^*, Δp_t^*, with TTD, DCA, ΔP_{dc}, and Δp_t.

5.3 UNCERTAINTY CALCULATION PROCEDURES

This subsection discusses the procedures for calculating the effects of measurement uncertainties on the test results which are the five parameters listed in Subsection 1.3. A numerical example is provided as Appendix C. Refer to PTC 19.1 for a more complete description of the required calculations.

The effects of measurement uncertainty on the results can be analyzed using the following four steps.

1. Calculate the sensitivity of the final results to uncertainties of the measured variables.
2. Use the calculated sensitivities to determine the effects of precision uncertainties of the measured variables on the results.
3. Use the calculated sensitivities to determine the effects of bias limits of the measured variables on the results.
4. Determine the combined effects of precision uncertainties and bias limits.

Measurement uncertainties include precision uncertainties and bias uncertainties as discussed in Subsection 3.7.

5.3.1 Calculation of Sensitivity Factors. The sensitivity of a result is the ratio of the change in the result caused by a unit change in the measured value. Calculation of the sensitivity factors uses the procedures described in Subsection 5.2. For each measured variable the calculation is repeated twice, once with the measured value increased by a unit value and once with the measured value decreased by a unit value. (For temperature measurements, the unit is 1.0°F. For flows, pressures, and pressure losses, the unit change is 1.0%) The sensitivity factor is then calculated by taking the average of the change in the result (e.g., the difference between the calculated and measured TTD) resulting from the unit increase and the unit decrease in the measured value.

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5.3.2 Calculation of the Precision Uncertainty of the Result. The first step is to calculate the precision uncertainty of the result of each measured parameter using the following equation.

$$\text{Precision uncertainty} = \frac{(\text{Standard deviation } S_x)*(\text{Sensitivity})*t}{\sqrt{(\text{Number of measurements})}}$$

where

t = Student t factor associated with the number of test measurements ($t = 2$ for 30 or more measurements; refer to PTC 19.1)

and the uncertainty of the measurement is the standard deviation of the data point.

S_x = the standard deviation of a data sample; an estimate of the standard deviation of the population σ_x

$$S_x = \left[\frac{\sum_{k=1}^{N} (X_k - \overline{X})^2}{N - 1}\right]^{1/2}$$

where

$N - 1$ = degrees of freedom
X_k = k^{th} value of the variable
X = an individual observation in a data sample
$\overline{X}$ = the sample mean; the average of a set of N individual observations

$$\overline{X} = \frac{1}{N}\sum_{k=1}^{N} X_k$$

The precision uncertainty of the result is then calculated by taking the square root of the sum of the squares of the uncertainties of the average for all the measured parameters.

5.3.3 Calculation of the Bias Limit of the Result. The first step is to calculate the upper and lower bias limit of the result for each measured parameter using the following equations.

$$\text{Upper bias limit of the result} = (\text{Upper bias limit of measurement})*(\text{Sensitivity})$$
$$\text{Lower bias limit of the result} = (\text{Lower bias limit of measurement})*(\text{Sensitivity})$$

The total upper bias limit of the result is the square root of the sum of the squares of the upper bias limits of the results for all measured parameters. The total lower bias limit of the result is the square root of the sum of the squares of the lower bias limits of the results for all the measured parameters.

5.3.4 Calculation of the Combined Effect of Precision Uncertainties and Bias Limits. Finally, combining precision uncertainties and bias limits using the following formula will provide an uncertainty band that will bound the true values in 95% of cases.

$$\text{Total uncertainty} = \sqrt{(\text{Bias limit})^2 + (\text{Precision uncertainty})^2}$$

where

bias limit is calculated as in para. 5.3.3
precision uncertainty is calculated as in para. 5.3.2

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SECTION 6 — REPORT OF RESULTS

6.1 INTRODUCTION

This Section outlines the report of test results. Only the relevant items need to be reported in any particular case. The report should be complete in all respects and should be signed by the lead test engineer.

6.1.1 Brief Summary of Test

(a) Owner
(b) Name and location of plant
(c) Designation of unit and heater(s)
(d) Feedwater heater manufacturer and heater identification number
(e) Feedwater heater description
(f) Brief history of the feedwater heater(s)
(g) Object of test
(h) Date and time of test
(i) Key test personnel and relevant observers and their affiliations
(j) Stipulated agreements
(k) Executive summary of test results and conclusions (a tabular or graphical presentation may be used to show essential findings)

6.1.2 Discussion of Test

(a) Test procedure
(b) Data acquisition and instrumentation summary, including method of measurement, calibration, and location of test points
(c) All other pertinent information

6.1.3 Heater Data

(a) Tabulation of operating conditions, feedwater heater design data, and test data (after application of all calibration corrections)
(b) The required data shall be entered on tables similar to Tables 5.1.1 through 5.1.5 as applicable, for each run

6.1.4 Feedwater Heater Performance Computations

(a) Computed data shall be entered on tables similar to Tables 5.1.1 through 5.1.5, as applicable, for each run
(b) Supporting calculations for reference

6.1.5 Overall Uncertainty of Test Results

(a) Specified instrument and measurement uncertainties, and relevant sensitivities
(b) Calculation of overall uncertainty of final test results, similar to the example in Appendix C

6.1.6 Conclusion

(a) Statement of the conclusions

6.1.7 Appendices and Illustrations

(a) Any appendices and illustrations necessary to clarify description of the equipment or method and circumstances of the test

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NONMANDATORY APPENDIX A — BASIC HEAT TRANSFER EQUATIONS

This Appendix consists of basic heat transfer equations. Examples of how to use the performance calculation procedures are provided in Appendix B.

The basic heat transfer equations include commonly used heat transfer equations and the effectiveness-*NTU* method. The superscript j stands for 1, 2, 3 where 1 represents drain cooling zone, 2 represents condensing zone, and 3 represents desuperheating zone.

The following nomenclature is used in Appendices A and B in addition to the nomenclature shown in Section 2.

Symbol	Term	Units	
		U.S. Customary	SI
C_p	Specific heat	Btu/(lbm-°F)	J/(kg-K)
d_i	Tube inside diameter	in.	mm
d_o	Tube outside diameter	in.	mm
K	Thermal conductivity	Btu/(hr-ft-°F)	W/(m-K)
μ	Dynamic viscosity	lbm/(hr-ft)	Pa-s
ρ	Density	lbm/ft^3	kg/m^3
V	Velocity	ft/sec	m/s

Governing equation:

$$Q = w(h_2 - h_1) = U \cdot A \cdot (LMTD) \qquad (1)$$

where

$$LMTD = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\,[(T_1 - t_2)/(T_2 - t_1)]}$$

Overall heat transfer coefficient:

$$U_j = \frac{1}{r_{sj} + r_{fsj} + r_{mj} + r_{ftj} + r_{tj}} \qquad (2)$$

Metal resistance:

$$r_{mj} = \frac{d_o}{24K}\left[ln\left(\frac{d_o}{d_i}\right)\right] \qquad (3)$$

$$\left\{\text{SI: } r_{mj} = \frac{d_o}{2000K}\left[ln\left(\frac{d_o}{d_i}\right)\right]\right\}$$

Feedwater Film Resistance:

$$r_{tj} = 0.0378\left[\frac{\mu^{0.4}}{(K^{0.6})(\rho^{0.8})(C_p{}^{0.4})}\left(\frac{d_o}{d_i{}^{0.8}}\right)\left(\frac{1}{V^{0.8}}\right)\right] \qquad (4)$$

$$\{\text{SI: } r_{tj} = [0.023\ (Re)^{0.8}\ (P_r)^{0.4}]^{-1}$$

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where

$$\left.\begin{aligned} Re &= \text{Reynold number} \\ Pr &= \text{Prandtl number} \end{aligned}\right\}$$

Properties of water should be taken at the average water temperature for that zone. For simplicity, use the inlet feedwater temperature for the drain cooling zone, the average of inlet and outlet feedwater temperatures for the condensing zone, and the feedwater outlet temperature for the desuperheating zone.

Calculate the feedwater outlet temperature from each zone.

$$t_2 = \frac{Q_1}{w \cdot c_p} + t_1$$

Calculate the desuperheating zone steam outlet temperature.

$$T_{ds} = T_s - \frac{Q_3}{W \cdot C_p}$$

EFFECTIVENESS-NTU METHOD

Hourly heat capacity flow rate for feedwater:

$$c_j = \frac{w_j Q_j'}{w_j'(t_{j+1}' - t_j')}$$

Hourly heat capacity flow rates for shell side flows:

$$C_j = \frac{W_j Q_j'}{W_j'(T_{j+1}' - T_j')}$$

Heat capacity ratio for desuperheating and drain cooling zones:

$$R_j = c_j / C_j$$

Number of transfer units:

$$(NTU)_j = U_j A_j / c_j$$

Effectiveness in terms of NTU for the desuperheating and drain cooling zones:

$$\epsilon_j = \frac{1 - \exp\,[(NTU)_j(R_j - 1)]}{1 - R_j \exp\,[(NTU)_j\,(R_j - 1)]}$$

Since the heat capacity ratio is zero in the condensing zone, the effectiveness for this zone is:

$$\epsilon_2 = 1 - \exp\,[-(NTU)_2]$$

Feedwater outlet temperature in terms of effectiveness:

$$t_{j+1} = \epsilon_j\,(T_j - t_j) + t_j$$

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NONMANDATORY APPENDIX B — HEATER PERFORMANCE CALCULATION EXAMPLES

This Appendix contains three example calculations. Examples 1 and 2 illustrate methods to estimate design parameters used in the procedures in Subsection 5.2 in the event that those parameters are not available from the manufacturer. Example 1 illustrates using data from the manufacturer's specification data sheet to estimate the design film resistances for each zone when only the overall heat transfer coefficient is known. Example 2 illustrates a method to calculate the internal design temperatures (t_2', t_3', T_{ds}' and T_2'). Example 3 illustrates using the calculation procedure for a three zone feedwater heater from para. 5.2.1.

Example 1

Using data from the specification data sheet, illustrate how to calculate the resistances for each zone, if not available on the manufacturer's specification data sheet.

Input Data Required

Tube material:	Monel
Thermal conductivity of tube (k):	16 Btu-ft/(hr-ft^2-°F) [27.692 $W/(m\text{-}K)$]
Tube outside diameter (d_o):	0.625 in. (15.875 mm)
Tube inside diameter (d_i):	0.527 in. (13.386 mm)
Average feedwater tube velocity (V):	5.529 ft/sec (1.685 m/s)

Heat Transfer Coefficients

Drain Cooling Zone (U_1'):	375.2 Btu/(hr-ft^2-°F) [2130.5 W/(m^2-°C)]
Condensing Zone (U_2'):	732.6 Btu/(hr-ft^2-°F) [4159.9 W/(m^2-°C)]
Desuperheating Zone (U_3'):	104.2 Btu/(hr-ft^2-°F) [591.7 W/(m^2-°C)]
Feedwater inlet temperature (t_1'):	385.4°F (196.3°C)
Feedwater outlet temperature (t_2'):	457.9°F (236.6°C)
Feedwater operating pressure (p_1'):	1748.7 psia (12,056.9 kPa)

CALCULATION

Drain Cooling Zone

1. Based on *HEI* recommendations.

$$r_{fs1} = 0.00030 \text{ (hr-ft}^2\text{-°F)/Btu (0.00005m}^2\text{-K/W)}$$

$$r_{ft1} = 0.000237 \text{ (hr-ft}^2\text{-°F)/Btu (0.000042m}^2\text{-K/W)}$$

(r_{ft1} has been corrected to the outside diameter)

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2. Calculate the metal resistance using Eq. (3) from Appendix A.

$$r'_{m1} = 0.625/(24 \times 16)[\ln(0.625/0.527)]$$

$$= 0.000278 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000049\text{m}^2\text{-K/W})$$

3. Calculate the feedwater film resistance using Eq. (4) from Appendix A. Note: Use physical properties corresponding to feedwater inlet temperature.

$$r'_{f1} = 0.0378\ [0.37^{0.4}/(0.4^{0.6} \times 55.6^{0.8} \times 1.04^{0.4})]\ [0.625/0.527^{0.8}]\ [1/5.529^{0.8}]$$

$$= 0.000462 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000081\text{m}^2\text{-K/W})$$

4. Calculate condensate film resistance using Eq. (2) from Appendix A.

$$r'_{s1} = (1/375.2) - (0.0003000 + 0.000278 + 0.000237 + 0.000462)$$

$$= 0.001388 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000244\text{m}^2\text{-K/W})$$

Condensing Zone

1. $r_{fs2} = 0.0$ (hr-ft^2-°F/Btu) (0.0m^2-K/W)

   $r_{ft2} = 0.000237$ (hr-ft^2-°F)/Btu (0.000042m^2-K/W)

2. $r'_{m2} = 0.000278$ (hr-ft^2-°F)/Btu (0.000049m^2-K/W)

3. Calculate the feedwater film resistance using Eq. (4) from Appendix A. Note: Use physical properties corresponding to average feedwater temperature.

$$r'_{t2} = 0.0378[0.32^{0.4}/(0.39^{0.6} \times 53.7^{0.8} \times 1.07^{0.8})][0.625/0.527^{0.8}][1/5.529^{0.8}]$$

$$= 0.000450 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000079\text{m}^2\text{-K/W})$$

4. Calculate steam condensing zone film resistance using Eq. (2) from Appendix A.

$$r'_{s2} = (1/732.6) - (0.0 + 0.000278 + 0.000237 + 0.00045)$$

$$= 0.000450 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000079\text{m}^2\text{-K/W})$$

Desuperheating Zone

1. $r_{fs3} = 0.000300$ (hr-ft^2-°F)/Btu (0.000053m^2-K/W)

   $r_{ft3} = 0.000237$ (hr-ft^2-°F)/Btu (0.000042m^2-K/W)

2. $r'_{m3} = 0.000278$ (hr-ft^2-°F)/Btu (0.000049m^2-K/W)

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3. Calculate the feedwater film resistances using Eq. (4) from Appendix A. Note: Use physical properties corresponding to feedwater outlet temperature.

$$r'_{t3} = 0.0378[0.28^{0.4}/(0.28^{0.4}/0.37^{0.6} \times 51.5^{0.8} \times 1.11^{0.4})][0.625/0.527^{0.8}[1/5.529^{0.8}]$$

$$= 0.000449 \text{ (hr-ft}^2\text{-°F)/Btu } (0.00079 \text{ m}^2\text{-K/W})$$

4. Calculate steam film resistance using Eq. (2) from Appendix A.

$$r'_{s3} = (1/104.2) - (0.000300 + 0.000278 + 0.000237 + 0.000449)$$

$$= 0.008333 \text{ (hr-ft}^2\text{-°F)/Btu } (0.001468 \text{m}^2\text{-K/W})$$

Example 2

Illustrate a method to calculate the internal design temperatures (t'_2, t'_3, T'_{ds} and T'_2) if they are not available on the manufacturer's specification data sheet.

Input Data Required

Feedwater flow (w'):	689,777 lbm/hr (86.9098 kg/s)
Feedwater inlet temperature (t'_1):	385.4°F (196.3°C)
Feedwater outlet temperature (t'_4):	457.9°F (236.6°C)
Feedwater operating pressure (p'_1):	1748.7 psia (12,057 kPa)
Steam flow (W'_s):	52,270 lbm/hr (6.5859 kg/s)
Steam inlet temperature (T'_3):	701.9°F (372.2°C)
Steam inlet pressure (P'_3):	440.1 psia (3,034 kPa)
Desuperheater pressure loss ($\Delta P'_{ds}$):	1.6 psia (11.0 kPa)

Heat Exchanged

Drain Cooling Zone (Q'_1):	4,948,370 Btu/hr (1,450,219 W)
Desuperheating Zone (Q'_3):	5,268,816 Btu/hr (1,544,138 W)

CALCULATION

1. Calculate the feedwater temperature leaving the drain cooling zone.

$$t'_2 = t'_1 + Q'_1/(w'c_p)$$
$$= 385.4 + 4{,}948{,}370/(689{,}777 \times 1.065)$$
$$= 392.1\text{°F } (200.1\text{°C})$$

2. Calculate the feedwater temperature leaving the condensing zone.

$$t'_3 = t'_4 - Q'_3/(\text{w}'\text{c}_p)$$
$$= 457.9 - 5{,}268{,}816/(689{,}777 \times 1.1)$$
$$= 451.0\text{°F } (232.8\text{°C})$$

3. Calculate the desuperheating zone outlet steam temperature.

$$T'_{ds} = t'_3 - Q'_3/(W'_s c_p)$$
$$= 701.9 - 5{,}268{,}816/(52{,}270 \times 0.59)$$
$$= 531.0\text{°F } (277.2\text{°C})$$

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4. Calculate the saturation temperature in the condensing zone.

$$P_2' = P_3' - \Delta P_{ds}'$$
$$= 440.1 - 1.6 = 438.5 \text{ psia } (3.023 \text{ kPa})$$
$$T_2' = 453.7°\text{F } (234.3°\text{C})$$

Example 3

This example gives a step-by-step calculation using the procedure described in para. 5.2.1 for a three-zone heater. Hypothetical design data and test data are given in Table B.1 using the form shown in Table 5.1.1.

1. Calculate the assumed feedwater outlet temperature. For the first iteration let

$$t_{4a} = T_s - TTD'$$
$$= 443.6 - (-3.9) = 447.5°\text{F } (230.8°\text{C})$$

and let

$$T_{1a}^* = t_1 + DCA'$$
$$= 375.4 + 10$$
$$= 385.4°\text{F } (196.3°\text{C})$$

In reiteration, if $| t_{4a}^* - t_4^* | > 0.1$, let

$$t_{4a}^* = t_4^*$$

using t_4^* as calculated in Step 30.

2. Calculate the feedwater outlet enthalpy.

$$h_4^* = 428.3 \text{ Btu/lbm } (996.2 \text{ kJ/kg})$$

Calculate the drain cooling zone outlet enthalpy.

$$H_1^* = 359.6 \text{ Btu/lbm } (836.4 \text{ kJ/kg})$$

3. Calculate the total heat transferred.

$$Q^* = w(h_4^* - h_1^*)$$
$$= (621{,}000)(428.3 - 350.9)$$
$$= 48{,}065{,}400 \text{ Btu/hr } (14{,}087 \text{ W})$$

4. Calculate H_d^* from P_d and T_d for single drain stream or by flow weighted average of enthalpies for multiple inlet drain streams and calculate steam flow rate.

$$W_s^* = Q^* - [\Sigma W_d(H_d^* - H_1^*)]/[H_3^* - H_1^*]$$
$$= [(48{,}065{,}400) - (25{,}000)(460 - 359.6)]/[1363.6 - 359.6]$$
$$= 45{,}374 \text{ lbm/hr } (5.7170 \text{ kg/s})$$

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5. Calculate the total condensate flow into the drain cooling zone.

$$W_1^* = W_s^* + \Sigma W_d$$
$$= 45{,}374 + 25{,}000 = 70{,}374 \text{ lbm/hr } (8.8669 \text{ kg/s})$$

6. Calculate the desuperheating zone pressure loss.

$$\Delta P_{ds}^* = \Delta P_{ds}'(W_s^*/W_s')^{1.8}$$
$$= 1.6\ (45{,}374/52{,}270)^{1.8} = 1.24 \text{ psi } (8.55 \text{ kPa})$$

7. Calculate the drain cooling zone pressure loss.

$$\Delta P_{dc}^* = \Delta P_{dc}^*\ (W_1^*/W_s')^{1.8}$$
$$= 1.8\ (70{,}374/77{,}270)^{1.8} = 1.52 \text{ psi } (10.48 \text{ kPa})$$

8. Calculate the feedwater pressure loss.

$$\Delta p_t^* = \Delta p_t'(w/w')^{1.8}$$
$$= 4.8\ (621{,}000/689{,}777)^{1.8} = 3.97 \text{ psi } (27.37 \text{ kPa})$$

9. Calculate the steam pressure and temperature inside the condensing zone.

$$P_2^* = P_3 - \Delta P_{ds}^*$$
$$= 396 - 1.24 = 394.76 \text{ psia } (2721.8 \text{ kPa})$$
$$T_2^* = 443.3°\text{F } (228.5°\text{C})$$

10. Calculate the drain cooling zone condensate film resistance.

$$r_{s1}^* = r_{s1}'(W_1'/W_1^*)^{0.6}$$
$$= 0.001388\ (77{,}270/70{,}374)^{0.6}$$
$$= 0.001468 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000259 \text{ m}^2\text{-K/W})$$

11. Calculate the drain cooling zone feedwater film resistance.

$$r_{t1}^* = r_{t1}'(w'/w)^{0.8}$$
$$= 0.000462\ (689{,}777/621{,}000)^{0.8}$$
$$= 0.000502 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000088 \text{ m}^2\text{-K/W})$$

12. Calculate the condensing zone feedwater film resistance.

$$r_{t2}^* = r_{t2}'\ (w'/w)^{0.8}$$
$$= 0.000450\ (689{,}777/621{,}000)^{0.8}$$
$$= 0.000489 \text{ (hr-ft}^2\text{-°F)/Btu } (0.000086 \text{ m}^2\text{-K/W})$$

13. Calculate the desuperheating zone steam film resistance.

$$r_{t3}^* = r_{t3}'(W_s'/W_s^*)^{0.6}$$
$$= 0.008333\ (52{,}270/45{,}374)^{0.6}$$
$$= 0.009071 \text{ (hr-ft}^2\text{-°F)/Btu } (0.001598 \text{ m}^2\text{-K/W})$$

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14. Calculate the desuperheating zone feedwater film resistance.

$$r^*_{t3} = r'_{t3}(w'/w)^{0.8}$$
$$= 0.000449\ (689{,}777/621{,}000)^{0.8}$$
$$= 0.000488\ \text{(hr-ft}^2\text{-°F)/Btu}\ (0.000086\ \text{m}^2\text{-K/W})$$

15. Calculate the drain cooling zone overall heat transfer coefficient.

$$U^*_1 = 1/(r^*_{s1} + r_{fs1} + r'_{m1} + r_{ft1} + r^*_{t1})$$
$$= 1/(0.001468 + 0.000300 + 0.000278 + 0.000237 + 0.000502)$$
$$= 359\ \text{Btu/(hr-ft}^2\text{-°F)}\ (2038\ \text{W/m}^2\text{-K})$$

16. Calculate the condensing zone overall heat transfer coefficient.

$$U^*_2 = 1/(r'_{s2} + r_{fs2} + r'_{m2} + r_{ft2} + r^*_{t2})$$
$$= 1/(0.000400 + 0 + 0.000278 + 0.000237 + 0.000489)$$
$$= 712\ \text{Btu/(hr-ft}^2\text{-°F)}\ (4043\ \text{W/m}^2\text{-K})$$

17. Calculate the desuperheating zone overall heat transfer coefficient.

$$U^*_3 = 1/(r^*_3 + r_{fs3} + r'_{m3} + r_{ft3} + r^*_{t3})$$
$$= 1/(0.009071 + 0.000300 + 0.000278 + 0.000237 + 0.000488)$$
$$= 96.4\ \text{Btu/(hr-ft}^2\text{-°F)}\ (547.4\ \text{W/m}^2\text{-K})$$

18. Calculate the drain cooling zone condensate hourly heat capacity flow rate.

$$C^*_1 = W^*_1 Q'_1/W'_1(T'_2 - T'_1)$$
$$= (70{,}374 \times 4{,}948{,}370)/[77{,}270(453.7 - 395.4)]$$
$$= 77{,}303\ \text{Btu/(hr-°F)}\ (12.6\ \text{kW/°C})$$

19. Calculate the drain cooling zone feedwater hourly capacity flow rate.

$$c^*_1 = wQ'_1/w'(t'_2 - t'_1)$$
$$= (621{,}000 \times 4{,}948{,}370)/[689{,}777(392.1 - 385.4)]$$
$$= 664{,}921\ \text{Btu/(hr-°F)}\ (108\ \text{kW/°C})$$

20. Calculate the drain cooling zone heat capacity ratio and $(NTU)_1$.

$$R^*_1 = c^*_1/C^*_1$$
$$= 664{,}921/77{,}303 = 8.6$$

$$(NTU)^*_1 = U^*_1 A'_1/c^*_1$$
$$= 359 \times (464/664{,}921) = 0.251$$

21. Calculate the drain cooling zone effectiveness.

$$\epsilon^*_1 = [(1 - e^{(NTU)^*_1(R^*_1 - 1)}]/[1 - R^*_1 e^{(NTU)^*_1(R^*_1 - 1)}]$$
$$= [1 - e^{(0.251) \times (8.6 - 1)}]/[1 - (8.6)e^{(0.251) \times (86 - 1)}]$$
$$= 0.1007$$

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22. Calculate the feedwater temperature leaving the drain cooling zone.

$$\begin{aligned} t_2^* &= \epsilon_1^*(T_2^* - t_1) + t_1 \\ &= (0.1007)(443.3 - 375.4) + 375.4 \\ &= 382.2°F\ (194.6°C) \end{aligned}$$

23. Calculate the condensing zone feedwater hourly heat-capacity flow rate and $(NTU)_2$.

$$\begin{aligned} c_2^* &= wQ_2'/[w'(t_3' - t_2')] \\ &= (621{,}000 \times 43{,}861{,}331)/[689{,}777(451 - 392.1)] \\ &= 670{,}424\ \text{Btu/(hr-°F)}\ (109\ \text{kW/°C}) \end{aligned}$$

$$\begin{aligned} (NTU)_2^* &= U_2^*(A_2'/c_2^*) \\ &= 712 \times (3{,}185/670{,}424) \\ &= 3.383 \end{aligned}$$

24. Calculate the condensing zone effectiveness.

$$\begin{aligned} \epsilon_2^* &= 1 - e^{-(NTU)_2^*} \\ &= 1 - e^{-(3.383)} = 0.966 \end{aligned}$$

25. Calculate the feedwater temperature leaving the condensing zone.

$$\begin{aligned} t_3^* &= \epsilon_2^*(T_2^* - t_2^*) + t_2^* \\ &= 0.966(443.3 - 382.2) + 382.2 \\ &= 441.2°F\ (227.3°C) \end{aligned}$$

26. Calculate the desuperheating zone steam hourly heat-capacity flow rate.

$$\begin{aligned} C_3^* &= W_s^* Q_3'/[W_s'(T_3' - T_{ds}')] \\ &= (45{,}374 \times 5{,}268{,}816)/[52{,}270(701.9 - 531)] \\ &= 26{,}762\ \text{Btu/(hr-°F)}\ (4\ \text{kW/°C}) \end{aligned}$$

27. Calculate the desuperheating zone feedwater hourly heat-capacity flow rate.

$$\begin{aligned} c_3^* &= wQ_3'/[w'(t_4' - t_3')] \\ &= 621{,}000 \times 5{,}268{,}816/[689{,}777(457.9 - 451)] \\ &= 687{,}459\ \text{Btu/(hr-°F)}\ (112\ \text{kW/°C}) \end{aligned}$$

28. Calculate the desuperheating zone heat capacity ratio and $(NTU)_3$.

$$\begin{aligned} R_3^* &= c_3^*/C_3^* \\ &= 687{,}459/26{,}762 = 25.69 \end{aligned}$$

$$\begin{aligned} (NTU)_3^* &= U_3^* A_3'/c_3^* \\ &= 96.4\ (343/687{,}459) = 0.0481 \end{aligned}$$

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29. Calculate the desuperheating zone effectiveness.

$$\epsilon_3^* = [(1 - e^{(NTU)_3^*(R_3^* - 1)}]/[1 - R_3^* e^{(NTU)_3^*(R_3^* - 1)}]$$
$$= [1 - e^{(0.0481) \times (25.69 - 1)}]/[1 - (25.69)\, e^{(0.0481) \times (25.69 - 1)}]$$
$$= 0.0274$$

30. Calculate the final feedwater temperature leaving the desuperheating zone.

$$t_4^* = \epsilon_3^*(T_3 - t_3^*) + t_3^*$$
$$= (0.0274)(700 - 441.2) + 441.2$$
$$= 448.3°F\ (231.3°C)$$

Since the difference between the calculated feedwater outlet temperature [448.3°F (231.3°C)] and the initially assumed feedwater outlet temperature [447.5°F (230.8°C)] is greater than 0.1°F, another iteration is necessary. Calculations continue at this point to illustrate the procedure.

31. Calculate the drain outlet temperature.

$$T_1^* = T_2^* - R_1^* \epsilon_1^*(T_2^* - t_1)$$
$$= 443.3 - (8.6)(0.1007)(443.3 - 375.4)$$
$$= 384.5°F\ (195.8°C)$$

32. Calculate the predicted Terminal Temperature Difference.

$$TTD^* = T_s - t_4^*$$
$$= 443.6 - 448.3 = -4.7°F\ (-2.6°C)$$

33. Calculate the predicted drain cooler approach temperature.

$$DCA^* = T_1^* - t_1$$
$$= 384.5 - 375.4 = 9.1°F\ (5.1°C)$$

Using 448.3°F as the initial feedwater outlet temperature, repeat the calculation from Step 2 through 30 which will yield:

$$W_s^* = 46{,}302\ lbm/hr\ (5.834\ kg/s)$$

$$t_4^* = 448.4°F\ (231.3°C)$$

34. Calculate the drain outlet temperature.

$$T_1^* = T_2^* - R_1^* \epsilon_1^*(T_2^* - t_1)$$
$$= 443.3 - (8.5)(0.1014)(443.3 - 375.4) = 384.8°F\ (196.0°C)$$

35. Calculate the predicted terminal temperature difference.

$$TTD^* = T_s - t_4^*$$
$$= 443.6 - 448.4 = -4.8°F\ (-2.7°C)$$

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36. Calculate the predicted drain cooler approach temperature.

$$DCA^* = T_1^* - t_1$$
$$= 384.8 - 375.4 = 9.4°F\ (5.2°C)$$

37. Calculate terminal temperature difference at the test point.

$$TTD = T_s - t_4 = 443.6 - 448.6 = -5.0°F\ (-2.8°C)$$

38. Calculate the drain cooler approach temperature at the test point.

$$DCA = T_1 - t_1 = 384.1 - 375.4 = 8.7°F\ (4.8°C)$$

39. If directly measured differential pressure is not available, calculate the drain cooling zone pressure loss at the test point.

$$\Delta p_{dc} = P_2 - P_1$$

40. If directly measured differential pressure is not available, calculate the desuperheating zone pressure loss at the test point.

$$\Delta p_{ds} = P_3 - P_2$$

41. If directly measured differential pressure is not available, calculate feedwater pressure loss at the test point.

$$\Delta p_t = p_1 - p_4$$

42. Compare TTD^*, DCA^*, Δp_{dc}^*, Δp_{ds}^*, Δp_t^*, with TTD, DCA, Δp_{dc}, Δp_{ds}, and Δp_t.

$TTD < TTD^*$
$-5.0 < -4.8°F\ (-2.8 < -2.7°C)$

$DCA < DCA^*$
$8.7 < 9.4°F\ (4.8 < 5.2°C)$

$\Delta p_{ds} < \Delta p_{ds}^*$
$1.1 < 1.24$ psi $(7.6 < 8.55$ kPa$)$

$\Delta p_{dc} < \Delta p_{dc}^*$
$1.5 < 1.52$ psi $(10.3 < 10.48$ kPa$)$

$\Delta p_t < \Delta p_t^*$
$3.5 < 3.97$ psi $(24.1 < 27.4$ kPa$)$

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TABLE B.1
THREE-ZONE HEATER

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Design Data						
1	Feedwater flow rate	w'		w'		w'	
	lbm/hr		689,777		689,777		689,777
	(kg/s)		(87)		(87)		(87)
2	Steam flow rate	w'_s		w'_s			
	lbm/hr		52,270		52,270		
	(kg/s)		(7)		(7)		
3	Drains flow rate			w'_d		w'_1	
	lbm/hr				25,000		77,270
	(kg/s)				(3)		(3)
4	Inlet steam pressure	P'_3					
	psia (kPa)		440.1 (3034.4)				
5	Shell side pressure loss	$\Delta P'_{ds}$				$\Delta P'_{dc}$	
	psia (kPa)		1.6 (11.0)				1.8 (12.4)
6	Shell side temperature in	T'_3		T'_2		T'_2	
	°F(°C)		701.9 (372.2)		453.7 (234.3)		453.7 (234.3)
7	Shell side temperature out	T'_{ds}		T'_2		T'_1	
	°F(°C)		531 (277.2)		453.7 (234.3)		395.4 (201.9)
8	Feedwater temperature in	t'_3		t'_2		t'_1	
	°F(°C)		451 (283)		392.1 (200.1)		385.4 (196.3)
9	Feedwater temperature out °F(°C)	t'_4	457.9 (236.6)	t'_3	451 (233)	t'_2	392.1 (200.1)
10	Feedwater pressure loss			$\Delta p'_t$			
	psia (kPa)				4.8 (33.1)		
11	Heat transferred	Q'_3		Q'_2		Q'_1	
	Btu/hr		5,268,816		43,861,331		4,948,370
	(kW)		(1,544)		(12,854)		(1450)
12	Heat transfer surface area	A'_3		A'_2		A'_1	
	ft^2 (m^2)		353 (32.8)		3,185 (295.9)		464 (43.1)
13	Feedwater film resistance	r'_{t3}		r'_{t2}		r'_{t1}	
	(hr-ft^2-°F)/Btu		0.000449		0.000450		0.000462
	[m^2-K]/W		(0.000079)		(0.000079)		(0.000081)

(continued)

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TABLE B.1 (CONT'D)
THREE-ZONE HEATER

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Design Data						
14	Feedwater fouling resistance	r'_{ft3}		r'_{ft2}		r'_{ft1}	
	(hr-ft²-°F)/Btu		0.000237		0.000237		0.000237
	[m²K]/W		(0.000042)		(0.000042)		(0.000042)
15	Tube material resistance	r'_{m3}		r'_{m2}		r'_{m1}	
	(hr-ft²-°F)/Btu		0.000278		0.000278		0.000278
	[m²-K]/W		(0.000049)		(0.000049)		(0.000049)
16	Shell side fouling resistance	r'_{fs3}		r'_{fs2}	0	r'_{fs1}	
	(hr-ft²-°F)/Btu		0.000300				0.000300
	[m²-K]/W		(0.000053)				(0.000053)
17	Shell side film resistance (r'_{s1} corrected for reheat by the manufacturer)	r'_{s3}		r'_{s2}		r'_{s1}	
	(hr-ft²-°F)/Btu		0.008333		0.000400		0.001388
	[m²-K]/W		(0.001468)		(0.000070)		(0.000244)
18	Terminal temperature difference	*TTD'*					
	°F(°C)		−3.9 (−2.2)				
19	Drain cooler approach °F(°C)	*DCA'*					10 (5.6)

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Test Data						
20	Actual feedwater flow rate	w		w		w	
	lbm/hr		621,000		621,000		621,000
	(kg/s)		(78)		(78)		(78)
21	Actual drains flow rate in			w_d			
	lbm/hr				25,000		
	(kg/s)				(3)		
22	Actual shell side temperature in	T_3					
	°F(°C)		700 (371)				
23	Actual shell side temperature out					T_1	
	°F(°C)						384.1 (195.6)

(continued)

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TABLE B.1 (CONT'D)
THREE-ZONE HEATER

Line No.	Term	Desuperheating Symbol	Desuperheating Value	Condensing Symbol	Condensing Value	Drain Cooling Symbol	Drain Cooling Value
	Test Data						
24	Actual drains temperature in °F(°C)			T_d	476.1 (246.7)		
25	Actual feedwater outlet temperature °F(°C)	t_4	448.6 (231.4)				
26	Actual feedwater inlet temperature °F(°C)					t_1	375.4 (190.8)
27	Actual shell side pressure loss psia (kPa)	ΔP_{ds}	1.1 (7.6)			ΔP_{dc}	1.5 (10.3)
28	Actual feedwater pressure loss psia (kPa)			Δp_t	3.5 (24.1)		
29	Actual steam inlet pressure psia (kPa)	P_3	396 (2730)				
30	Actual drains inlet pressure psia (kPa)			P_d	697.3 (4,807.7)		
31	Actual feedwater pressure in psia (kPa)					P_1	1,790 (12,342)

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NONMANDATORY APPENDIX C — UNCERTAINTY CONSIDERATIONS

C.1 SAMPLE CALCULATION OF TEST UNCERTAINTY

This Appendix contains a sample calculation of sensitivity coefficients, precision uncertainty and bias limits of the results, and combined uncertainty using the methods described in Subsection 5.3 and the typical test data used in Appendix B. For simplicity, the example assumes that the bias limits are symmetrical. In cases in which unsymmetrical bias limits are expected, the example calculations in para. C.3.3 would need to be done twice, once for the upper bias limit and once for the lower bias limit.

Table C.2 shows assumed precision and bias uncertainties that meet the criteria in Subsection 4.6 for each measured parameter. Subsection C.2 calculates the sensitivity of the results to uncertainties in the measured value of feedwater inlet temperature. Subsection C.3 describes the calculation of the effects of uncertainties for all the measured values.

C.2 SENSITIVITY OF THE RESULTS TO FEEDWATER INLET TEMPERATURE MEASUREMENT UNCERTAINTY

The calculations in Appendix B were done using a measured value of feedwater inlet temperature of 375.4°F. To determine the sensitivity of the results to variations in feedwater inlet temperature, those calculations are repeated twice using 376.4°F and 374.4°F for the measured feedwater inlet temperature. Table C.1 shows the results.

C.3 COMBINED UNCERTAINTY DUE TO ALL MEASUREMENTS

C.3.1 Sensitivity. In Subsection C.2 only feedwater inlet temperature was perturbed. By perturbing each of the measurements, it is possible to determine the sensitivity of each of the results to unit uncertainties (1% or 1.0°F) in the measured parameters. The sensitivity values calculated for the example in Appendix B appear in Tables C.2 through C.6.

C.3.2 Precision. Table C.2 shows that the standard deviation of the data sample of the feedwater inlet temperature is 0.30°F, the sensitivity of the *TTD* to the feedwater inlet temperature is 0.044 °F/°F, and 40 measurements were made. Therefore, the precision uncertainty of the difference between the predicted and measured *TTD* due to feedwater inlet temperature precision uncertainty is

$$(2)\ (0.30°F)\ (0.444°F/°F)/\sqrt{40} = 0.004174°F$$

$$(0.004174)^2 = 1.74E{-}05$$

The contributions of the other measured parameters are calculated in the same way. The total precision uncertainty of the difference between the predicted and measured *TTD* is calculated by taking the square root of the sum of the squares of the precision uncertainty of the result of each measured parameter. The value calculated, 0.0629°F, appears in Table C.2. The calculations for other results appear in Tables C.3 through C.6. Note that standard deviations must be calculated on the basis of actual test data, and that bias errors must be based on instruments and calibration of equipment used in the test.

C.3.3 Bias. Table C.2 shows that the bias limit of the feedwater inlet temperature is 0.231°F and the sensitivity of the *TTD* to the feedwater inlet temperature is 0.044°F/°F. Therefore, the bias limit of the difference between the predicted and measured *TTD* due to feedwater inlet temperature bias is

$$(0.231°F) \times (0.044°F/°F) = 0.01018°F$$

$$(0.01018)^2 = 1.04E{-}4$$

The contributions of the other measured parameters are calculated in the same way. The total bias

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TABLE C.1
SENSITIVITY OF THE RESULTS TO FEEDWATER INLET TEMPERATURE MEASUREMENT UNCERTAINTY

	$-\Delta$	Avg	$+\Delta$	Sensitivity
Measured feedwater inlet temperature	374.4	375.4	376.4	
Difference between calculated *TTD* and measured *TTD*	0.156	0.2	0.244	0.044
Difference between calculated *DCA* and measured *DCA*	−0.036	0.7	1.436	0.736
Difference between calculated *FW* Δp and measured *FW* Δp	0.47	0.47	0.47	0.0
Difference between calculated drain cooler Δp and measured drain cooler Δp	−0.008	0.02	0.048	0.028
Difference between calculated desuperheater Δp and measured desuperheater Δp	0.438	0.47	0.502	0.032

limit of the difference between the predicted and measured *TTD* is the square root of the sum of the squares of the bias limit of the result of each measured parameter. The value calculated, 0.339°F, also appears in Table C.2. The calculations for other results are in Tables C.3 through C.6.

C.3.4 Combination of Uncertainties. The total uncertainty of the difference between the predicted and measured *TTD* is calculated using the equation in para. 5.3.4 and the result, ±0.36°F appears in Table C.2. The calculations for other results are in Tables C.3 through C.6.

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TABLE C.2
UNCERTAINTY ANALYSIS FOR THE DIFFERENCE BETWEEN PREDICTED AND MEASURED *TTD*

Number of Measurements	**40**
Student *t*	**2**

Measured Parameter	Standard Deviation of Data Sample	Bias Limit	Sensitivity	Precision Uncertainty of Result	Bias Uncertainty of Result	Precision Uncertainty Squared	Bias Uncertainty Squared
FLOW RATES							
Feedwater	1.00%	0.949%	0.074°F/%	0.011700°F	0.07020°F	1.37E−04	4.93E−03
Drains	1.00%	0.949%	0.0022°F/%	0.000348°F	0.00209°F	1.21E−07	4.36E−06
PRESSURE							
Desuperheater *DP*	1.00%	0.949%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
Steam inlet	0.25%	0.237%	−0.996°F/%	−0.039370°F	−0.23622°F	1.55E−03	5.58E−02
Feedwater inlet	2.00%	1.897%	0.0009°F/%	0.000285°F	0.00171°F	8.10E−08	2.92E−06
Feedwater *DP*	1.00%	0.949%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
Drain cooler *DP*	1.00%	0.949%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
Drains inlet	2.00%	1.897%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
TEMPERATURE							
Steam inlet	1.00°F	0.949°F	−0.027°F/°F	−0.004269°F	−0.02561°F	1.82E−05	6.56E−04
Drains inlet	0.30°F	0.231°F	0.003°F/°F	0.000142°F	0.00069°F	2.02E−08	4.82E−07
Drain outlet	0.30°F	0.231°F	−0.008°F/°F	−0.000379°F	−0.00185°F	1.44E−07	3.42E−06
Feedwater inlet	0.30°F	0.231°F	0.044°F/°F	0.002087°F	0.01018°F	4.36E−06	1.04E−04
Feedwater outlet	0.30°F	0.231°F	1°F/°F	0.047434°F	0.23130°F	2.25E−03	5.35E−02
TOTAL PRECISION UNCERTAINTY OF THE RESULT				±0.063°F			
TOTAL BIAS UNCERTAINTY OF THE RESULT					±0.339°F		
TOTAL UNCERTAINTY OF THE RESULT			±0.36°F				

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TABLE C.3
UNCERTAINTY ANALYSIS FOR THE DIFFERENCE BETWEEN PREDICTED AND MEASURED *DCA*

Number of Measurements	**40**
Student *t*	**2**

Measured Parameter	Standard Deviation of Data Sample	Bias Limit	Sensitivity	Precision Uncertainty of Result	Bias Uncertainty of Result	Precision Uncertainty Squared	Bias Uncertainty Squared
FLOW RATES							
Feedwater	1.00%	0.949%	0.043°F/%	0.006799°F	0.04079°F	4.62E–05	1.66E–03
Drains	1.00%	0.949%	0.0422°F/%	0.006672°F	0.04003°F	4.45E–05	1.60E–03
PRESSURE							
Desuperheater *DP*	1.00%	0.949%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
Steam inlet	0.25%	0.237%	0.264°F/%	0.010436°F	0.06261°F	1.09E–04	3.92E–03
Feedwater inlet	2.00%	1.897%	–0.0016°F/%	–0.000506°F	–0.00304°F	2.56E–07	9.22E–06
Feedwater *DP*	1.00%	0.949%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
Drain cooler *DP*	1.00%	0.949%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
Drains inlet	2.00%	1.897%	0°F/%	0.000000°F	0.00000°F	0.00E+00	0.00E+00
TEMPERATURE							
Steam inlet	1.00°F	0.949°F	–0.001°F/°F	–0.000158°F	–0.00095°F	2.50E–08	9.00E–07
Drains inlet	0.30°F	0.231°F	–0.005°F/°F	–0.000237°F	0.00116°F	5.62E–08	1.34E–06
Drain outlet	0.30°F	0.231°F	–0.984°F/°F	–0.046675°F	–0.22760°F	2.18E–03	5.18E–02
Feedwater inlet	0.30°F	0.231°F	0.736°F/°F	0.034912°F	0.17024°F	1.22E–03	2.90E–02
Feedwater outlet	0.30°F	0.231°F	0°F/°F	0.000000°F	0.00000°F	0.00E+00	0.00E+00
TOTAL PRECISION UNCERTAINTY OF THE RESULT				±0.060°F			
TOTAL BIAS UNCERTAINTY OF THE RESULT					±0.297°F		
TOTAL UNCERTAINTY OF THE RESULT			±0.32°F				

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TABLE C.4
UNCERTAINTY ANALYSIS FOR THE DIFFERENCE BETWEEN PREDICTED AND MEASURED TUBESIDE PRESSURE LOSS

Number of Measurements	**40**
Student *t*	**2**

Measured Parameter	Standard Deviation of Data Sample	Bias Limit	Sensitivity	Precision Uncertainty of Result	Bias Uncertainty of Result	Precision Uncertainty Squared	Bias Uncertainty Squared
FLOW RATES							
Feedwater	1.00%	0.949%	−0.072 psi/%	−0.011384 psi	−0.06831 psi	1.30E−04	4.67E−03
Drains	1.00%	0.949%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
PRESSURE							
Desuperheater *DP*	1.00%	0.949%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Steam inlet	0.25%	0.237%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Feedwater inlet	2.00%	1.897%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Feedwater *DP*	1.00%	0.949%	0.101 psi/%	0.015970 psi	0.09582 psi	2.55E−04	9.18E−03
Drain cooler *DP*	1.00%	0.949%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drains inlet	2.00%	1.897%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
TEMPERATURE							
Steam inlet	1.00°F	0.949°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drains inlet	0.30°F	0.231°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drain outlet	0.30°F	0.231°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Feedwater inlet	0.30°F	0.231°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Feedwater outlet	0.30°F	0.231°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
TOTAL PRECISION UNCERTAINTY OF THE RESULT				±0.020 psi			
TOTAL BIAS UNCERTAINTY OF THE RESULT					±0.118 psi		
TOTAL UNCERTAINTY OF THE RESULT			±0.12 psi				

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TABLE C.5
UNCERTAINTY ANALYSIS FOR THE DIFFERENCE BETWEEN PREDICTED AND MEASURED DESUPERHEATER PRESSURE LOSS

Number of Measurements	**40**
Student *t*	**2**

Measured Parameter	Standard Deviation of Data Sample	Bias Limit	Sensitivity	Precision Uncertainty of Result	Bias Uncertainty of Result	Precision Uncertainty Squared	Bias Uncertainty Squared
FLOW RATES							
Feedwater	1.00%	0.949%	−0.022 psi/%	−0.003479 psi	−0.02087 psi	1.21E−05	4.36E−04
Drains	1.00%	0.949%	0.0014 psi/%	0.000221 psi	0.00133 psi	4.90E−08	1.76E−06
PRESSURE							
Desuperheater *DP*	1.00%	0.949%	0.011 psi/%	0.001739 psi	0.01044 psi	3.03E−06	1.09E−04
Steam inlet	0.25%	0.237%	−0.036 psi/%	−0.001423 psi	−0.00854 psi	2.03E−06	7.29E−05
Feedwater inlet	2.00%	1.897%	0.0004 psi/%	0.000126 psi	0.00076 psi	1.60E−08	5.76E−07
Feedwater *DP*	1.00%	0.949%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drain cooler *DP*	1.00%	0.949%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drains inlet	2.00%	1.897%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
TEMPERATURE							
Steam inlet	1.00°F	0.949°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drains inlet	0.30°F	0.231°F	0.001 psi/°F	0.000047 psi	0.00023 psi	2.25E−09	5.35E−08
Drain outlet	0.30°F	0.231°F	−0.004 psi/°F	−0.000190 psi	−0.00093 psi	3.60E−08	8.56E−07
Feedwater inlet	0.30°F	0.231°F	0.032 psi/°F	0.001518 psi	0.00740 psi	2.30E−06	5.48E−05
Feedwater outlet	0.30°F	0.231°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
TOTAL PRECISION UNCERTAINTY OF THE RESULT				±0.004 psi			
TOTAL BIAS UNCERTAINTY OF THE RESULT					±0.026 psi		
TOTAL UNCERTAINTY OF THE RESULT			±0.03 psi				

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TABLE C.6
UNCERTAINTY ANALYSIS FOR THE DIFFERENCE BETWEEN PREDICTED AND MEASURED DRAIN COOLER PRESSURE LOSS

Number of Measurements	**40**						
Student *t*	**2**						
Measured Parameter	**Standard Deviation of Data Sample**	**Bias Limit**	**Sensitivity**	**Precision Uncertainty of Result**	**Bias Uncertainty of Result**	**Precision Uncertainty Squared**	**Bias Uncertainty Squared**
FLOW RATES							
Feedwater	1.00%	0.949%	−0.017 psi/%	−0.002688 psi	−0.01613 psi	7.23E−06	2.60E−04
Drains	1.00%	0.949%	−0.0088 psi/%	−0.001391 psi	−0.00835 psi	1.94E−06	6.97E−05
PRESSURE							
Desuperheater *DP*	1.00%	0.949%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Steam inlet	0.25%	0.237%	−0.028 psi/%	−0.001107 psi	−0.00664 psi	1.23E−06	4.41E−05
Feedwater inlet	2.00%	1.897%	0.0003 psi/%	0.000095 psi	0.00057 psi	9.00E−09	3.24E−07
Feedwater *DP*	1.00%	0.949%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drain cooler *DP*	1.00%	0.949%	0.018 psi/%	0.002846 psi	0.01708 psi	8.10E−06	2.92E−04
Drains inlet	2.00%	1.897%	0 psi/%	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
TEMPERATURE							
Steam inlet	1.00°F	0.949°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
Drains inlet	0.30°F	0.231°F	0.001 psi/°F	0.000047 psi	0.00023 psi	2.25E−09	5.35E−08
Drain outlet	0.30°F	0.231°F	−0.004 psi/°F	−0.000190 psi	−0.00093 psi	3.60E−08	8.56E−07
Feedwater inlet	0.30°F	0.231°F	0.028 psi/°F	0.001328 psi	0.00648 psi	1.76E−06	4.19E−05
Feedwater outlet	0.30°F	0.231°F	0 psi/°F	0.000000 psi	0.00000 psi	0.00E+00	0.00E+00
TOTAL PRECISION UNCERTAINTY OF THE RESULT				±0.005 psi			
TOTAL BIAS UNCERTAINTY OF THE RESULT					±0.027 psi		
TOTAL UNCERTAINTY OF THE RESULT			±0.03 psi				

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NONMANDATORY APPENDIX D — PRINCIPAL QUANTITIES AND COMMONLY USED CONVERSION FACTORS IN HEAT TRANSFER (SI UNITS)

CONVERSION FACTORS

LENGTH

Multiply	By	To obtain
in.	$2.54^* \times 10^{1}$	mm
ft	$3.048^* \times 10^{-1}$	m

AREA

Multiply	By	To obtain
in^2	$6.451\ 600 \times 10^{-4}$	m^2
ft^2	$9.290\ 304 \times 10^{-2}$	m^2

VOLUME

Multiply	By	To obtain
ft^3	$2.831\ 685 \times 10^{-2}$	m^3

MASS

Multiply	By	To obtain
lbm	$4.535\ 924 \times 10^{-1}$	kg

TEMPERATURE

$$t_C = (t_F - 32)/1.8$$

POWER (ENERGY/TIME)

Multiply	By	To obtain
Btu/hr	$2.930\ 711 \times 10^{-1}$	W

PRESSURE

Multiply	By	To obtain
lbm/in^2 (psi)	$6.894\ 757 \times 10^{3}$	Pa
lbm/in^2 (psi)	$6.894\ 757$	kPa
lbm/in^2 (psi)	$7.030\ 696 \times 10^{-2}$	kgf/cm^2

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VELOCITY

Multiply	By	To obtain
ft/sec	$3.048^* \times 10^{-1}$	m/s

MASS FLOW RATE

Multiply	By	To obtain
lbm/hr	$1.259\ 979 \times 10^{-4}$	kg/s

DENSITY

Multiply	By	To obtain
lbm/ft^3	$1.601\ 846 \times 10^{1}$	kg/m^3

ENTHALPY

Multiply	By	To obtain
Btu/lbm	$2.326^* \times 10^{3}$	J/kg
Btu/lbm	2.326^*	kJ/kg

SPECIFIC HEAT

Multiply	By	To obtain
Btu/(lbm-°F)	$4.186\ 8^* \times 10^{3}$	J/(kg-K)
Btu/(lbm-°F)	$4.186\ 8^*$	kJ/(kg-K)

THERMAL CONDUCTIVITY

Multiply	By	To obtain
$(Btu-ft)/(hr-ft^2-°F)$	1.730 735	W/(m-K)

DYNAMIC VISCOSITY

Multiply	By	To obtain
lbm/(hr-ft)	$4.133\ 789 \times 10^{-4}$	Pa-s

HEAT TRANSFER COEFFICIENT

Multiply	By	To obtain
$Btu/(hr-ft^2-°F)$	5.678 263	$W/(m^2-K)$

FOULING RESISTANCE

Multiply	By	To obtain
$(hr-ft^2-°F)/Btu$	$1.761\ 102 \times 10^{-4}$	$(m^2-K)/W$

* Exact relationship in terms of the base unit.

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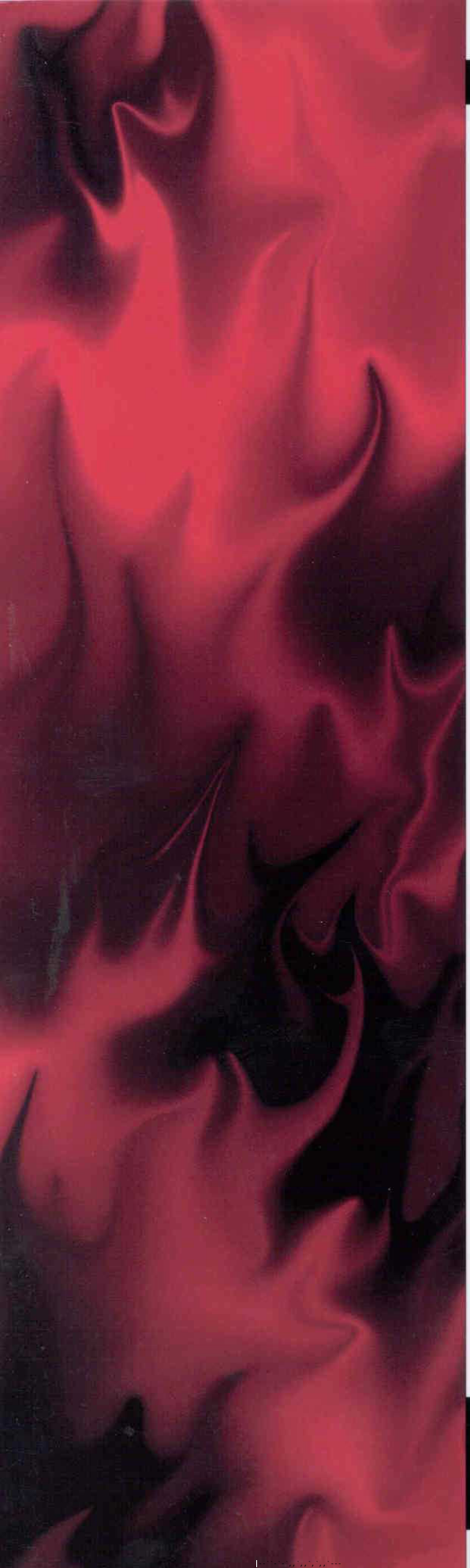
General Instructions ..... PTC 1-1999
Definitions and Values ..... PTC 2-1980(R1985)
Diesel and Burner Fuels ..... PTC 3.1-1958(R1992)
Coal and Coke ..... PTC 3.2-1990
Gaseous Fuels ..... PTC 3.3-1969(R1992)
Fired Steam Generators ..... PTC 4-1998
Steam-Generating Units (With 1968 and 1969 Addenda) ..... PTC 4.1-1964(R1991)
Diagram for Testing of a Steam Generator, Figure 1 (Pad of 100)
Heat Balance of a Steam Generator, Figure 2 (Pad of 100)
ASME Test Form for Abbreviated Efficiency Test — Summary Sheet (Pad of 100) ..... PTC 4.1a-1964
ASME Test for Abbreviated Efficiency Test — Calculation Sheet (Pad of 100) ..... PTC 4.1b-1964(R1965)
Coal Pulverizers ..... PTC 4.2-1969(R1997)
Air Heaters ..... PTC 4.3-1968(R1991)
Gas Turbine Heat Recovery Steam Generators ..... PTC 4.4-1981(R1992)
Reciprocating Steam Engines ..... PTC 5-1949
Performance Test Code 6 on Steam Turbines ..... PTC 6-1996
Interim Test Codes for an Alternative Procedure for Testing Steam Turbines ..... PTC 6.1-1984
Appendix A to Test Code for Steam Turbines ..... PTC 6A-1982(R1995)
PTC 6 on Steam Turbines — Interpretations ..... PTC 6
Guidance for Evaluation of Measurement Uncertainty in Performance Tests of Steam Turbines ..... PTC 6 Report-1985(R1997)
Procedures for Routine Performance Test of Steam Turbines ..... PTC 6S-1988(R1995)
Reciprocating Steam-Driven Displacement Pumps ..... PTC 7-1949(R 1969)
Displacement Pumps ..... PTC 7.1-1962(R1969)
Centrifugal Pumps ..... PTC 8.2-1990
Displacement Compressors, Vacuum Pumps and Blowers (With 1972 Errata) ..... PTC 9-1970(R1992)
Performance Test Code on Compressors and Exhausters ..... PTC 10-1997
Fans ..... PTC 11-1984(R1995)
Closed Feedwater Heaters ..... PTC 12.1-2000
Performance Test Code on Steam Surface Condensers ..... PTC 12.2-1998
Deaerators ..... PTC 12.3-1997
Moisture Separator Reheaters ..... PTC 12.4-1992(R1997)
Reciprocating Internal-Combustion Engines ..... PTC 17-1973(R1997)
Hydraulic Turbines ..... PTC 18-1992
Pumping Mode of Pump/Turbines ..... PTC 18.1-1978(R1984)
Test Uncertainty ..... PTC 19.1-1998
Pressure Measurement ..... PTC 19.2-1987
Temperature Measurement ..... PTC 19.3-1974(R1986)
Application, Part II of Fluid Meters: Interim Supplement on Instruments and Apparatus ..... PTC 19.5-1972
Weighing Scales ..... PTC 19.5.1-1964
Electrical Measurements ..... PTC 19.6-1955
Measurement of Shaft Power ..... PTC 19.7-1980(R1988)
Measurement of Indicated Power ..... PTC 19.8-1970(R1985)
Part 10 Flue and Exhaust Gas Analyses ..... PTC 19.10-1981
Steam and Water Sampling, Conditioning, and Analysis in the Power Cycle ..... PTC 19.11-1997
Measurement of Time ..... PTC 19.12-1958
Measurement of Rotary Speed ..... PTC 19.13-1961
Linear Measurements ..... PTC 19.14-1958
Density Determinations of Solids and Liquids ..... PTC 19.16-1965
Determination of the Viscocity of Liquids ..... PTC 19.17-1965
Digital Systems Techniques ..... PTC 19.22-1986
Part 23 Guidance Manual for Model Testing ..... PTC 19.23-1980(R1985)
Speed and Load Governing Systems for Steam Turbine-Generator Units ..... PTC 20.1-1977(R1988)
Overspeed Trip Systems for Steam Turbine-Generator Units ..... PTC 20.2-1965(R1986)
Pressure Control Systems Used on Steam Turbine Generator Units ..... PTC 20.3-1970(R1991)
Particulate Matter Collection Equipment ..... PTC 21-1991
Performance Test Code on Gas Turbines ..... PTC 22-1997
Atmospheric Water Cooling Equipment ..... PTC 23-1986(R1997)
Ejectors ..... PTC 24-1976(R1982)
Pressure Relief Devices ..... PTC 25-1994
Safety and Relief Valves ..... PTC 25.3-1988
Speed Governing Systems for Internal Combustion Engine Generator Units ..... PTC 26-1962
Determining the Properties of Fine Particulate Matter ..... PTC 28-1965(R1985)
Speed-Governing Systems for Hydraulic Turbine-Generator Units ..... PTC 29-1965(R1985)
Air Cooled Heat Exchangers ..... PTC 30-1991(R1998)
Ion Exchange Equipment ..... PTC 31-1972(R1991)
Nuclear Steam Supply Systems ..... PTC 32.1-1969(R1992)

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Appendix to PTC 33-1978 ..... PTC 33a-1980(R1991)
ASME Form for Abbreviated Incinerator Efficiency Test ..... Form PTC 33a-1980(R1991)
Measurement of Industrial Sound ..... PTC 36-1985
Determining the Concentration of Particulate Matter in a Gas Stream ..... PTC 38-1980(R1985)
Condensate Removal Devices for Steam Systems ..... PTC 39.1-1980(R1991)
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