NUREG/CR-1534
EPRI NP-1461
WCAP-9724

PWR FLECHT SEASET Steam Generator Separate Effects Task Data Analysis and Evaluation Report

NRC/EPRI/Westinghouse Report No. 9

Prepared by R. C. Howard, L. E. Hochreiter

Jointly Sponsored by
USNRC, EPRI, and Westinghouse

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Available from

GPO Sales Program
Division of Technical Information and Document Control
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Printed copy price: $12.50

and

National Technical Information Service
Springfield, Virginia 22161

FLECHT SEASET Program
NRC/EPRI/Westinghouse Report No. 9
NUREG/CR-1534
NP-1461
WCAP-9724

PWR FLECHT SEASET
STEAM GENERATOR SEPARATE EFFECTS TASK
DATA ANALYSIS AND EVALUATION REPORT

February 1982

R. C. Howard
L. E. Hochreiter

prepared for

United States Nuclear Regulatory Commission
Washington, DC 20555

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94303

and

Westinghouse Electric Corporation
Nuclear Energy Systems
P. O. Box 355
Pittsburgh, Pennsylvania 15230

by

Westinghouse Electric Corporation

under

Contract No. NRC-04-77-127, EPRI Project No. RP959-1

Program Management Group

NRC -- H. Sullivan
EPRI -- K. H Sun
Westinghouse -- D. G. Agate

NRC FIN B6204

LEGAL NOTICE

This report was prepared as an account of work sponsored by the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute, Inc., and the Westinghouse Electric Corporation. Neither the United States government nor any agency thereof, nor the Institute or members thereof, nor the Westinghouse Electric Corporation, nor any of their employes, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product, or process disclosed in this report or represents that its use by such third party would not infringe privately owned rights.

ABSTRACT

This report presents the evaluation of the data from the Steam Generator Separate Effects Task of the Full-Length Emergency Cooling Heat Transfer Separate Effects and Systems Effects Test Program (FLECHT SEASET). In this task a series of heat transfer tests were run on a model steam generator operating under simulated loss-of-coolant conditions. The model steam generator was made up of 32 full-length U-tubes instrumented with thermocouples to measure secondary fluid, tube wall, and primary steam temperatures. The separate effects tests measured steam generator bundle heat transfer with known boundary conditions to provide better understanding of the steam generator behavior in the systems effects tests. The test results are presented in NRC/EPRI/Westinghouse Report No. 4. This report describes the analysis of the data and an analytical model that adequately predicts the test data.

ACKNOWLEDGMENTS

The work of the following Westinghouse Nuclear Energy Systems contributors is hereby acknowledged:

NTD PROJECTS

L. Chajson

SAFEGUARDS DEVELOPMENT

R. P. Vijuk
M. A. Emery
D. P. Kitzmiller
K. M. Beatty
D. Dixon

The work of the following members of the Program Management Group and their consultants is hereby acknowledged:

EPRI	K. H. Sun
NRC-RSR	H. Sullivan A. L. M. Hon
NRC-NRR	M. W. Hodges
EG&G	G. E. Wilson
NUS	D. A. Prelewicz

TABLE OF CONTENTS

Section	Title	Page
1	SUMMARY	1-1
2	INTRODUCTION	2-1
	2-1. Task Objectives	2-1
	2-2. Phenomenological Description of Steam Generator Heat Transfer During Reflood	2-2
	2-3. Data Requirements	2-4
	2-4. Parameter Ranges and Reference Conditions	2-4
3	TEST FACILITY DESCRIPTION	3-1
	3-1. Description	3-1
	3-2. Facility Layout and Component Description	3-2
	3-3. Instrumentation Description	3-5
	3-4. Data Acquisition	3-16
	3-5. Facility Operation	3-17
4	RUN CONDITIONS AND TEST RESULTS	4-1
	4-1. Test Matrix and Run Conditions	4-1
	4-2. Data Reduction	4-9
	4-3. Summary of Test Results	4-24
5	DATA ANALYSIS	5-1
	5-1. Introduction	5-1
	5-2. Analysis of Reference Run	5-12
	5-3. Evaluation of Replicate Runs	5-55
	5-4. Single-Parameter Variations	5-61
	5-5. Mass Velocity Sensitivity	5-75
	5-6. Quality Sensitivity	5-85
	5-7. Primary System Pressure Sensitivity	5-97
	5-8. Secondary System Temperature Sensitivity	5-114
	5-9. Secondary Water Level Sensitivity	5-126
	5-10. Tubesheet Liquid-Phase Flow Distribution Effects	5-135

TABLE OF CONTENTS (cont)

Section	Title	Page
6	EVALUATION MODEL	6-1
	6-1. Steam Generator Evaluation Model Development	6-1
	6-2 Evaluation Model Based on Local Liquid Film Parameters	6-1
	6-3. Evaluation Model Based on Local Critical Heat Flux	6-2
	6-4. Evaluation Model Based on Axial Conduction Controlled Rewet	6-7
	6-5. Evaluation Model Based on an Empirical Quench Velocity Correlation	6-12
	6-6. Evaluation Model Droplet Entrainment and Evaporation	6-18
	6-7. Evaluation Model Comparison With Test Data	6-23
7	SUMMARY AND CONCLUSIONS	7-1
	7-1. Summary	7-1
	7-2. Conclusions	7-2
APPENDIX A	STEAM GENERATOR SEPARATE EFFECTS TEST EVALUATION COMPUTER PROGRAM	A-1

LIST OF ILLUSTRATIONS

Figure	Title	Page
2-1	Heat Transfer Processes in Steam Generator Experiment	2-5
3-1	Detailed Schematic Diagram of Separate Effects Test Loop	3-3
3-2	FLECHT SEASET Steam Generator Separate Effects Test Instrumentation Locations (2 sheets)	3-5
3-3	FLECHT Outlet Plenum Baffle	3-10
3-4	FLECHT SEASET Steam Generator Separate Effects Test Instrumentation Schematic Diagram	3-11
3-5	FLECHT SEASET Separate Effects Test Simplified Flow Diagram	3-25
4-1	Steam Generator Test Data Reduction Hardware	4-11
4-2	Steam Generator Test Data Reduction Software	4-13
4-3	Steam Generator Nodalization	4-14
4-4	Linear and Semilogarithmic Plot of SGTEMPS Data (Run 22010)	4-15
4-5	Method Used To Determine Length in the Grashof Number	4-18
4-6	Comparison of Nusselt Numbers Calculated by Equation (4-1) With Data	4-19
4-7	Heat Transfer and Quality Calculation for a Single Primary Tube	4-22
5-1	Accumulator Liquid Flow Rate Versus Time, Reference Run	5-13
5-2	Boiler Steam Flow Rate Versus Time, Reference Run	5-13
5-3	Containment Steam Flow Rate Versus Time, Reference Run	5-14
5-4	Outlet Plenum Differential Pressure Versus Time, Reference Run	5-14
5-5	Containment Tank Pressure Versus Time, Reference Run	5-15
5-6	Mixer Pressure Versus Time, Reference Run	5-15
5-7	Hot Leg Differential Pressure Versus Time, Reference Run	5-16
5-8	Inlet Plenum Differential Pressure Versus Time, Reference Run	5-16
5-9	Inlet Plenum Steam Probe Temperature Versus Time, Reference Run	5-17
5-10	Outlet Plenum Exit Vapor Temperature Versus Time, Reference Run	5-17

Figure	Title	Page
5-11	Superheater Power Versus Time, Reference Run	5-18
5-12	Superheater Exhaust Fluid Temperature Versus Time, Reference Run	5-18
5-13	Mass Balance Versus Time, Reference Run	5-19
5-14	Secondary to Primary Heat Flow Rate Versus Time, Reference Run	5-19
5-15	Inlet Plenum Quality Versus Time, Reference Run	5-20
5-16	Outlet Plenum Quality Versus Time, Reference Run	5-20
5-17	Nodal Temperatures, Reference Run, 0.30 m (1 ft) Elevation, Radial Position 1	5-21
5-18	Nodal Temperatures, Reference Run, 1.22 m (4 ft) Elevation, Radial Position 1	5-21
5-19	Nodal Temperatures, Reference Run, 3.0 m (10 ft) Elevation, Radial Position 1	5-22
5-20	Nodal Temperatures, Reference Run, 0.30 m (1 ft) Elevation, Radial Position 4	5-22
5-21	Nodal Temperatures, Reference Run, 1.22 m (4 ft) Elevation, Radial Position 4	5-23
5-22	Nodal Temperatures, Reference Run, 3.0 m (10 ft) Elevation, Radial Position 4	5-23
5-23	Nodal Temperatures, Reference Run, 21.0 m (69 ft) Elevation, Radial Position 1	5-24
5-24	Nodal Temperatures, Reference Run, 20.1 m (66 ft) Elevation, Radial Position 1	5-24
5-25	Nodal Temperatures, Reference Run, 18.3 m (60 ft) Elevation, Radial Position 1	5-25
5-26	Nodal Temperatures, Reference Run, 21.0 m (69 ft) Elevation, Radial Position 4	5-25
5-27	Nodal Temperatures, Reference Run, 20.1 m (66 ft) Elevation, Radial Position 4	5-26
5-28	Nodal Temperatures, Reference Run, 18.3 m (60 ft) Elevation, Radial Position 4	5-26
5-29	Fluid Temperature Versus Distance Above Inlet, Reference Run	5-27

Figure	Title	Page
5-30	Fluid Temperature Versus Distance Above Inlet, Reference Run (Semilogarithmic Plot)	5-27
5-31	Fluid Temperature Versus Distance Above Outlet, Reference Run (Semilogarithmic Plot)	5-28
5-32	Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 2	5-37
5-33	Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 2	5-38
5-34	Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 3	5-39
5-35	Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 4	5-40
5-36	Tube Wall Heat Flux, 0.30 m (1 ft) Elevation, Radial Position 1	5-41
5-37	Tube Wall Heat Flux, 0.30 m (1 ft) Elevation, Radial Position 2	5-42
5-38	Tube Wall Heat Flux, 0.30 m (1 ft) Elevation, Radial Position 4	5-43
5-39	Tube Wall Heat Flux, 1.22 m (4 ft) Elevation, Radial Position 1	5-44
5-40	Tube Wall Heat Flux, 1.22 m (4 ft) Elevation, Radial Position 2	5-45
5-41	Tube Wall Heat Flux, 1.22 m (4 ft) Elevation, Radial Position 3	5-46
5-42	Quench Elevation Versus Quench Time	5-49
5-43	Typical Tube Wall Heat Flux Versus Elevation Near Quench Elevation	5-51
5-44	Boiling Curve for Nodes With Maximum Heat Flux $\simeq$227 kw/m2 (20 Btu/sec-ft2)	5-53
5-45	Boiling Curve for Nodes With Maximum Heat Flux $\simeq$340 kw/m2 (30 Btu/sec-ft2)	5-54
5-46	Isometric Plot of Secondary Fluid Temperatures at 3.4 Minutes Into Transient, Reference Run	5-56

LIST OF ILLUSTRATIONS (cont)

Figure	Title	Page
5-47	Isometric Plot of Secondary Fluid Temperatures at 6.1 Minutes Into Transient, Reference Run	5-57
5-48	Isometric Plot of Secondary Fluid Temperatures at 12.1 Minutes Into Transient, Reference Run	5-58
5-49	Isometric Plot of Secondary Fluid Temperatures at 18.0 Minutes Into Transient, Reference Run	5-59
5-50	Nodal Temperatures, Replicate Run 21711, 0.30 m (1 ft) Elevation, Radial Position 1	5-60
5-51	Nodal Temperatures, Replicate Run 21711, 1.22 m (4 ft) Elevation, Radial Position 1	5-60
5-52	Nodal Temperatures, Replicate Run 21711, 3.05 m (10 ft) Elevation, Radial Position 1	5-61
5-53	Nodal Temperatures, Replicate Run 21711, 0.30 m (1 ft) Elevation, Radial Position 4	5-61
5-54	Nodal Temperatures, Replicate Run 21711, 1.22 m (4 ft) Elevation, Radial Position 4	5-62
5-55	Nodal Temperatures, Replicate Run 21711, 3.05 m (10 ft) Elevation, Radial Position 4	5-62
5-56	Nodal Temperatures, Replicate Run 21711, 21.0 m (69 ft) Elevation, Radial Position 1	5-63
5-57	Nodal Temperatures, Replicate Run 21711, 20.1 m (66 ft) Elevation, Radial Position 1	5-63
5-58	Nodal Temperatures, Replicate Run 21711, 18.3 m (60 ft) Elevation, Radial Position 1	5-64
5-59	Nodal Temperatures, Replicate Run 21711, 21.0 m (69 ft) Elevation, Radial Position 4	5-64
5-60	Nodal Temperatures, Replicate Run 21711, 20.1 m (66 ft) Elevation, Radial Position 4	5-65
5-61	Nodal Temperatures, Replicate Run 21711, 18.3 m (60 ft) Elevation, Radial Position 4	5-65
5-62	Nodal Temperatures, Replicate Run 22010, 0.30 m (1 ft) Elevation, Radial Position 1	5-66

Figure	Title	Page
5-63	Nodal Temperatures, Replicate Run 22010, 1.22 m (4 ft) Elevation, Radial Position 1	5-66
5-64	Nodal Temperatures, Replicate Run 22010, 3.05 m (10 ft) Elevation, Radial Position 1	5-67
5-65	Nodal Temperatures, Replicate Run 22010, 0.30 m (1 ft) Elevation, Radial Position 4	5-67
5-66	Nodal Temperatures, Replicate Run 22010, 1.22 m (4 ft) Elevation, Radial Position 4	5-68
5-67	Nodal Temperatures, Replicate Run 22010, 3.05 m (10 ft) Elevation, Radial Position 4	5-68
5-68	Nodal Temperatures, Replicate Run 22010, 21.0 m (69 ft) Elevation, Radial Position 1	5-69
5-69	Nodal Temperatures, Replicate Run 22010, 20.1 m (66 ft) Elevation, Radial Position 1	5-69
5-70	Nodal Temperatures, Replicate Run 22010, 18.3 m (60 ft) Elevation, Radial Position 1	5-70
5-71	Nodal Temperatures, Replicate Run 22010, 21.0 m (69 ft) Elevation, Radial Position 4	5-70
5-72	Nodal Temperatures, Replicate Run 22010, 20.1 m (66 ft) Elevation, Radial Position 4	5-71
5-73	Nodal Temperatures, Replicate Run 22010, 18.3 m (60 ft) Elevation, Radial Position 4	5-71
5-74	1.22 m (4 ft) Quench Time Parameter Sensitivity	5-74
5-75	Fluid Temperatures, Reference and Flow Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-76
5-76	Tube Wall Temperatures, Reference and Flow Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-77
5-77	Tube Wall Heat Flux, Reference and Flow Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 1	5-78
5-78	Tube Wall Heat Flux, Reference and Flow Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 4	5-79
5-79	Fluid Temperatures, Reference and Flow Sensitivity Runs, End of Test, Radial Position 1	5-80

LIST OF ILLUSTRATIONS (cont)

Figure	Title	Page
5-80	Liquid Collected, Reference and Flow Sensitivity Runs	5-81
5-81	Heat Flow Rate, Reference and Flow Sensitivity Runs	5-82
5-82	Tube Bundle Pressure Drop, Reference and Flow Sensitivity Runs	5-83
5-83	Steam Temperatures, Reference and Flow Sensitivity Runs, End of Test, Radial Position 1	5-86
5-84	Fluid Temperatures, Reference and Quality Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-87
5-85	Tube Wall Temperatures, Reference and Quality Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-88
5-86	Local Heat Flux, Reference and Quality Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-91
5-87	Fluid Temperatures, Reference and Quality Sensitivity Runs, End of Test, Radial Position 1	5-92
5-88	Steam Temperatures, Reference and Quality Sensitivity Runs, End of Test, Radial Position 1	5-93
5-89	Overall Heat Transfer, Reference and Quality Sensitivity Runs	5-95
5-90	Overall Bundle Pressure Drop, Reference and Quality Sensitivity Runs	5-96
5-91	Fluid Temperatures, Reference and Pressure Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-98
5-92	Tube Wall Temperatures, Reference and Pressure Sensitivity Runs 1.22 m (4 ft) Elevation, Radial Position 1	5-99
5-93	Quench Front Velocity Versus Biot Number and Interface Temperature	5-102
5-94	Tube Wall Heat Flux, Reference and Pressure Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-103
5-95	Tube Wall Heat Flux, Run 20904, 0.41 MPa (60 psia), 1.22 m (4 ft) Elevation, Radial Position 2	5-107
5-96	Fluid Temperatures, Reference and Pressure Sensitivity Runs, End of Test, Radial Position 1	5-108

LIST OF ILLUSTRATIONS (cont)

Figure	Title	Page
5-97	Steam Temperatures, Reference and Pressure Sensitivity Runs, End of Test, Radial Position 1	5-109
5-98	Outlet Plenum Liquid Collection, Reference and Pressure Sensitivity Runs	5-110
5-99	Overall Bundle Pressure Drop, Reference and Pressure Sensitivity Runs	5-112
5-100	Overall Bundle Heat Transfer, Reference and Pressure Sensitivity Runs	5-113
5-101	Fluid Temperatures, Reference and Secondary Temperature Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-115
5-102	Tube Wall Temperatures, Reference and Secondary Temperature Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-116
5-103	Tube Wall Heat Flux, Reference and Secondary Temperature Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 1	5-118
5-104	Tube Wall Heat Flux, Reference and Secondary Temperature Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 4	5-119
5-105	Tube Wall Heat Flux, Reference and Secondary Temperature Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-120
5-106	Fluid Temperatures, Reference and Secondary Temperature Sensitivity Runs, End of Test, Radial Position 1	5-121
5-107	Steam Temperatures, Reference and Secondary Temperature Sensitivity Runs, End of Test, Radial Position 1	5-122
5-108	Outlet Plenum Liquid Collection, Reference, Replicate, and Secondary Temperature Sensitivity Runs	5-123
5-109	Overall Bundle Pressure Drop, Reference and Secondary Temperature Sensitivity Runs	5-124
5-110	Overall Bundle Heat Transfer, Reference and Secondary Temperature Sensitivity Runs	5-125

Figure	Title	Page
5-111	Tube Wall Temperatures, Reference and Secondary Level Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-128
5-112	Fluid Temperatures, Reference and Secondary Level Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-129
5-113	Tube Wall Heat Flux, Reference and Secondary Level Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 1	5-130
5-114	Local Heat Flux, Reference and Secondary Level Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 4	5-131
5-115	Tube Wall Heat Flux, Reference and Secondary Level Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1	5-132
5-116	Fluid Temperatures, Reference and Secondary Level Sensitivity Runs, End of Test, Radial Position 1	5-133
5-117	Steam Temperatures, Reference and Secondary Level Sensitivity Runs, End of Test, Radial Position 1	5-134
5-118	Outlet Plenum Liquid Collection, Reference, Replicate, and Secondary Level Sensitivity Runs	5-136
5-119	Overall Bundle Heat Transfer, Reference and Secondary Level Sensitivity Runs	5-137
5-120	Overall Bundle Pressure Drop, Reference and Secondary Level Sensitivity Runs	5-138
5-121	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22112, 0.30 m (1 ft) Elevation, Radial Position 1	5-141
5-122	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22112, 0.30 m (1 ft) Elevation, Radial Position 4	5-142
5-123	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22112, 1.22 m (4 ft) Elevation, Radial Position 1	5-143
5-124	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22213, 0.30 m (1 ft) Elevation, Radial Position 1	5-144
5-125	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22213, 0.30 m (1 ft) Elevation, Radial Position 4	5-145
5-126	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22213, 1.22 m (4 ft) Elevation, Radial Position 1	5-146

Figure	Title	Page
5-127	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22314, 0.30 m (1 ft) Elevation, Radial Position 1	5-148
5-128	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22314, 0.30 m (1 ft) Elevation, Radial Position 4	5-149
5-129	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22314, 1.22 m (4 ft) Elevation, Radial Position 1	5-150
5-130	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22415, 0.30 m (1 ft) Elevation, Radial Position 1	5-151
5-131	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22415, 0.30 m (1 ft) Elevation, Radial Position 4	5-152
5-132	Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22415, 1.22 m (4 ft) Elevation, Radial Position 1	5-153
6-1	Quench Elevation Versus Quench Time, Reference Case, Measured and Preliminary Calculations	6-4
6-2	Axial Temperature Distribution, Reference Run, 1.22 m (4 ft) Elevation	6-9
6-3	Quench Velocity Versus Interface Temperature, Reference Run	6-11
6-4	Quench Velocity Calculated From Axial Conduction Model With Differential Temperature = 5.5°C (10°F)	6-13
6-5	Reference Run Prediction Versus Data, Outlet Plenum Steam Temperature	6-25
6-6	Reference Run Prediction Versus Data, Outlet Plenum Liquid Flow Rate	6-26
6-7	Reference Run Prediction Versus Data, Total Energy Transfer	6-27
6-8	Reference Run Prediction Versus Data, Quench Elevation (Empirical Correlation)	6-28
6-9	Reference Run Prediction Versus Data, Primary Steam and Secondary Fluid Temperatures, t = 300 sec	6-29
6-10	Reference Run Prediction Versus Data, Primary Steam and Secondary Fluid Temperatures, t = 600 sec	6-30
6-11	Reference Run Prediction Versus Data, Primary Steam and Secondary Fluid Temperatures, t = 900 sec	6-31

LIST OF ILLUSTRATIONS (cont)

Figure	Title	Page
6-12	Reference Run Prediction Versus Data, Inlet Region Local Temperature	6-33
6-13	Reference Run Prediction Versus Data, Outlet Region Local Temperature	6-34
6-14	Reference Run Prediction Versus Data, Tube Wall Heat Flux, 1.22 m (4 ft) Elevation	6-35
6-15	Flow Sensitivity Run Prediction Versus Data, Outlet Plenum Steam Temperature	6-36
6-16	Pressure Sensitivity Run [0.14 MPa (20 psia)] Prediction Versus Data, Outlet Plenum Steam Temperature	6-37
6-17	Pressure Sensitivity Run [0.41 MPa (60 psia)] Prediction Versus Data, Outlet Plenum Steam Temperature	6-38
6-18	Quality Sensitivity Run (x=0.5) Prediction Versus Data, Outlet Plenum Steam Temperature	6-39
6-19	Quality Sensitivity Run (x=0.2) Prediction Versus Data, Outlet Plenum Steam Temperature	6-40
6-20	Secondary Temperature Sensitivity Run [204°C (400°F)] Prediction Versus Data, Outlet Plenum Steam Temperature	6-41
6-21	Postbundle Quench Run [x=0.10, Flow Rate = 0.45 kg/sec (1.0 lb/sec)] Prediction Versus Data, Outlet Plenum Steam Temperature	6-42
6-22	Flow Sensitivity Run Prediction Versus Data, Outlet Plenum Liquid Flow	6-43
6-23	Pressure Sensitivity Run [0.14 MPa (20 psia)] Prediction Versus Data, Outlet Plenum Liquid Flow	6-44
6-24	Pressure Sensitivity Run [0.41 MPa (60 psia)] Prediction Versus Data, Outlet Plenum Liquid Flow	6-45
6-25	Quality Sensitivity Run (x=0.5) Prediction Versus Data, Outlet Plenum Liquid Flow	6-46
6-26	Quality Sensitivity Run (x=0.2) Prediction Versus Data, Outlet Plenum Liquid Flow	6-47
6-27	Secondary Temperature Sensitivity Run [204°C (400°F)] Prediction Versus Data, Outlet Plenum Liquid Flow	6-48

Figure	Title	Page
6-28	Postbundle Quench Run [x=0.10, Flow Rate = 0.45 kg/sec (1.0 lb/sec)] Prediction Versus Data, Outlet Plenum Liquid Flow	6-49
6-29	Flow Sensitivity Run Prediction Versus Data, Axial Temperature Variation of Secondary Fluid	6-50
6-30	Pressure Sensitivity Run [0.14 MPa (20 psia)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid	6-51
6-31	Pressure Sensitivity Run [0.41 MPa (60 psia)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid	6-52
6-32	Quality Sensitivity Run (x=0.5) Prediction Versus Data, Axial Temperature Variation of Secondary Fluid	6-53
6-33	Quality Sensitivity Run (x=0.2) Prediction Versus Data, Axial Temperature Variation of Secondary Fluid	6-54
6-34	Secondary Temperature Sensitivity Run [204°C (400°F)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid	6-55
6-35	Postbundle Quench Run [x=0.10, Flow Rate = 0.45 kg/sec (1.0 lb/sec)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid	6-56

LIST OF TABLES

Table	Title	Page
2-1	Basic Data Obtained in the Steam Generator Separate Effects Task To Meet Data Requirements	2-6
2-2	Parameter Ranges and Reference Conditions	2-8
3-1	Axial Distribution of Tube Wall and Fluid Thermocouples and Steam Probes	3-13
3-2	Steam Generator Separate Effects Test Channel List	3-18
3-3	Steam Generator Separate Effects Test Continuous Strip Chart Channel List	3-23
4-1	Test Matrix for Steam Generator Separate Effects Test	4-2
4-2	Run Conditions and Test Results	4-5
5-1	Reference Run Summary Sheet	5-2
5-2	Summary Sheet for Replicate of Reference Run (Run 21711)	5-4
5-3	Summary Sheet for Replicate of Reference Run (Run 22010)	5-6
5-4	Summary Sheet for Quality Sensitivity Run (Run 23606)	5-8
5-5	Summary Sheet for Quality Sensitivity Run (Run 21806)	5-10
5-6	Steam Generator Separate Effects Test Reference Run Data	5-33
5-7	Quench Time Versus Quality for 0.30, 1.22, and 3.05 m (1, 4, and 10 ft) Elevations	5-89
5-8	Critical Heat Flux Local Parameters	5-104
5-9	Tubesheet Liquid-Phase Flow Distribution Effects	5-140
6-1	Steam Generator Model Heat Transfer Coefficients	6-5
6-2	Implicit Calculation of Quench Time, 1.22 m (4 ft) Elevation	6-14
6-3	Empirical Calculation of Quench Time, 1.22 m (4 ft) Elevation	6-16
6-4	Secondary Fluid Temperature at 1.22 m (4 ft) Elevation at 1.22 m (4 ft) Quench Time	6-17
6-5	Drop Size Distribution	6-19

SECTION 1
SUMMARY

As part of the NRC/EPRI/Westinghouse FLECHT SEASET reflood and natural circulation test program, a series of separate effects tests were conducted on a model U-tube steam generator.[1] The purpose of these tests was to measure and to characterize the steam generator secondary side to primary side heat release under postulated inlet fluid conditions for a calculated hypothetical pressurized water reactor loss-of-coolant accident. The test results are presented in NRC/EPRI/Westinghouse Report No.4.[2] This document presents the evaluation of the test results.

In this test program, a special heat transfer facility was constructed such that the steam generator primary side inlet two-phase flow conditions could be varied in a parametric fashion. Sufficient instrumentation was placed in the steam generator and flow loop that heat transfer rates within the steam generator tube bundle could be calculated from the resulting data. The results of these tests were used to develop a model which describes the FLECHT SEASET steam generator heat release characteristics.

The steam generator heat transfer model uses two regimes to represent the primary side heat transfer. Below the wet/dry interface, the model uses a two-phase forced convection film coefficient; above the interface, a single-phase steam forced convection film coefficient is used. The wet/dry interface is assumed to move with a constant velocity. An empirical correlation was developed from the data to determine the velocity of the wet/dry interface. Residual liquid at the wet/dry interface is assumed to be atomized and entrained in the steam. Droplet evaporation to the steam phase is modeled.

Model predictions were compared with test data to demonstrate the model's ability to accurately predict steam generator heat transfer in a LOCA environment.

1. The model steam generator consists of 32 full-length U-tubes arranged in a circular bundle. The bundle diameter is 31.8 cm (12.3 in.) and the tube pitch is approximately 2.5 cm (1 in.).

SECTION 2
INTRODUCTION

2-1. TASK OBJECTIVES

The separate effects test described in the FLECHT SEASET Unblocked Bundle Task Plan Report[1] concentrated on the rod bundle heat transfer and thermal-hydraulic behavior. The systems effects tests focus on the entire simulated thermal-hydraulic response of a pressurized water reactor primary system during reflood. However, the bundle inlet flooding rate in systems effects tests is dependent on the transient hydraulic and heat transfer behavior of the whole loop, which includes the bundle and different system components.

Therefore, to understand the performance of the simulated primary system, the thermal-hydraulic behavior of the principal components of the system must be defined. The objective of the steam generator separate effects task is to determine the heat transfer characteristics from the larger steam generator for various known inlet fluid conditions and secondary side conditions.[2] To meet this objective, separate experiments on the main components of the simulated primary system, notably the steam generator, are being performed before the integral systems tests. In this way, the thermal-hydraulic behavior of these important components will be better understood.

The FLECHT SET Phase B tests indicated that, during the reflood portion of a postulated loss-of-coolant accident (LOCA), not all the incoming entrained liquid flow would be vaporized in the steam generators, and that droplets could be carried out of the generator into the cold leg.[1] Carrying entrained liquid through the steam generators reduces the specific volume of the primary fluid. As the specific volume decreases, its density increases correspondingly, and a larger mass flow can be vented through the loops at the same loop pressure drop. Hence, the venting capacity of the

1. Hochreiter, L. E., et al., "PWR FLECHT SEASET Unblocked Bundle, Forced and Gravity Reflood Task: Task Plan Report," NRC/EPRI/Westinghouse-3, March 1978.

2. Previous FLECHT SET Phase B tests utilized two scaled steam generators. The larger one represented three PWR reactor steam generators on the unbroken loops during a postulated loss-of-coolant accident, and the smaller one represented the steam generator in the remaining broken loop.

primary system is increased, and steam binding effects are less severe. The increased venting capacity could result in larger core flooding rates and correspondingly increased core heat transfer and lower peak cladding temperatures.

To model steam generator behavior during reflood, detailed knowledge of how the steam generator releases its heat, where the heat is transferred, and how the secondary side fluid behaves during the reflood transient must be known. Because the steam generator and the primary system interact, the easiest way to examine the steam generator behavior is to isolate it and perform separate component tests. This is the approach used in this experiment. Known inlet two-phase flows were injected into the generator; the resulting two-phase mixture leaving the steam generator was separated, collected, and measured. This permitted a primary fluid energy balance which can be related to the secondary side energy release.

A number of secondary fluid thermocouples, tube wall thermocouples, and shell wall thermocouples were installed in the steam generator such that a secondary side heat release rate could be calculated. Selected tubes were instrumented with primary side steam probes and differential pressure transducers (probes) to measure superheat of steam and liquid accumulation in the entrance region of the tubes. The steam probe data allow an evaluation of thermodynamic nonequilibrium in the tubes, and the pressure drop transducers allow an evaluation of the mass storage in the entrance region of selected tubes.

Prior to the steam generator separate effects tests, a series of tests were run on the inlet plenum using air and water to simulate the two-phase steam mixture. The objective of these tests was to investigate the effect of the inlet plenum geometry on the flow distribution at the entrance to the steam generator tube bundle.

Two steam generator inlet plenum geometries were tested: one of the plenums duplicated the model steam generator inlet plenum, and the other plenum resembled the hemispherical shape of a plenum in a typical PWR with inverted U-tube steam generators.

2-2. PHENOMENOLOGICAL DESCRIPTION OF STEAM GENERATOR HEAT TRANSFER DURING REFLOOD

During the reflood portion of a postulated loss-of-coolant accident, the core generates a two-phase mixture as it refloods and quenches. The two-phase mixture is swept into the

reactor upper plenum and travels down the hot leg into the steam generator inlet plenum. The steam generators, which have been isolated because of the postulated accident, are dry on the primary side, and the secondary side collapsed level covers the tubes. The tube wall temperature is at the secondary side temperature, typically 277°C (532°F), as reflood begins. As the two-phase mixture enters the steam generator tubes, film boiling occurs on the tube walls until the tube walls and adjacent secondary fluid are cooled sufficiently that intermittent liquid contact occurs and the tube is eventually quenched. The heat transfer process on the secondary side is natural convection heating of the cooler primary fluid. The density gradients direct the cooler and more dense secondary fluid to flow downward along the tubes toward the steam generator tubesheet. The cooler secondary fluid then forms a cooler layer at approximately the saturation temperature of the primary side two-phase mixture. This cooler layer flows across the tubesheet, covering both the inlet and outlet tubes.

The quench front inside the primary tubes is the heat transfer boundary between a dry wall tube (above the wetting temperature) and a quenched tube. Below the quench front, the liquid film on the tube keeps the tube wall in nucleate boiling or forced convection at the saturation temperature of the primary side. Above the quench front, film boiling occurs in the primary tube and the heat transfer is from the superheated tube wall to the vapor (which then becomes superheated) to the entrained liquid droplets. Therefore, the dispersed two-phase flow above the quench front is in thermal nonequilibrium, since the vapor phase is superheated relative to the satura- tion temperature at the primary side pressure. The dispersed two-phase flow above the quench front provides sufficient film boiling heat transfer and precursory cooling that the quench front advances up the tube with time. The quench front advance is believed to be due to both precursory cooling and axial conduction effects which lower the local tube wall temperature.

At the exit of the U-tube, the nonequilibrium two-phase mixture in the tubes is now cooled by the cooler layer of secondary side fluid. The vapor in the primary tube desuperheats as it transfers heat to the cooler secondary fluid, such that the steam generator primary side exit temperature is less than the original secondary side temperature but higher than the primary side saturation temperature. As the steam generator cools down, the primary side exit temperature becomes closer to the saturation temperature of the primary side.

The heat transfer pattern for these tests is quite complex, as described above. The various test parameters resulted in the same overall heat transfer mechanisms. However, the time scale for the tube rewetting would change; that is, higher primary side flows, lower quality, or higher pressures would cause faster tube wall rewetting. The heat transfer processes are shown in figure 2-1.

2-3. DATA REQUIREMENTS

The task data requirements were developed in the steam generator separate effects test task plan.[1] The basic thermal-hydraulic parameters measured to meet the data requirements are summarized in table 2-1.

A series of bench tests were performed to aid in the design, selection, and placement of the steam generator instrumentation. Separate tests were performed to examine tube wall thermocouple mounting, ability to measure pressure drop in a two-phase flow using static probes with a continuous nitrogen purge flow, and the two-phase flow inlet distribution at the steam generator tubesheet. These tests were described in section 6 and appendix C of the task plan.[1] The results of these bench tests are presented in appendixes A and B of NRC/EPRI/Westinghouse Report No. 4.[2]

2-4. PARAMETER RANGES AND REFERENCE CONDITIONS

Parameter ranges and reference conditions for the steam generator separate effects test were developed in section 4 of the Steam Generator Separate Effects Test Task Plan.[1] The parameter ranges and reference conditions are listed in table 2-2. It should be noted that all units in table 2-2 and throughout this report are given in metric units, followed by English units in parentheses.

1. Hochreiter, L. E., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task: Task Plan Report," NRC/EPRI/Westinghouse-2, March 1978.
2. Howard, R. C., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task Data Report," NRC/EPRI/Westinghouse-4, January 1980.

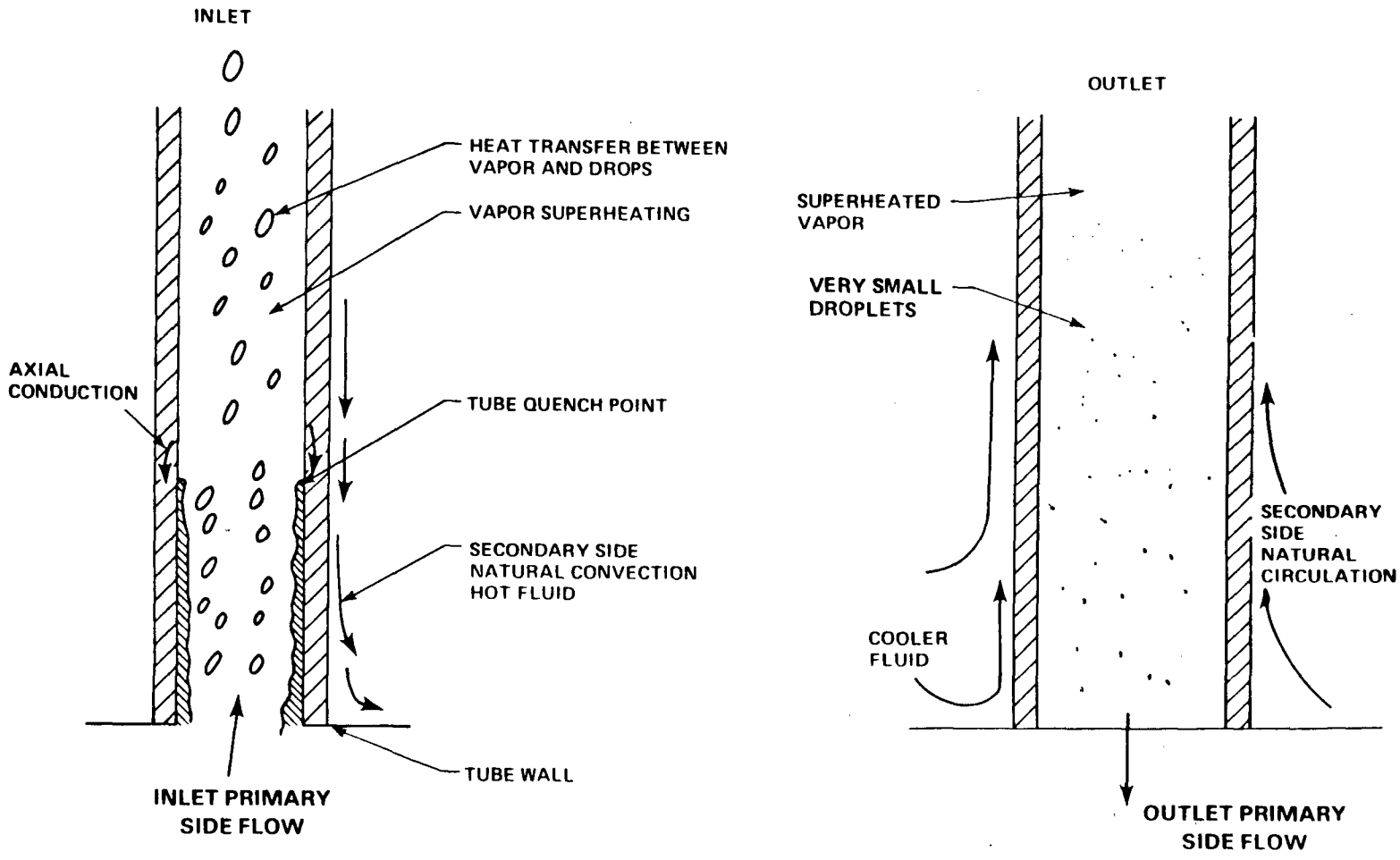


Figure 2-1. Heat Transfer Processes in Steam Generator Experiment

16817-86

TABLE 2-1

BASIC DATA OBTAINED IN THE STEAM GENERATOR SEPARATE EFFECTS TASK TO MEET DATA REQUIREMENTS

Desired Data	Measuring Device	Location
Steam generator secondary fluid temperatures	Fluid thermocouples	Various radial locations at several different levels on the secondary side of the steam generator
Steam generator tube wall temperatures	Wall thermocouples	Various locations on the steam generator tube walls
Steam generator primary side vapor temperatures	Steam probes (aspirating)	Within the steam generator tubes and inlet plenum
Water flow rate	Turbine meter	Mixer inlet line
Steam flow rate	Vortex meters	Mixer inlet line, steam separator outlet line
System pressure	Pressure transducers and transmitters	Steam generator secondary side, containment tank, and loop piping
Primary loop fluid temperatures	Thermocouples/ RTDs[a]	In loop piping
Pipe wall temperatures	Thermocouples	On piping, steam generator shell, plenum, and tanks

a. RTD - resistance temperature detector

TABLE 2-1 (cont)

BASIC DATA OBTAINED IN THE STEAM GENERATOR SEPARATE EFFECTS TASK TO MEET DATA REQUIREMENTS

Desired Data	Measuring Device	Location
System pressure drops	Differential pressure transducers and transmitters	Hot leg and inlet plenum, steam generator inlet tube, inlet to outlet plenum
Separator exit water mass rate	Differential pressure transducers	Steam separator collection tanks
Mass storage	Differential pressure transducer	Inlet plenum, water storage tanks
Secondary side fluid level	Differential pressure transducer	Secondary side of steam generator
Flow regimes	Photography	Steam generator inlet and outlet plenums

TABLE 2-2

PARAMETER RANGES AND REFERENCE CONDITIONS

Parameter	Reference Condition	Range
Primary side pressure	0.275 MPa[a] (40 psia)	0.138 to 0.414 MPa (20 to 60 psia)
Secondary side pressure	5.86 MPa (850 psia)	1.72 to 5.86 MPa (250 to 850 psia)
Primary side temperature	130.5°C (267°F)	109°C to 145°C (228°F to 293°F)
Secondary side temperature	274°F (525°F)	204°C to 274°C (400°F to 525°F)
Primary side mass velocity[b]	64.9 kg/sec/m^2 (13.3 lb/sec/ft^2)	64.9 to 129.9 kg/sec/m^2 (13.3 to 26.6 lb/sec/ft^2)
Inlet quality	0.80	0.10 to 1.0
Secondary side water level	100%	25% to 100%

a. Megapascals

b. Total steam plus water mass flow divided by hot leg flow area of 0.0035 m^2 (0.0375 ft^2)

SECTION 3
TEST FACILITY DESCRIPTION

3-1. DESCRIPTION

Figure 3-1 is a detailed schematic diagram of the separate effects test loop. The major components in the loop are the boiler, water supply tank, steam/water mixer, steam generator, steam separator, and containment tank. The boiler and water supply tank supply steam and water to a mixing chamber, which generates a two-phase flow in the hot leg upstream of the steam generator. The test facility is designed to supply the steam generator with a steady-state two-phase mixture. The test loop and steam generator response are essentially steady-state except for the secondary water, which cools down slowly. Steam separators in the steam generator discharge flow path separate the two-phase effluent from the steam generator tube bundle to allow each component of the two-phase flow to be measured. A bypass line around the steam generator was provided to permit monitoring of the mixer effluent during shakedown testing, using the instrumentation downstream of the steam generator. An auxiliary steam line from the boiler to the hot leg was also provided to permit use of the boiler for loop heatup. A vent line off the bypass line allowed the two-phase mixture to be dumped to the atmosphere while test parameters were being stabilized prior to running a test.

The steam/water mixer consists of a liquid spray nozzle located inside the hot leg. The two-phase flow in the steam generator hot leg and lower plenum is generated by spraying saturated liquid into the steam. An alternate liquid injection point was provided inside the steam generator inlet plenum in four of the matrix tests. Here a spray nozzle was used to direct the liquid flow at the tubesheet. The same spray nozzle arrangement was utilized as in the air-water bench tests described in appendix B of NRC/EPRI/Westinghouse Report No. 4.[1]

1. Howard, R. C., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task Data Report," NRC/EPRI/Westinghouse-4, January 1980.

The model steam generator outlet plenum was modified by the addition of an integral steam separator in the plenum to minimize time delays and energy losses between the tube bundle exit and the liquid collection site. For most tests, the outlet plenum was used to collect the separated liquid. For tests where significant carryover was anticipated, the larger steam generator collection tank was utilized. Data were collected for a period of 31 minutes -- 1 minute of pretest data, 25 minutes of test data, and 5 minutes of posttest data.

3-2. FACILITY LAYOUT AND COMPONENT DESCRIPTION

The loop shown schematically in figure 3-1 was built using as many of the FLECHT SET test series loop components as possible. This included the steam generator, containment tank, and some connecting piping. The detailed piping layout drawings for the test loop are shown in appendix C of NRC/EPRI/Westinghouse Report No. 4.

The major loop components procured for this test included a water supply tank, a boiler for supplying steam, a close-coupled water collection tank at the steam generator outlet plenum, a steam separator and collection tank, and the necessary loop valves and piping. Facility components are described in detail in NRC/EPRI/Westinghouse Report No. 4.

The steam generator used during the separate effects task was the large steam generator simulator used in a previous FLECHT test program.[1] Certain modifications were made to the generator for the separate effects task. All but one of the stub tubes previously plugged for the previous FLECHT test series were opened. A total of 32 of 33 tubes were needed to preserve, as closely as possible, the flow area scaling relationship, because of the increased heater rod bundle flow area in the FLECHT SEASET systems effects test. The tube chosen for plugging was the tube in column A of figure 3-2; this tube would be most strongly affected by edge effects of the shell on the steam generator secondary side and edge effects of the inlet plenum on the primary side.

An instrumentation ring with multiple radial penetrations was added between the tubesheet flange and the lower plenum flange to bring out primary side instrumentation.

1. Waring, J. P., and Hochreiter, L. E., "PWR FLECHT SEASET Phase B1 Evaluation Report," WCAP-8583, August 1975.

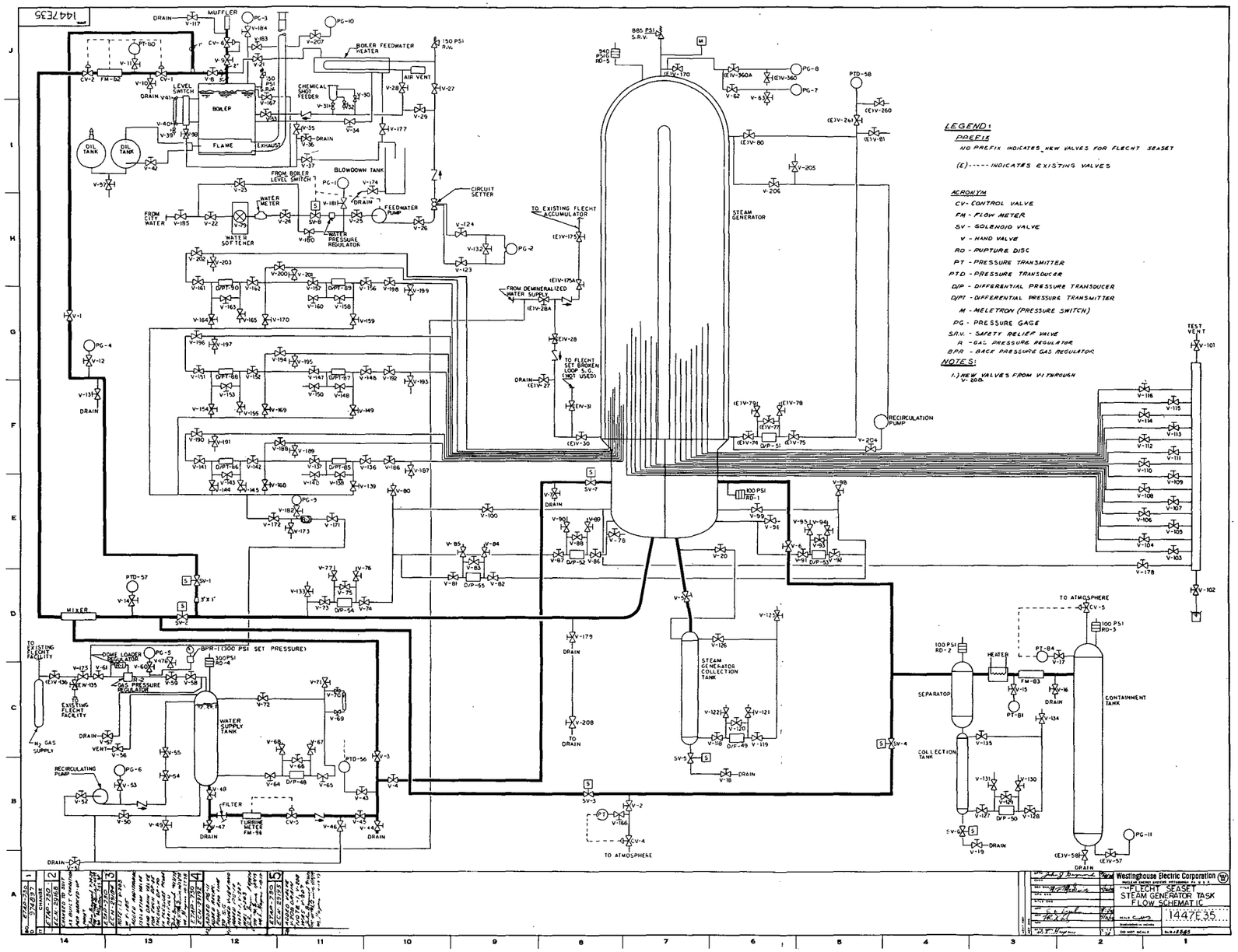
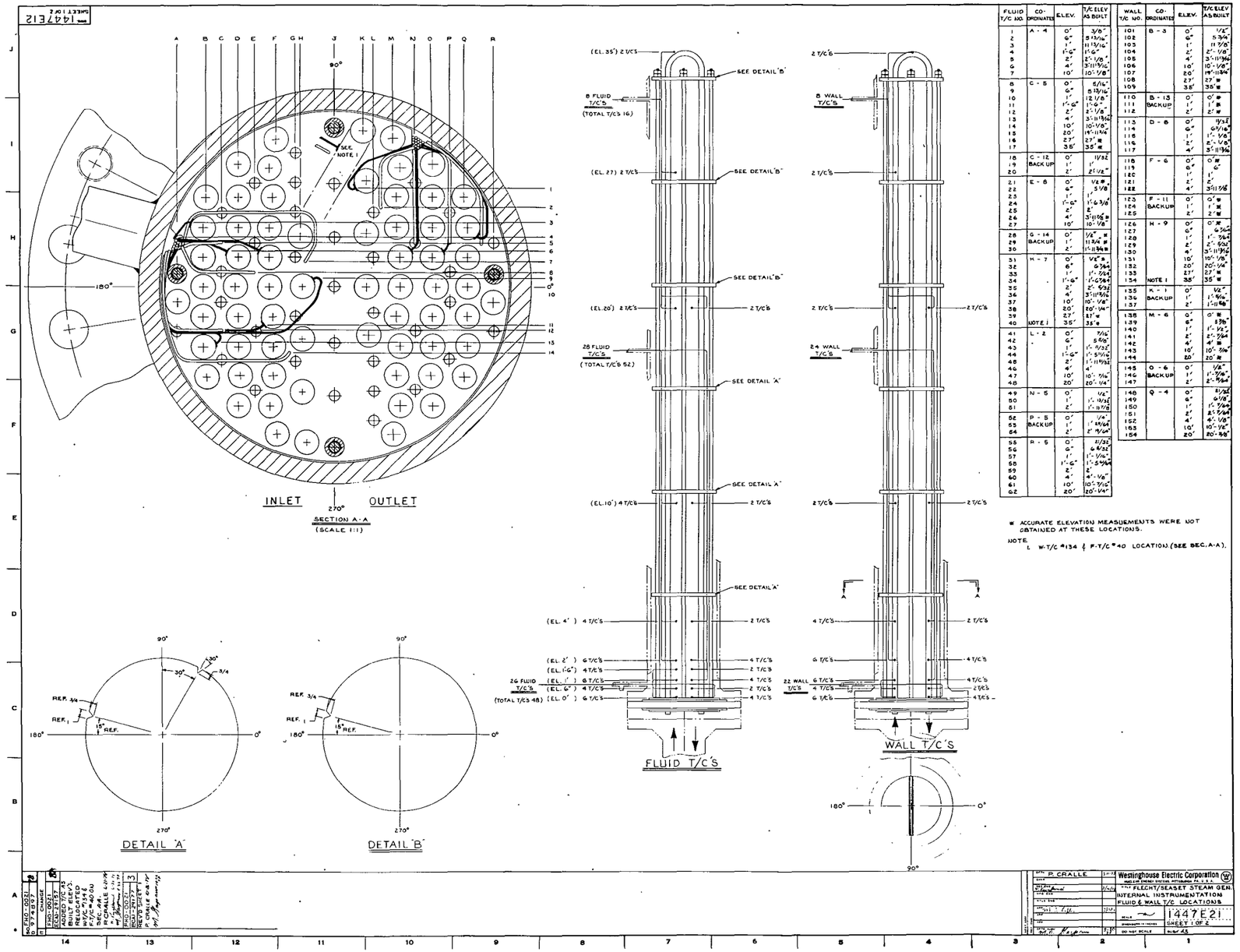


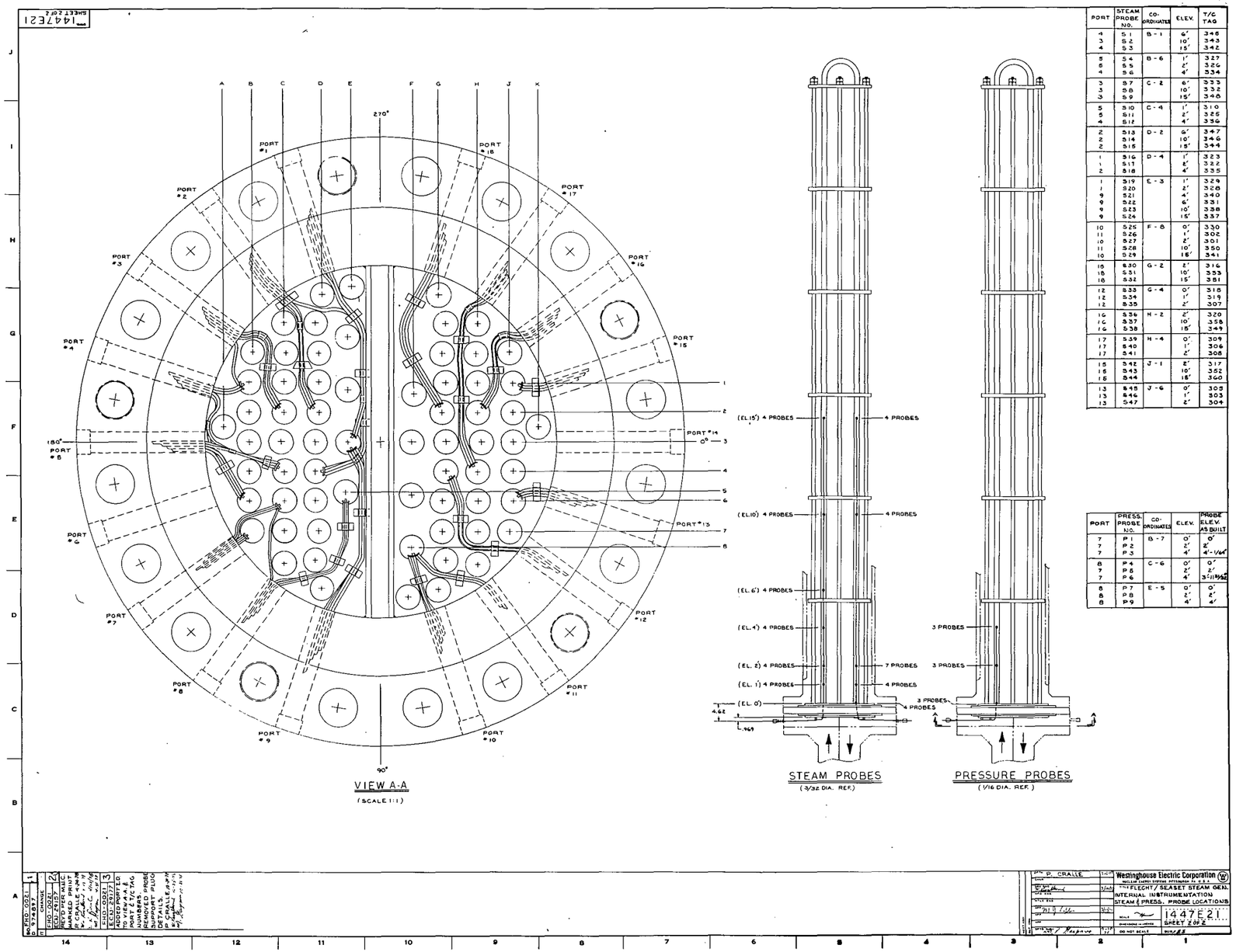
Figure 3-1. Detailed Schematic Diagram of Separate Effects Test Loop



FLUID T/C NO.	CO-ORDINATES	ELEV.	T/C ELEV AS BUILT
1	A - 4	0'	3/8"
2		6"	5 3/4"
3		1'	11 13/16"
4		1'-6"	1'-6"
5		2'	2'-1/8"
6		4'	3'-11 9/16"
7		10'	10'-1/8"
8	C - 5	0'	5/16"
9		6"	5 13/16"
10		1'	12 1/8"
11		1'-6"	1'-6"
12		2'	2'-1/8"
13		4'	3'-11 13/16"
14		10'	10'-1/8"
15		20'	19'-11 1/4"
16		27'	27' *
17		35'	35' *
18	C - 12 BACK UP	0'	11/32"
19		1'	1'
20		2'	2'-1/8"
21	E - 8	0'	1/4 *
22		6"	5 1/8"
23		1'	1'
24		1'-6"	1'-6 3/8"
25		2'	2'
26		4'	3'-11 15/16" *
27		10'	10'-1/8"
28	G - 14 BACK UP	0'	1/4" *
29		1'	11 3/4 *
30		2'	1'-11 3/4 *
31	H - 7	0'	1/4" *
32		6"	6 3/4"
33		1'	1'-2 3/4"
34		1'-6"	1'-6 3/4"
35		2'	2'-6 3/4"
36		4'	3'-11 3/16"
37		10'	10'-1/8"
38		20'	20'-1/4"
39		27'	27' *
40	NOTE 1	35'	35' *
41	L - 2	0'	7/16"
42		6"	5 5/8"
43		1'	1'-11/32"
44		1'-6"	1'-5 9/16"
45		2'	1'-11 7/32"
46		4'	4'
47		10'	10'-1/8"
48		20'	20'-1/4"
49	N - 5	0'	1/4"
50		1'	1'-10 1/2"
51		2'	1'-11 7/8"
52	P - 5 BACK UP	0'	1/4"
53		1'	1' 5/64"
54		2'	2' 9/64"
55	R - 5	0'	21/32"
56		6"	6 21/32"
57		1'	1'-1/16"
58		1'-6"	1'-5 9/64"
59		2'	2'
60		4'	4'-1/8"
61		10'	10'-1/16"
62		20'	20'-1/4"

WALL T/C NO.	CO-ORDINATES	ELEV.	T/C ELEV AS BUILT
101	B - 3	0'	1/2"
102		6"	5 3/4"
103		1'	11 7/8"
104		2'	2'-1/8"
105		4'	3'-11 13/16"
106		10'	10'-1/8"
107		20'	19'-11 3/4"
108		27'	27' *
109		35'	35' *
110	B - 13 BACKUP	0'	0' *
111		1'	1' *
112		2'	2' *
113	D - 8	0'	11/32"
114		6"	6 11/16"
115		1'	1'-1/8"
116		2'	2'-1/8"
117		4'	3'-11 3/16"
118	F - 6	0'	0' *
119		6"	6'
120		1'	1'
121		2'	2'
122		4'	3'-11 7/16"
123	F - 11 BACKUP	0'	0' *
124		1'	1' *
125		2'	2' *
126	H - 9	0'	0' *
127		6"	6 3/4"
128		1'	1'-5/8"
129		2'	2'-5/64"
130		4'	3'-11 13/16"
131		10'	10'-1/8"
132		20'	20'-1/4"
133		27'	27' *
134	NOTE 1	35'	35' *
135	K - 1 BACKUP	0'	1/2"
136		1'	1'-9/16"
137		2'	1'-11 5/8"
138	M - 6	0'	0' *
139		6"	5 7/8"
140		1'	1'-1/2"
141		2'	2'-7/64"
142		4'	4' *
143		10'	10'-7/64"
144		20'	20' *
145	O - 6 BACKUP	0'	1/8"
146		1'	1'-7/64"
147		2'	2'-9/64"
148	Q - 4	0'	21/32"
149		6"	6 1/8"
150		1'	1'-7/64"
151		2'	2'-7/64"
152		4'	4'-1/8"
153		10'	10'-1/8"
154		20'	20'-5/8"

Figure 3-2. FLECHT SEASET Steam Generator Separate Effects Test Instrumentation Locations (sheet 1 of 2)



PORT	STEAM PROBE NO.	CO-ORDINATES	ELEV.	T/C TAG
4	S1	B-1	6'	346
3	S2		10'	343
4	S3		15'	342
5	S4	B-6	1'	327
5	S5		2'	326
4	S6		4'	334
3	S7	C-2	6'	333
3	S8		10'	332
3	S9		15'	348
5	S10	C-4	1'	310
5	S11		2'	325
4	S12		4'	336
2	S13	D-2	6'	347
2	S14		10'	346
2	S15		15'	344
1	S16	D-4	1'	323
1	S17		2'	322
2	S18		4'	335
1	S19	E-3	1'	329
1	S20		2'	328
9	S21		4'	340
9	S22		6'	331
9	S23		10'	338
9	S24		15'	337
10	S25	F-8	0'	330
11	S26		1'	302
10	S27		2'	301
11	S28		10'	350
10	S29		15'	341
16	S30	G-2	2'	316
16	S31		10'	333
16	S32		15'	351
12	S33	G-4	0'	318
12	S34		1'	319
12	S35		2'	307
16	S36	H-2	2'	320
16	S37		10'	358
16	S38		15'	349
17	S39	H-4	0'	309
17	S40		1'	306
17	S41		2'	308
15	S42	J-1	2'	317
15	S43		10'	352
15	S44		15'	360
13	S45	J-6	0'	305
13	S46		1'	303
13	S47		2'	304

PORT	PRESS. PROBE NO.	CO-ORDINATES	ELEV.	PROBE ELEV. AS BUILT
7	P1	B-7	0'	0'
7	P2		2'	2'
7	P3		4'	4'-1/64"
8	P4	C-6	0'	0'
7	P5		2'	2'
7	P6		4'	3'-11 15/32"
8	P7	E-5	0'	0'
8	P8		2'	2'
8	P9		4'	4'

Figure 3-2. FLECHT SEASET Steam Generator Separate Effects Test Instrumentation Locations (sheet 2 of 2)

Two sight glass nozzles were added to the discharge side of the lower plenum section for viewing and photographic study. An alternate 125 mm (5 in.) discharge nozzle was added to the lower plenum. This served as an outlet for steam and also supported an internal baffle assembly. The baffle helped to separate any entrained liquid carried through the generator. The separated liquid drained through the old discharge nozzle to a new 3.05 m (10 ft) long collection tank made from 15.2 cm (6 in.) pipe. The baffle is illustrated in figure 3-3.

3-3. INSTRUMENTATION DESCRIPTION

Loop instrumentation (figure 3-4) was designed to measure mass and energy transport across the primary side inlet and primary side exit boundaries of the steam generator. Flowmeters in the boiler steam line, liquid supply tank feed line, and steam separator exhaust line established the mass flow rates of steam and liquid in these lines. The separator liquid flow rate was measured by the rate of change of liquid level in the liquid collection tanks. The energy content of the steam and liquid was calculated from measurements of the fluid temperature and pressure at the collection and flow measuring points. The difference between the steam generator primary side inlet quality and the primary side exit quality, for a given constant mass flow, represents the total energy exchange from the secondary to primary sides of the steam generator. Any steam generator exit vapor superheat was also considered in the overall energy balance.

Within the tube bundle, the heat transfer process was monitored by thermocouples in the secondary fluid and on the tube wall, and by steam probes inside the tubes. The steam generator bundle instrumentation locations are shown in figures 3-2 and 3-4. A summary of the bundle instrumentation is presented in table 3-1. The tube bundle instrumentation was specifically designed to measure a radial variation in heat transfer rate due to expected nonuniform two-phase flow in the inlet plenum.

The distribution of secondary fluid and tube wall thermocouples was skewed toward the bottom of the bundle, because prior FLECHT-SET Phase B test data showed that most secondary temperature variation occurred below the 0.61 m (24 in.) elevation.

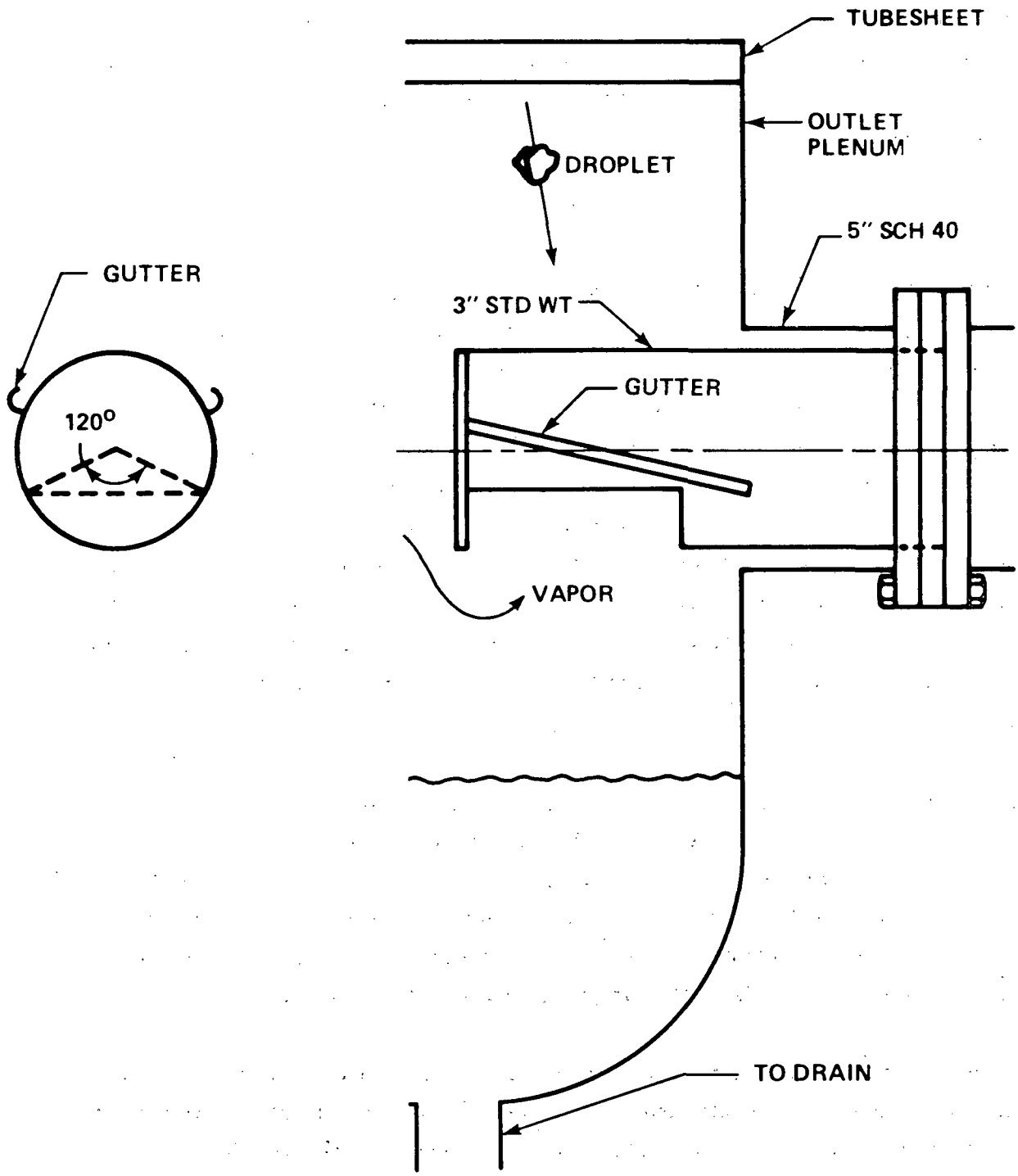


Figure 3-3. FLECHT Outlet Plenum Baffle

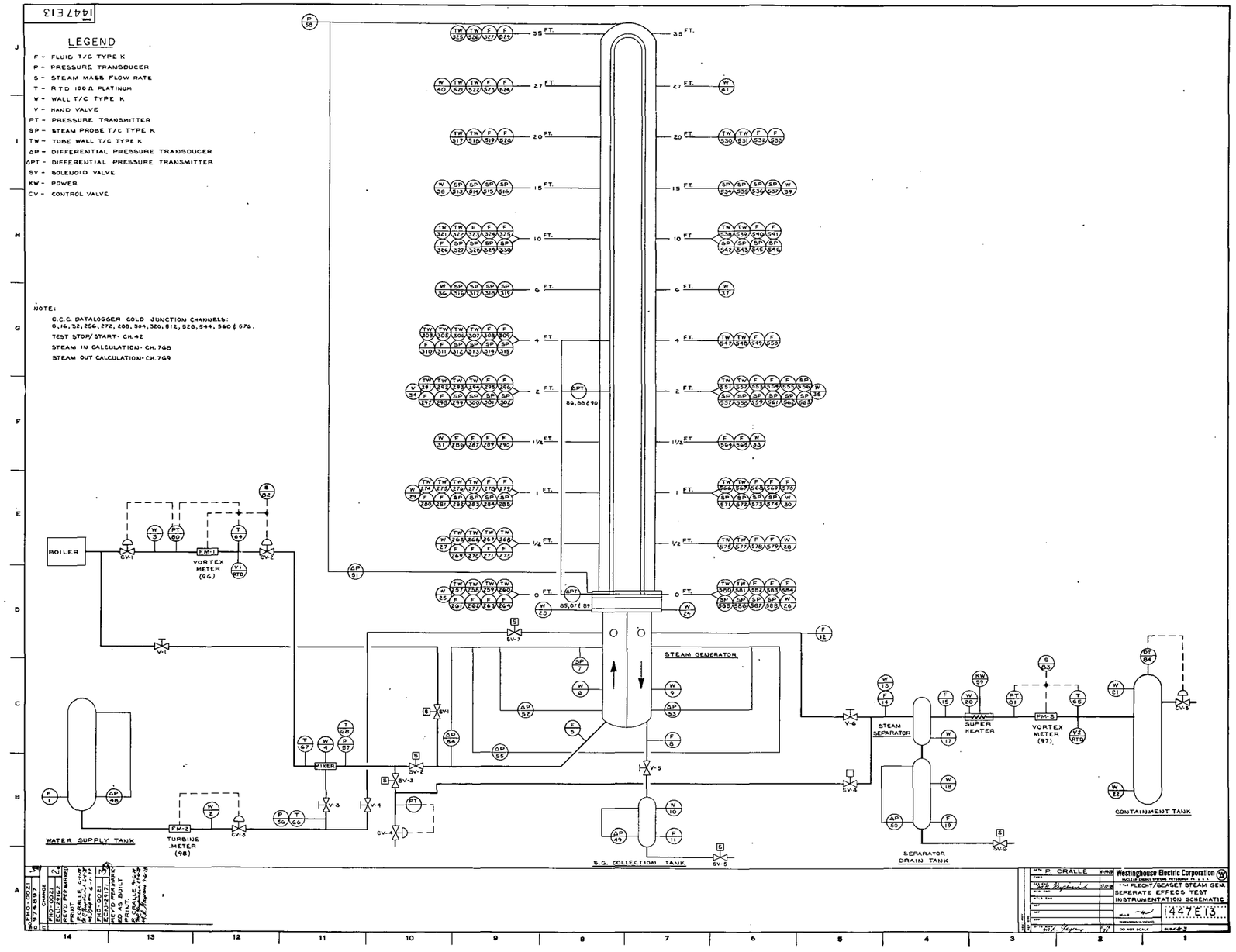


Figure 3-4. FLECHT SEASET Steam Generator Separate Effects Test Instrumentation Schematic Diagram

TABLE 3-1

AXIAL DISTRIBUTION OF TUBE WALL AND FLUID THERMOCOUPLES AND STEAM PROBES

Elevation in Meters (Feet)	Steam Generator Inlet				Steam Probes	Steam Generator Outlet				Steam Probes
	Tube Wall T/Cs		Fluid T/Cs			Tube Wall T/Cs		Fluid T/Cs		
	Primary	Backup	Primary	Backup	Primary	Primary	Backup	Primary	Backup	Primary
0	4	2	4	2	-	2	2	3	1	4
0.153 (0.5)	4	-	4	-	-	2	-	2	-	-
0.305 (1)	4	2	4	2	4	2	2	3	1	4
0.458 (1.5)	-	-	4	-	-	-	-	2	-	-
0.610 (2)	4	2	4	2	4	2	2	3	1	7
1.220 (4)	4	-	4	-	4	2	-	2	-	-
1.830 (6)	-	-	-	-	4	-	-	-	-	-
3.050 (10)	2	-	4	-	4	2	-	2	-	4
4.575 (15)	-	-	-	-	4	-	-	-	-	4
6.100 (20)	2	-	2	-	-	2	-	2	-	-

TABLE 3-1 (cont)

AXIAL DISTRIBUTION OF TUBE WALL AND FLUID THERMOCOUPLES AND STEAM PROBES

Elevation in Meters (Feet)	Steam Generator Inlet					Steam Generator Outlet				
	Tube Wall T/Cs		Fluid T/Cs		Steam Probes Primary	Tube Wall T/Cs		Fluid T/Cs		Steam Probes Primary
	Primary	Backup	Primary	Backup		Primary	Backup	Primary	Backup	
8.235 (27)	2	-	2	-	-	-	-	-	-	-
10.675 (35)	2	-	2	-	-	-	-	-	-	-
Total[a]	28	6	34	6	24	14	6	19	3	23

a. Total tube wall T/Cs + fluid T/Cs = 116; total steam probes = 47

The steam probe axial spacing was based on calculations of vapor temperature versus tube length from a model of the two-phase heat transfer process in the tubes.[1]

The tubes in the inlet side of the tube bundle were instrumented with differential pressure probes to monitor differential pressure over the zero to 1.2 m (zero to 4 ft) elevation. The differential pressure transducers had a range of zero to 6.9 kPa (zero to 1 psi), which is much larger than the calculated vapor frictional or hydrostatic differential pressure within the tubes, assuming uniform conditions at the tube entrance. However, a larger differential pressure develops in the tube entrance when liquid accumulation occurs in a tube. The purpose of the differential pressure probes was to detect this mass accumulation when it occurred. To prevent spurious differential pressure signals due to liquid migration into the differential pressure probe, a continuous nitrogen purge flow was provided. The nitrogen flowed from the differential pressure cell to the probe and prevented any liquid from entering the probe. The volumetric flow rate of the nitrogen flowing into the steam generator tubes, which was much less than 1 percent of the total flow rate, was neglected in the overall loop mass balance. The effect of the nitrogen purge on the heat transfer was minimal, because none of the tubes instrumented with thermocouples had differential pressure probes. Also, because of the low nitrogen purge flow and because the probe only perturbed a local zone within the total circumference of the tube, the heat transfer effect was minimal. The continuous purge concept was tested successfully in a single-tube bench test (appendix A, NRC/EPRI/Westinghouse Report No. 4).

The steam probes used to measure the primary side steam temperatures were aspirating-type probes inserted in selected steam generator tubes from the lower plenum. The probes were constructed of 2.4 mm (0.094 in.) diameter outer tubing with a 0.6 mm (0.025 in.) diameter inner sheathed thermocouple. The maximum reduction in steam generator tube flow area due to the steam probes was less than 10 percent, and the flow area reduction averaged over the total tube length was less than 2 percent.

1. Hochreiter, L. E., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task: Task Plan Report," NRC/EPRI/Westinghouse-2, March 1978, figure 6-4 and appendix B.

All steam probes in the steam generator aspirated less than 3 percent of the total loop mass flow rate. Aspirated steam was condensed, collected, and accounted for in the overall loop mass and energy balance.

Photographic techniques were used to identify the two-phase flow regime in the steam generator inlet and outlet plenum. Droplet size and velocity information was obtained from high-speed movies and still photographs (appendix D of NRC/EPRI/Westinghouse Report No. 4). Movies and still photographs were taken in each of four different test runs. The movies were taken with two Redlake Hycam model 41-0004 high-speed cameras using a 25 mm lens at an F-stop of 1.4. The light source was a 1000-watt incandescent lamp. The still photographs were taken with Nikon and Mamiya cameras synchronized with Vivitar model/283 flash units, which have a flash duration of 25 microseconds.

Motion pictures were taken for matrix runs 2, 5, 6, and 10. Two 400-foot rolls of film were exposed at the inlet plenum window at the beginning and at the end of the run. Four 400-foot rolls of film were exposed at the outlet plenum window at 1, 3, 5, and 7 minutes into the run. All film was shot at 2500 frames per second to allow tracking of individual drops in the plenums.

Still photographs were taken in matrix runs 3, 4, 9, and 11. Inlet plenum photos were taken at 1-minute intervals, starting at 1 minute into the test and terminating at 20 minutes. Outlet plenum photos were taken for 10 minutes at 30-second intervals, starting at 30 seconds into the test. High-intensity flash units were synchronized with the camera shutter to freeze the droplet action in the plenum.

3-4. DATA ACQUISITION

The first stage of the data processing sequence was the data acquisition system. The hardware was a microprocessor-based data logger which could record on either 21-column paper or digital magnetic tape. The paper readout feature was used to monitor loop heatup, and the digital magnetic tape recorder stored data acquired during a test. Data were recorded in engineering units either from standard conversion tables for thermocouples and RTDs or from preprogrammed calibration files for the pressure and flow sensors. Input signals from the loop sensors were conditioned so that the

input to the A/D converter was a zero- to 1-volt signal. These input conditioning cards were specialized for different types of sensors. Three A/D converters were used simultaneously to provide a system scan rate of 45 channels per second. With 212 channels, the data acquisition system was able to scan each channel every 6 seconds; this scan rate was acceptable for the slow transient response in this task. In addition to data collection on magnetic tape, three strip charts continuously recorded the signals from 12 test instruments. The strip chart recorders were used for operator indication of loop operation during the test and for recording the cycling of the power to the immersion heater located downstream of the loop separator. A channel list of the data recorded on the magnetic tape is shown in table 3-2, and a list of the data recorded continuously on the strip charts is shown in table 3-3.

After each test, the digital magnetic tape was processed on the existing FLECHT computer data acquisition system (a Digital Equipment Corporation PDP 11/20). A printout of all the data was made immediately following each test so that the test director could evaluate its reliability. A subroutine of the PDP 11/20 compiled specific data points so that the test director could determine if the test met the requirements of the test matrix. Finally, the PDP 11/20 produced a data tape which was processed by the CDC 7600 computer at the Westinghouse Nuclear Center in Monroeville, Pennsylvania. All of the data reduction and data analysis was carried out on the CDC 7600.

3-5. FACILITY OPERATION

To perform a steam generator separate effects experiment, the facility and the steam generator must be brought to the desired initial conditions. The steam generator secondary side was heated using electrical strip heaters on the steam generator shell and lower flanges. Previous experiments[1] have shown that this method of heating produces a uniform temperature on the steam generator secondary side. In addition, a low-pressure recirculation pump was utilized to eliminate any stratified temperature distribution which might be present from the preceding day's test. During heatup, the secondary side temperature was monitored, and the strip heaters at a given elevation were deenergized when that elevation reached the desired temperature.

1. Waring, J. P., and Hochreiter, L. E., "PWR FLECHT SET Phase B-1 Evaluation Report," WCAP-8583, August 1975.

TABLE 3-2

STEAM GENERATOR SEPARATE EFFECTS TEST CHANNEL LIST

Channel	Data
1	Accumulator fluid T/C
2	Water injection line wall T/C
3	Steam line wall T/C
4	Mixer wall T/C
5	Steam generator inlet plenum fluid T/C
6	Steam generator inlet plenum wall T/C
7	Steam generator inlet plenum steam probe
8	Steam generator outlet plenum fluid T/C
9	Steam generator outlet plenum wall T/C
10	Steam generator collection tank wall T/C
11	Steam generator collection tank fluid T/C
12	Steam generator plenum exit fluid T/C
13	Steam separator entrance wall T/C
14	Steam separator entrance fluid T/C
15	Steam separator exit fluid T/C
17	Steam separator wall T/C
18	Steam separator drain tank wall T/C
19	Steam separator drain tank fluid T/C
20	Superheater wall T/C
21	Containment tank top wall T/C
22	Containment tank bottom wall T/C
23	Steam generator plenum flange inlet wall T/C
24	Steam generator plenum flange outlet wall T/C
25	Steam generator 0 ft inlet wall T/C
26	Steam generator 0 ft outlet wall T/C
27	Steam generator 0.5 ft inlet wall T/C
28	Steam generator 0.5 ft outlet wall T/C
29	Steam generator 1.0 ft inlet wall T/C
30	Steam generator 1.0 ft outlet wall T/C
31	Steam generator 1.5 ft inlet wall T/C
33	Steam generator 1.5 ft outlet wall T/C
34	Steam generator 2.0 ft inlet wall T/C
35	Steam generator 2.0 ft outlet wall T/C
36	Steam generator 6.0 ft inlet wall T/C
37	Steam generator 6.0 ft outlet wall T/C
38	Steam generator 15 ft inlet wall T/C
39	Steam generator 15 ft outlet wall T/C
40	Steam generator 27 ft inlet wall T/C
41	Steam generator 27 ft outlet wall T/C
42	Test start/stop
48	Accumulator level (psid)
49	Steam generator collection tank level (psid)
50	Steam separator drain tank level (psid)

TABLE 3-2 (cont)

STEAM GENERATOR SEPARATE EFFECTS TEST CHANNEL LIST

Channel	Data
51	Steam generator secondary level (psid)
52	Steam generator inlet plenum pressure (psid)
53	Steam generator outlet plenum pressure (psid)
54	Steam generator hot leg pressure (psid)
55	Steam generator plenum inlet/outlet pressure (psid)
56	Water injection line pressure (psig)
57	Mixer pressure (psig)
58	Steam generator secondary side pressure (psig x 10)
59	Superheater power (kw)
64	Steam supply fluid RTD
65	Steam exhaust fluid RTD
66	Water injection fluid RTD
67	Steam before mixer fluid RTD
68	Mixer fluid RTD
80	Steam supply pressure (psia)
81	Steam exhaust pressure (psia)
82	Steam supply flow (lbm/sec)
83	Steam exhaust flow (lbm/sec)
84	Containment tank pressure (psig)
85	Generator tube B-7[a], 0 - 2 ft pressure (psid)
86	Generator tube B-7, 2 - 4 ft pressure (psid)
87	Generator tube C-6, 0 - 2 ft pressure (psid)
88	Generator tube C-6, 2 - 4 ft pressure (psid)
89	Generator tube E-5, 0 - 2 ft pressure (psid)
90	Generator tube E-5, 2 - 4 ft pressure (psid)
96	Steam supply vortex meter (cfm)
97	Steam exhaust vortex meter (cfm)
98	Injection water flow turbine meter (gpm)
257	Generator 0 ft inlet tube B-6 wall T/C
258	Generator 0 ft inlet tube C-4 wall T/C
259	Generator 0 ft inlet tube D-4 wall T/C
260	Generator 0 ft inlet tube E-3 wall T/C
261	Generator 0 ft inlet secondary B-6 fluid T/C
262	Generator 0 ft inlet secondary C-4 fluid T/C
263	Generator 0 ft inlet secondary D-4 fluid T/C
264	Generator 0 ft inlet secondary E-3 fluid T/C
265	Generator 0.5 ft inlet tube B-6 wall T/C
266	Generator 0.5 ft inlet tube C-4 wall T/C
267	Generator 0.5 ft inlet tube D-4 wall T/C
268	Generator 0.5 ft inlet tube E-3 wall T/C
269	Generator 0.5 ft inlet secondary B-6 fluid T/C
270	Generator 0.5 ft inlet secondary C-4 fluid T/C
271	Generator 0.5 ft inlet secondary D-4 fluid T/C

a. This pressure transducer was not connected to the data acquisition system.

TABLE 3-2 (cont)

STEAM GENERATOR SEPARATE EFFECTS TEST CHANNEL LIST

Channel	Data
273	Generator 0.5 ft inlet secondary E-3 fluid T/C
274	Generator 1 ft inlet tube B-5 wall T/C
276	Generator 1 ft inlet tube D-4 wall T/C
277	Generator 1 ft inlet tube E-3 wall T/C
278	Generator 1 ft inlet secondary B-6 fluid T/C
279	Generator 1 ft inlet secondary C-4 fluid T/C
280	Generator 1 ft inlet secondary D-4 fluid T/C
281	Generator 1 ft inlet secondary E-3 fluid T/C
282	Generator 1 ft inlet primary B-6 steam probe
283	Generator 1 ft inlet primary C-4 steam probe
284	Generator 1 ft inlet primary D-4 steam probe
285	Generator 1 ft inlet primary E-3 steam probe
286	Generator 1.5 ft inlet secondary B-6 fluid T/C
287	Generator 1.5 ft inlet secondary C-4 fluid T/C
289	Generator 1.5 ft inlet secondary D-4 fluid T/C
290	Generator 1.5 ft inlet secondary E-3 fluid T/C
291	Generator 2 ft inlet tube B-6 wall T/C
292	Generator 2 ft inlet tube C-4 wall T/C
293	Generator 2 ft inlet tube D-4 wall T/C
294	Generator 2 ft inlet tube E-3 wall T/C
295	Generator 2 ft inlet secondary B-6 fluid T/C
296	Generator 2 ft inlet secondary C-4 fluid T/C
297	Generator 2 ft inlet secondary D-4 fluid T/C
298	Generator 2 ft inlet secondary E-3 fluid T/C
299	Generator 2 ft inlet primary B-6 steam probe
300	Generator 2 ft inlet primary C-4 steam probe
301	Generator 2 ft inlet primary D-4 steam probe
302	Generator 2 ft inlet primary E-3 steam probe
303	Generator 4 ft inlet tube B-6 wall T/C
305	Generator 4 ft inlet tube C-4 wall T/C
306	Generator 4 ft inlet tube D-4 wall T/C
307	Generator 4 ft inlet tube E-3 wall T/C
308	Generator 4 ft inlet secondary B-6 fluid T/C
309	Generator 4 ft inlet secondary C-4 fluid T/C
310	Generator 4 ft inlet secondary D-4 fluid T/C
311	Generator 4 ft inlet secondary E-3 fluid T/C
312	Generator 4 ft inlet primary B-6 steam probe
313	Generator 4 ft inlet primary C-4 steam probe
314	Generator 4 ft inlet primary D-4 steam probe
315	Generator 4 ft inlet primary E-3 steam probe
316	Generator 6 ft inlet primary B-1 steam probe
317	Generator 6 ft inlet primary C-2 steam probe
318	Generator 6 ft inlet primary D-2 steam probe

TABLE 3-2 (cont)

STEAM GENERATOR SEPARATE EFFECTS TEST CHANNEL LIST

Channel	Data
319	Generator 6 ft inlet primary E-3 steam probe
321	Generator 10 ft inlet tube B-6 wall T/C
322	Generator 10 ft inlet tube E-3 wall T/C
323	Generator 10 ft inlet secondary B-6 fluid T/C
324	Generator 10 ft inlet secondary C-4 fluid T/C
325	Generator 10 ft inlet secondary D-4 fluid T/C
326	Generator 10 ft inlet secondary E-3 fluid T/C
327	Generator 10 ft inlet primary B-1 steam probe
328	Generator 10 ft inlet primary C-2 steam probe
329	Generator 10 ft inlet primary D-2 steam probe
330	Generator 10 ft inlet primary E-3 steam probe
513	Generator 15 ft inlet primary B-1 steam probe
514	Generator 15 ft inlet primary C-2 steam probe
515	Generator 15 ft inlet primary D-2 steam probe
516	Generator 15 ft inlet primary E-3 steam probe
517	Generator 20 ft inlet tube B-6 wall T/C
518	Generator 20 ft inlet tube E-3 wall T/C
519	Generator 20 ft inlet secondary C-4 fluid T/C
520	Generator 20 ft inlet secondary E-3 fluid T/C
521	Generator 27 ft inlet tube B-6 wall T/C
522	Generator 27 ft inlet tube E-3 wall T/C
523	Generator 27 ft inlet secondary C-4 fluid T/C
524	Generator 27 ft inlet secondary E-3 fluid T/C
525	Generator 35 ft inlet tube B-6 wall T/C
526	Generator 35 ft inlet tube E-3 wall T/C
527	Generator 35 ft secondary C-4 fluid T/C
529	Generator 35 ft secondary E-3 fluid T/C
530	Generator 20 ft outlet tube G-4 wall T/C
531	Generator 20 ft outlet tube J-6 wall T/C
532	Generator 20 ft outlet secondary F-8 fluid T/C
533	Generator 20 ft outlet secondary J-6 fluid T/C
534	Generator 15 ft outlet primary F-8 steam probe
535	Generator 15 ft outlet primary G-2 steam probe
536	Generator 15 ft outlet primary H-2 steam probe
537	Generator 15 ft outlet primary J-1 steam probe
538	Generator 10 ft outlet tube G-4 wall T/C
539	Generator 10 ft outlet tube J-6 wall T/C
540	Generator 10 ft outlet secondary F-8 fluid T/C
541	Generator 10 ft outlet secondary J-6 fluid T/C
542	Generator 10 ft outlet primary F-8 steam probe
543	Generator 10 ft outlet primary G-2 steam probe
545	Generator 10 ft outlet primary H-2 steam probe
546	Generator 10 ft outlet primary J-1 steam probe

TABLE 3-2 (cont)

STEAM GENERATOR SEPARATE EFFECTS TEST CHANNEL LIST

Channel	Data
547	Generator 4 ft outlet tube G-4 wall T/C
548	Generator 4 ft outlet tube J-6 wall T/C
549	Generator 4 ft outlet secondary F-8 fluid T/C
550	Generator 4 ft outlet secondary J-6 fluid T/C
551	Generator 2 ft outlet tube G-4 wall T/C
552	Generator 2 ft outlet tube J-6 wall T/C
553	Generator 2 ft outlet secondary F-8 fluid T/C
554	Generator 2 ft outlet secondary G-4 fluid T/C
555	Generator 2 ft outlet secondary H-4 fluid T/C, Location J-6 for runs before run 21001
556	Generator 2 ft outlet primary F-8 steam probe
557	Generator 2 ft outlet primary G-2 steam probe
558	Generator 2 ft outlet primary G-4 steam probe
559	Generator 2 ft outlet primary H-2 steam probe
561	Generator 2 ft outlet primary H-4 steam probe
562	Generator 2 ft outlet primary J-1 steam probe
563	Generator 2 ft outlet primary J-6 steam probe
564	Generator 1.5 ft outlet secondary F-8 fluid T/C
565	Generator 1.5 ft outlet secondary J-6 fluid T/C
566	Generator 1 ft outlet tube H-4 wall T/C, Location G-4 for runs before run 21001
567	Generator 1 ft outlet tube J-6 wall T/C
568	Generator 1 ft outlet secondary F-8 fluid T/C
569	Generator 1 ft outlet secondary G-4 fluid T/C
570	Generator 1 ft outlet secondary H-4 fluid T/C, Location J-6 for runs before run 21001
571	Generator 1 ft outlet primary F-8 steam probe
572	Generator 1 ft outlet primary G-4 steam probe
573	Generator 1 ft outlet primary H-4 steam probe
574	Generator 1 ft outlet primary J-6 steam probe
575	Generator 0.5 ft outlet tube G-4 wall T/C
577	Generator 0.5 ft outlet tube J-6 wall T/C
578	Generator 0.5 ft outlet secondary F-8 fluid T/C
579	Generator 0.5 ft outlet secondary J-6 fluid T/C
580	Generator 0 ft outlet tube G-4 wall T/C
581	Generator 0 ft outlet tube J-6 wall T/C
582	Generator 0 ft outlet secondary F-8 fluid T/C
583	Generator 0 ft outlet secondary G-4 fluid T/C
584	Generator 0 ft outlet secondary J-6 fluid T/C
585	Generator 0 ft outlet primary F-8 steam probe
586	Generator 0 ft outlet primary G-4 steam probe
587	Generator 0 ft outlet primary H-4 steam probe
588	Generator 0 ft outlet primary J-6 steam probe
768	Steam supply mass flow (lbm/sec)
769	Steam exhaust mass flow (lbm/sec)

TABLE 3-3

STEAM GENERATOR SEPARATE EFFECTS TEST
CONTINUOUS STRIP CHART CHANNEL LIST

Channel	Data
82	Boiler mass flow rate
98	Liquid mass flow rate
83	Exhaust steam mass flow rate
53	Liquid level, outlet plenum
49	Liquid level, steam generator collection tank
50	Liquid level, loop separator collection tank
51	Liquid level, steam generator secondary
59	Power to loop superheater
57	Loop pressure at mixer
84	Containment tank pressure
48	Liquid level, liquid supply tank
--[a]	Bypass loop pressure

a. Recorded on strip chart but not on the data acquisition system.

The primary side piping was heated to the primary side saturation temperature using bleed steam from the boiler. While the system was being heated, the instrumentation channels were checked, flowmeters and differential pressure transducer cells were zeroed, and solenoid valves were cycled. Once the system had been heated, the steam and liquid flows were adjusted to their desired values at the mixer, and the resulting two-phase flow was bypassed to the drain while these conditions were being established. When the desired inlet flow conditions had been established, the inlet two-phase flow was directed into the steam generator by proper alignment of the loop solenoid valves. Loop pressure and inlet flow were maintained constant by the control valves.

Pressure-reducing valve CV-1 (figure 3-5) was used to control the upstream pressure at the boiler vortex meter and to minimize system instabilities caused by boiler pressure fluctuations. The pressure drop of 0.28 to 0.52 MPa (40 to 75 psid) across CV-1 also helped to ensure a single-phase steam flow at the boiler vortex meter and the mixer. Steam flow control was accomplished with control valve CV-2; feedback to the valve was supplied by the boiler vortex meter.

Water flow to the mixer was controlled by valve CV-3. The turbine meter was used to measure the flow and provide feedback to the control valve.

Two-phase fluid leaving the generator primary side tubes went through a first stage of separation in the lower plenum section of the steam generator. An internal baffle assembly was used to separate the liquid, which was collected and measured in the outlet plenum or collection tank located below the plenum. The remaining steam passed through a commercial separator of the same type used in the FLECHT low flooding rate test series.[1] The separator removed any remaining entrained liquid, which was then collected and measured in the separator drain tank. Each collection tank was equipped with a solenoid drain valve which could be activated to drain the tanks as needed during low-quality test runs.

Dry steam leaving the separator passed through the exhaust vortex flowmeter prior to entering the containment tank. An immersion heater, inserted upstream of the flowmeter, was used to ensure that single-phase flow was being measured by the meter. The exhaust valve (CV-5), located downstream of the containment tank, controlled the

1. Lilly, G. P., et al., "PWR FLECHT Cosine Low Flooding Rate Test Series Evaluation Program," WCAP-8838, March 1977.

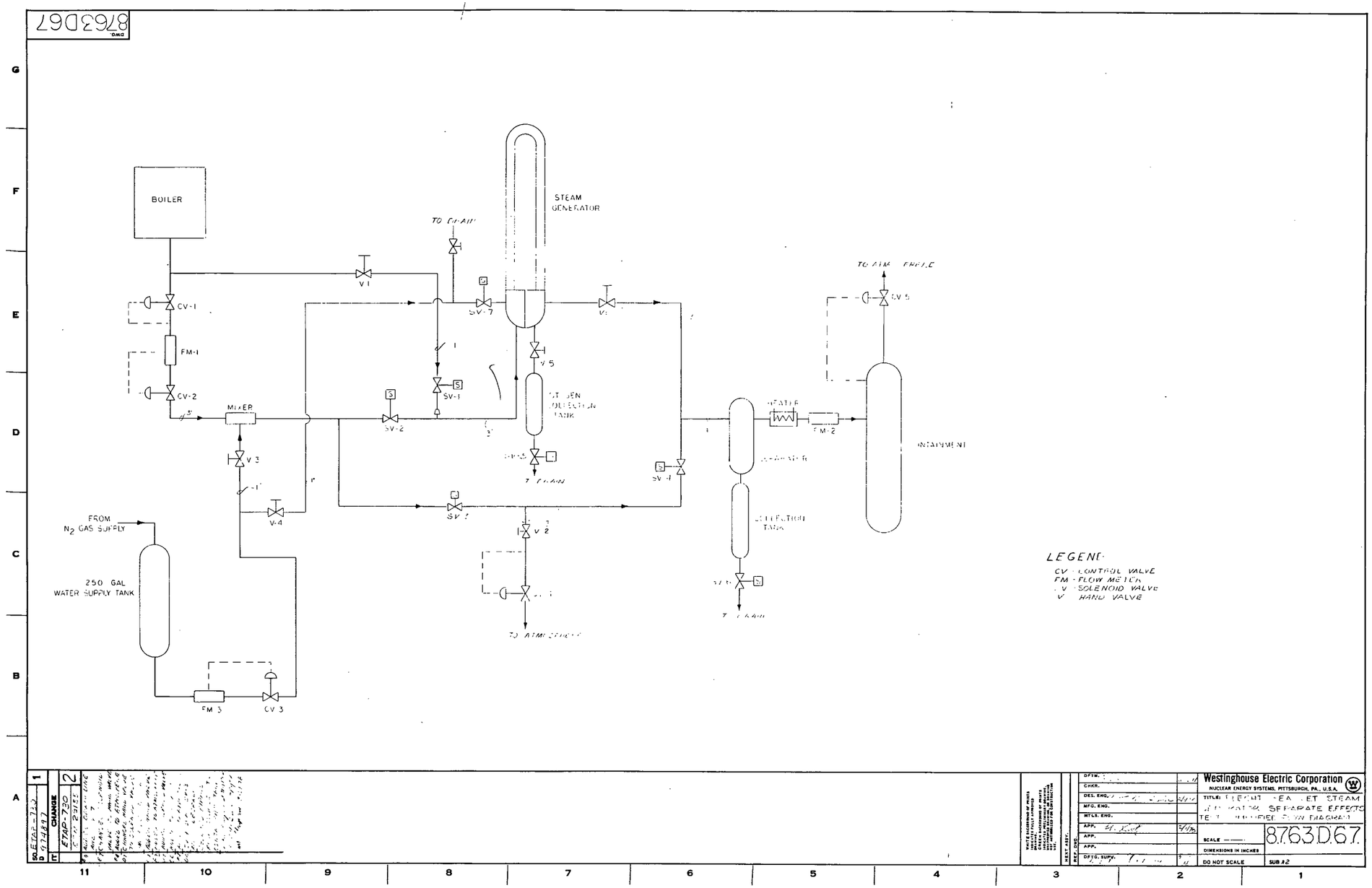


Figure 3-5. FLECHT SEASET Separate Effects Test Simplified Flow Diagram

system backpressure. Control feedback to the valve was supplied by a pressure transmitter located on the containment tank.

The following is a simplified test operating procedure for a typical run:

(1) Begin with all valves closed.

(2) Fill the steam generator and accumulator with water and heat up to desired conditions.

(3) Fire boiler. Open V-1, SV-1, V-5, V-6, and CV-5. Use steam to heat up steam generator primary side, separator, collection tank, containment, and interconnecting piping. Adjust backpressure with CV-5 and control steam flow with V-1.

(4) Open CV-1, CV-2, SV-3, and CV-4 and use boiler steam to heat up piping from boiler through mixer and steam generator bypass line. Control flow with CV-2 and backpressure with CV-4.

(5) When all loop components have reached desired conditions, set the desired test steam flow through the bypass line by using CV-1 to control FM-1 upstream pressure and CV-2 to control steam flow. Control bypass line backpressure with CV-4.

(6) Open V-3 and set water flow to mixer by appropriate adjustment of CV-3.

(7) To establish flow through the steam generator, close SV-1, SV-3, and CV-4 and open SV-2. Control backpressure with CV-5.

(8) To terminate the test, isolate the system by closing SV-2 and opening SV-3 and CV-4. Close CV-3 and shut down the boiler.

Appendix E of NRC/EPRI/Westinghouse Report No. 4 contains the detailed test procedure used to run each test, and appendix F discusses the shakedown testing of the facility and instrumentation calibration. The repair and testing of a leak in the steam generator lower plenum divider plate are covered in appendix G of the same report.

SECTION 4
RUN CONDITIONS AND TEST RESULTS

4-1. TEST MATRIX AND RUN CONDITIONS

The original test matrix for the steam generator separate effects tests is given in table 4-1. The test matrix of steam generator separate effects tests included runs 1 through 15 of the proposed test matrix in section 7.2 of the task plan[1] plus a single-phase steam and an isothermal (secondary temperature equal to primary temperature) test. Test runs 16 through 19 in the proposed test matrix could not be run because the required air/water tests with the spray nozzle in the inlet plenum duplicating the hemispherical plenum flow distribution were not successfully completed. The hemispherical plenum air/water flow distribution at the tubesheet was extremely non-uniform and it appeared to be highly unlikely that a nozzle mounted in the FLECHT inlet plenum could have reproduced the hemispherical plenum distribution. For this reason, tests 16 through 19, which would have used the inlet plenum nozzle to reproduce the hemispherical plenum distribution in the FLECHT steam generator, were not run.

The tests performed in the steam generator separate effects tests are given in table 4-2.

The five-digit run number in table 4-2 contains a 2 as the first digit, signifying a steam generator matrix test; the second and third digits indicate the sequence number of the test; and the fourth and fifth digits are the test matrix run number. Test parameters for each matrix test are given in table 4-1. Table 4-2 includes three runs (21001, 22415, and 23005) in which one of the controlled test parameters was outside of the allowable range for a valid test. Because the data from these tests are valid for the actual test run parameters, they can be thought of as tests at off-nominal test conditions. For this reason, they are included in the data report with results of the 17 valid runs at nominal test conditions.

1. Hochreiter, L. E., et al, "PWR FLECHT SEASET Steam Generator Separate Effects Task: Task Plan Report," NRC/EPRI/Westinghouse-2, March 1978.

TABLE 4-1

TEST MATRIX FOR STEAM GENERATOR SEPARATE EFFECTS TEST

Run No.	Run Description	Flow Rate [kg/sec (lb/sec)]	Primary Pressure [MPa (psia)]	Quality	SG Secondary Temperature [°C (°F)]	SG Secondary Level (%)
1	Reference run	0.23 (0.5)	0.28 (40)	0.80	274 (525)	100
2	Flow sensitivity	0.45 (1.0)	0.28 (40)	0.80	274 (525)	100
3	Pressure sensitivity	0.23 (0.5)	0.14 (20)	0.80	274 (525)	100
4	Pressure sensitivity	0.23 (0.5)	0.412 (60)	0.80	274 (525)	100
5	Quality sensitivity	0.23 (0.5)	0.28 (40)	0.50	274 (525)	100
6	Quality sensitivty	0.23 (0.5)	0.28 (40)	0.20	274 (525)	100
7	Secondary temperature sensitivity	0.23 (0.5)	0.28 (40)	0.80	204 (400)	100

TABLE 4-1 (cont)

TEST MATRIX FOR STEAM GENERATOR SEPARATE EFFECTS TEST

Run No.	Run Description	Flow Rate [kg/sec (lb/sec)]	Primary Pressure [MPa (psia)]	Quality	SG Secondary Temperature [°C (°F)]	SG Secondary Level (%)
8	Secondary level sensitivity	0.23 (0.5)	0.28 (40)	0.80	274 (525)	25
9	Postbundle quench	0.45 (1.0)	0.28 (40)	0.10	274 (525)	100
10	Replication of reference run	0.23 (0.5)	0.28 (40)	0.80	274 (525)	100
11	Replication of reference run	0.23 (0.5)	0.28 (40)	0.80	274 (525)	100
12[a]	Reference run	0.23 (0.5)	0.28 (40)	0.80	274 (525)	100
13[a]	Flow sensitivity	0.45 (1.0)	0.28 (40)	0.80	274 (525)	100
14[a]	Quality sensitivity	0.23 (0.5)	0.28 (40)	0.50	274 (525)	100

a. Runs with a liquid spray nozzle in the steam generator inlet plenum

TABLE 4-1 (cont)

TEST MATRIX FOR STEAM GENERATOR SEPARATE EFFECTS TEST

Run No.	Run Description	Flow Rate [kg/sec (lb/sec)]	Primary Pressure [MPa (psia)]	Quality	SG Secondary Temperature [°C (°F)]	SG Secondary Level (%)
15[a]	Quality sensitivity	0.23 (0.5)	0.28 (40)	0.20	274 (525)	100
16 to 19	Deleted from test matrix					
20	Single-phase steam	0.23 (0.5)	0.28 (40)	1.0	274 (525)	100
21	Isothermal	0.23 (0.5)	0.28 (40)	0.80	130 (267)	100

a. Runs with a liquid spray nozzle in the steam generator inlet plenum

TABLE 4-2A[a]

RUN CONDITIONS AND TEST RESULTS

Run No.	Time-Averaged Boundary Conditions			Steam Generator Secondary Initial Conditions		Outlet Plenum Steam Temperature				Outlet Plenum Liquid Collected	Total Energy Transport[c]	Mass Balance Error
	Total Flow (lb/sec)	Quality	Pressure (psig)	Temperature[b] (°F)	Level (ft)	T_{max} (°F)	Time (sec)	T_{min} (°F)	Time (sec)	(lb)	(Btux10^6)	(%)
20904	0.494	0.798	45.7	525	32.4	499	162	345	1584	7.26	0.142	-0.8
21001	0.499	0.779	25.3	525	32.5	498	79	325	1524	8.6	0.177	-3.1
21121	0.488	0.801	25.4	267	33.1	269	--	269	--	115.9	--	--
21711	0.494	0.800	25.2	520	32.4	498	103	333	1543	4.7	0.141	-0.2
21806	0.500	0.200	25.3	520	32.7	490	11	268	1691	143.8	0.406	1.5
21909	0.946	0.105	25.8	525	33.9	477	84	268	1560	790.5	0.415	-3.0
22010	0.503	0.801	25.3	525	33.6	499	150	333	1620	7.01	0.146	0.0
22112	0.496	0.799	25.6	523	34.0	500	90	333	1560	5.02	0.151	-1.3
22213	0.991	0.797	25.3	524	33.7	502	78	296	1560	2.0	0.321	-2.0
22314	0.499	0.495	25.4	526	34.2	498	85	289	1573	17.6	0.307	-0.8
22415	0.614	0.345	25.3	524	33.6	492	0	269	1632	146.0	0.430	-1.0
22503	0.494	0.798	5.2	525	33.6	498	12	319	1500	8.8	0.150	-1.1
22608	0.495	0.796	25.3	525	7.7	495	24	312	1482	10.1	0.161	-1.1
22701	0.495	0.798	25.3	524	33.0	500	18	334	1488	9.87	0.168	-1.1
22920	0.493	1.00	25.1	523	32.5	498	12	444	1494	0.0	0.068	-2.0
23005	0.754	0.671	26.7	522	33.3	497	12	289	1505	17.6	0.359	-2.1
23207	0.504	0.801	25.2	400	32.2	388	12	284	1488	5.71	0.132	-0.4
23315	0.495	0.201	25.2	523	32.3	494	12	267	1505	37.9	0.418	3.2
23402	0.989	0.799	25.3	523	32.1	500	12	301	1494	10.9	0.313	-1.6
23605	0.494	0.496	25.1	523	33.6	499	18	289	1476	22.2	0.321	-2.0

a. English units
b. Temperatures above 1 foot
c. Total from beginning to end of test. See appendix H, NRC/EPRI/Westinghouse Report No. 4, for the duration of each test.

TABLE 4-2B[a]

RUN CONDITIONS AND TEST RESULTS

Run No.	Time-Averaged Boundary Conditions			Steam Generator Secondary Initial Conditions		Outlet Plenum Steam Temperature				Outlet Plenum Liquid Collected	Total Energy Transport[c]	Mass Balance Error
	Total Flow (kg/sec)	Quality	Pressure (MPa)	Temperature[b] (°C)	Level (m)	T_{max} (°C)	Time (sec)	T_{min} (°C)	Time (sec)	(kg)	(mw-sec)	(%)
20904	0.224	0.798	0.315	274	10.6	259	162	174	1584	3.29	150	-0.8
21001	0.226	0.779	0.174	274	10.7	259	79	163	1524	3.90	187	-3.1
21121	0.221	0.801	0.175	131	10.9	132	--	132	--	52.6	--	--
21711	0.224	0.800	0.174	271	10.6	259	103	167	1543	2.13	149	-0.2
21806	0.227	0.200	0.174	271	10.7	254	11	131	1691	65.2	429	1.5
21909	0.429	0.105	0.178	274	11.1	247	84	131	1560	358.6	437	-3.0
22010	0.228	0.801	0.174	274	11.0	259	150	167	1620	3.18	154	0.0
22112	0.225	0.799	0.176	273	11.1	260	90	166	1560	2.28	159	-1.3
22213	0.450	0.797	0.174	273	11.1	261	78	147	1560	0.907	338	-2.0
22314	0.226	0.495	0.175	274	11.2	259	85	143	1573	7.98	324	-0.8
22415	0.279	0.345	0.174	273	11.0	256	0	132	1632	66.2	453	-1.0
22503	0.224	0.798	0.036	274	11.0	259	12	159	1500	3.99	158	-1.1
22608	0.225	0.796	0.174	274	2.5	257	24	156	1482	4.58	170	-1.1
22701	0.225	0.798	0.174	273	10.8	260	18	168	1488	4.48	177	-1.1
22920	0.224	1.00	0.173	273	10.7	259	12	229	1494	0.0	72	-2.0
23005	0.342	0.671	0.184	272	10.9	258	12	143	1505	7.98	378	-2.1
23207	0.229	0.801	0.174	204	10.6	198	12	140	1488	2.59	139	-0.4
23315	0.225	0.201	0.174	273	10.6	257	12	131	1505	17.2	441	3.2
23402	0.449	0.799	0.174	273	10.5	260	12	149	1494	4.94	330	-1.6
23605	0.224	0.496	0.173	273	11.0	259	18	143	1476	10.1	338	-2.0

a. Metric units
b. Temperatures above 30.5 cm
c. Total from beginning to end of test. See appendix H, NRC/EPRI/Westinghouse Report No. 4, for duration of each test.

4-2. DATA REDUCTION

The data were recorded in engineering units on a Consolidated Controls Corporation (CCC) data logger at the test site. The incoming signals from the instrumentation were converted to the desired engineering units by using preprogrammed calibration files. Each flowmeter, pressure sensor, and differential pressure transducer had unique calibration coefficients. The bundle and loop thermocouple data were converted to temperature units (^{o}F) using a common thermocouple calibration function. Data from the five loop resistance temperature detectors (RTDs) were also converted to temperature units (^{o}F) using a common RTD calibration function in data reduction program SGCATALOG. The RTD data were corrected for the individual RTD calibrations. Prior to each test, reference data from each pressure and flow transducer were recorded on the data tape. These reference data were used to subtract any bias due to drift in the instrumentation out of the data.

The CCC data logger created a magnetic tape with the data; the tape was then used to create a permanent retrievable data file on the CDC 7600 computer system at the Monroeville Nuclear Center. The data processing hardware is shown in figure 4-1. Once the steam generator data were on file on the CDC 7600, a series of data reduction and analysis programs were utilized to obtain the various thermal/hydraulic quantities desired from the experiment. The steam generator test data reduction software includes computer programs that perform the following functions:

- Plot the test data versus time
- Perform an overall mass and energy balance on the steam generator
- Interpolate the tube bundle temperature data
- Calculate the local bundle heat flux and quality from the bundle temperatures

The data reduction scheme is illustrated in figure 4-2.

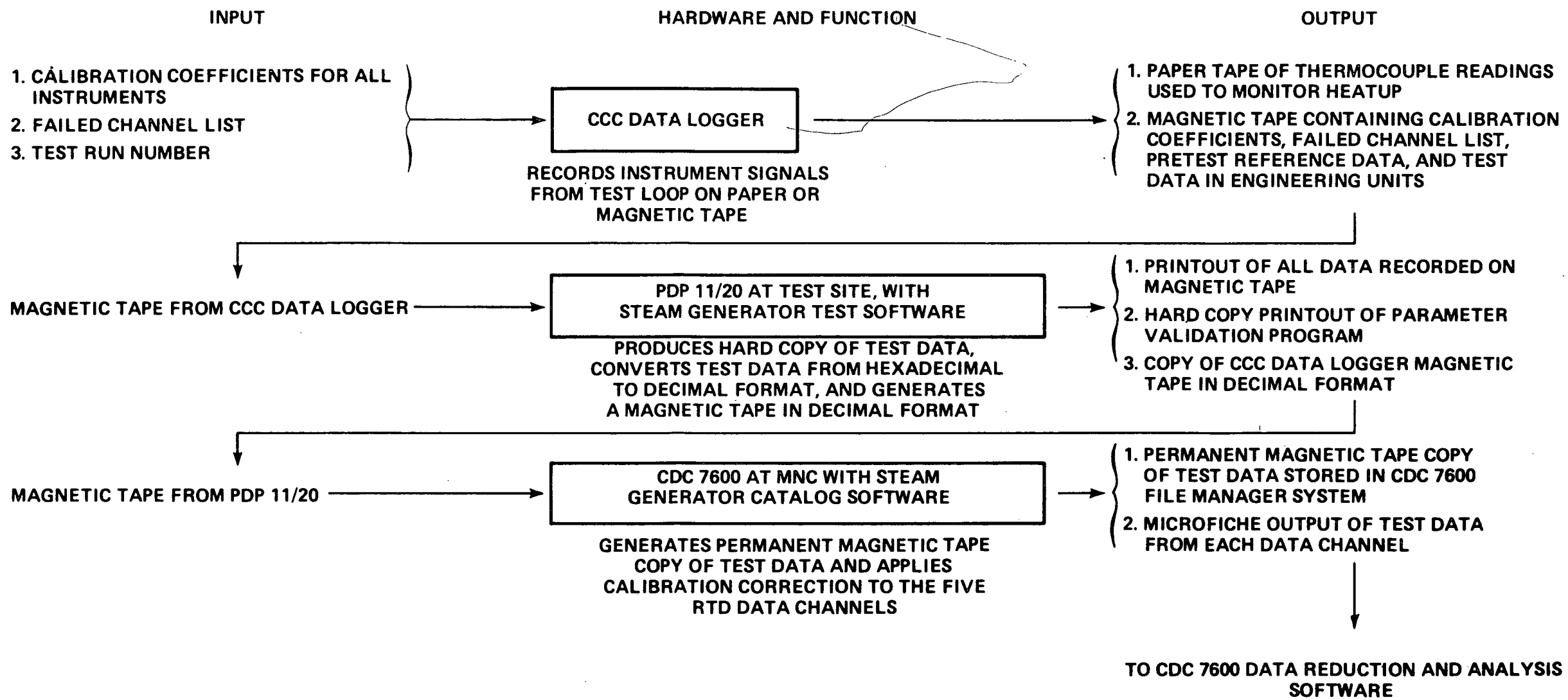


Figure 4-1. Steam Generator Test Data Reduction Hardware

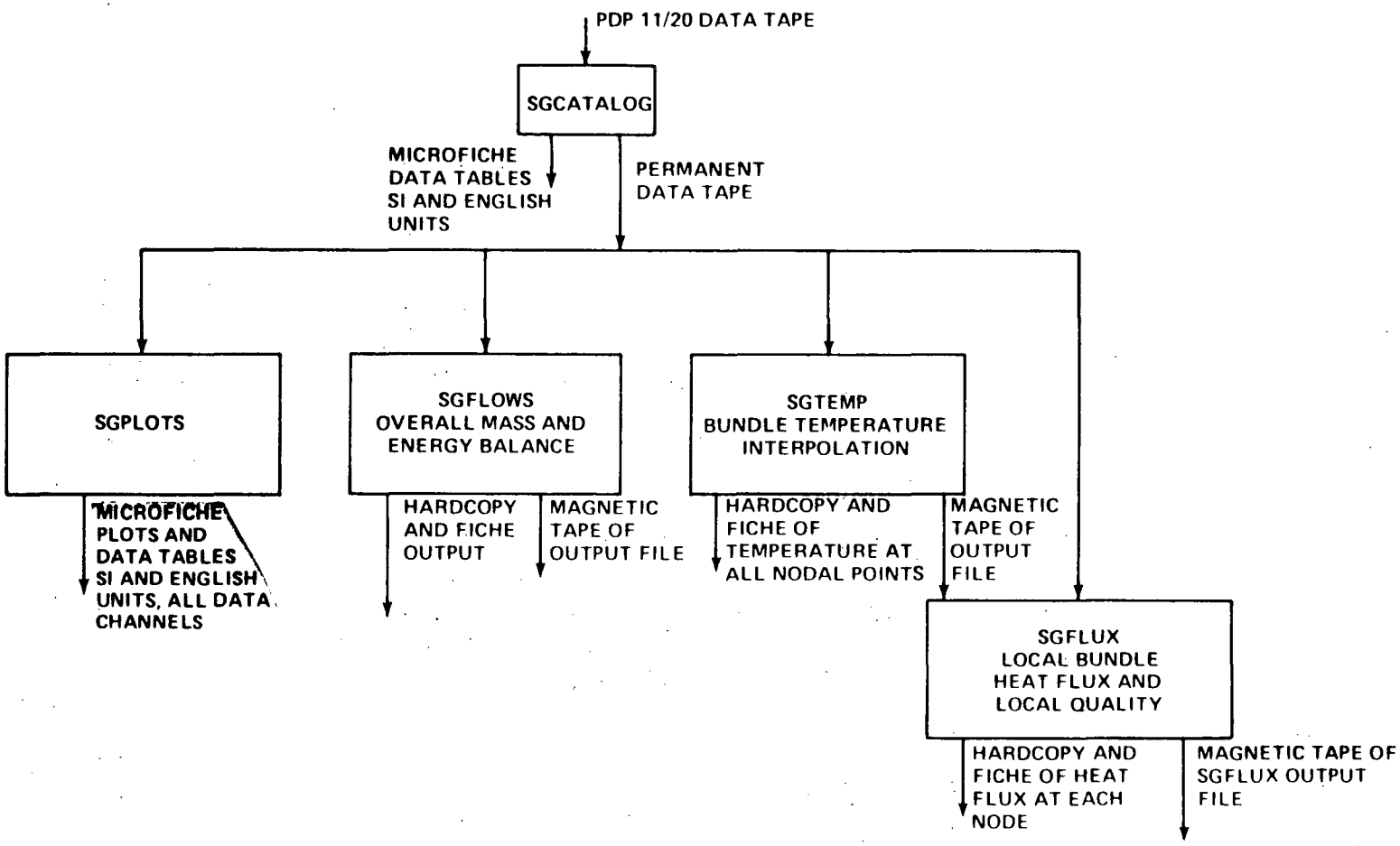


Figure 4-2. Steam Generator Test Data Reduction Software

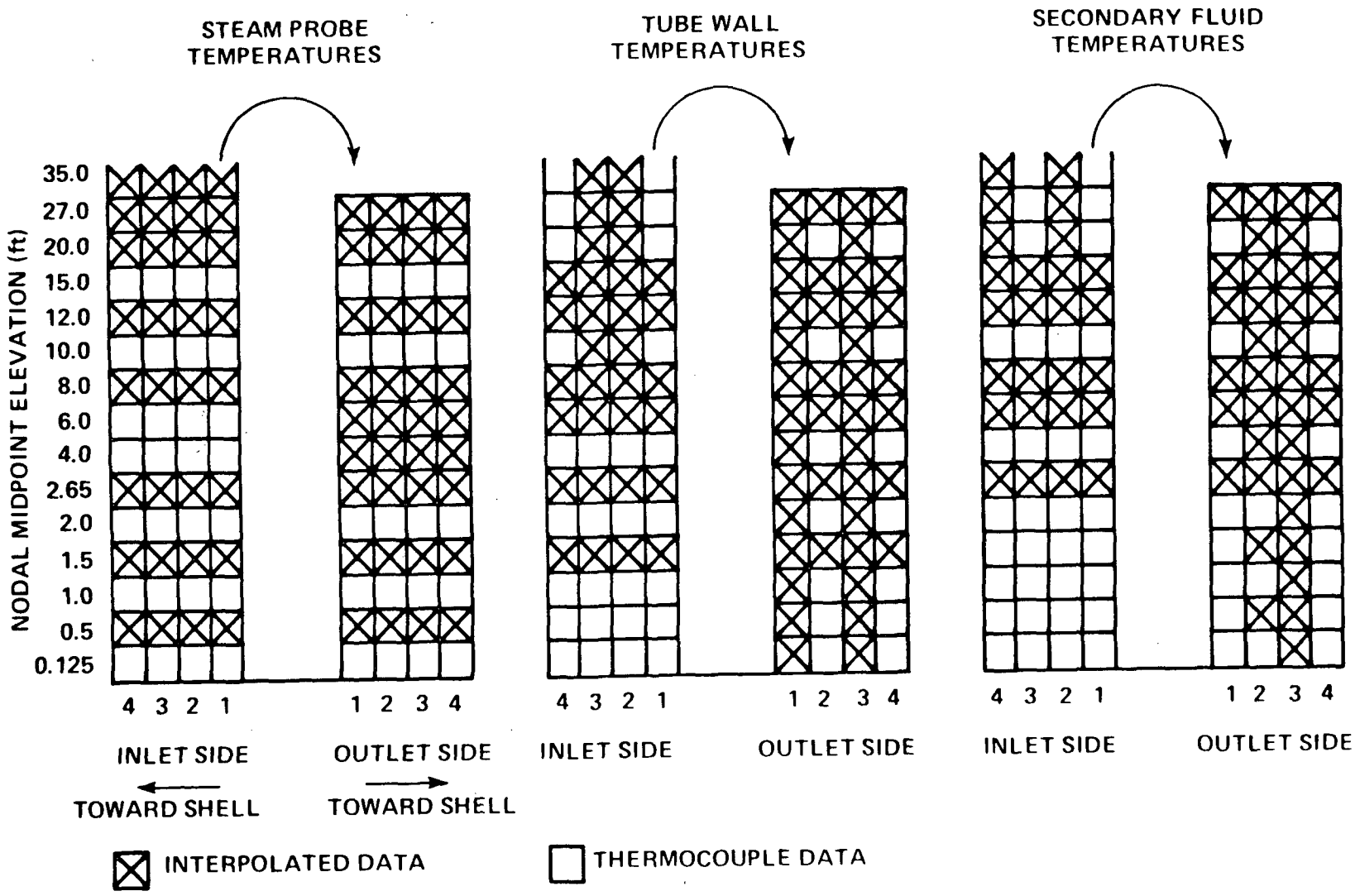
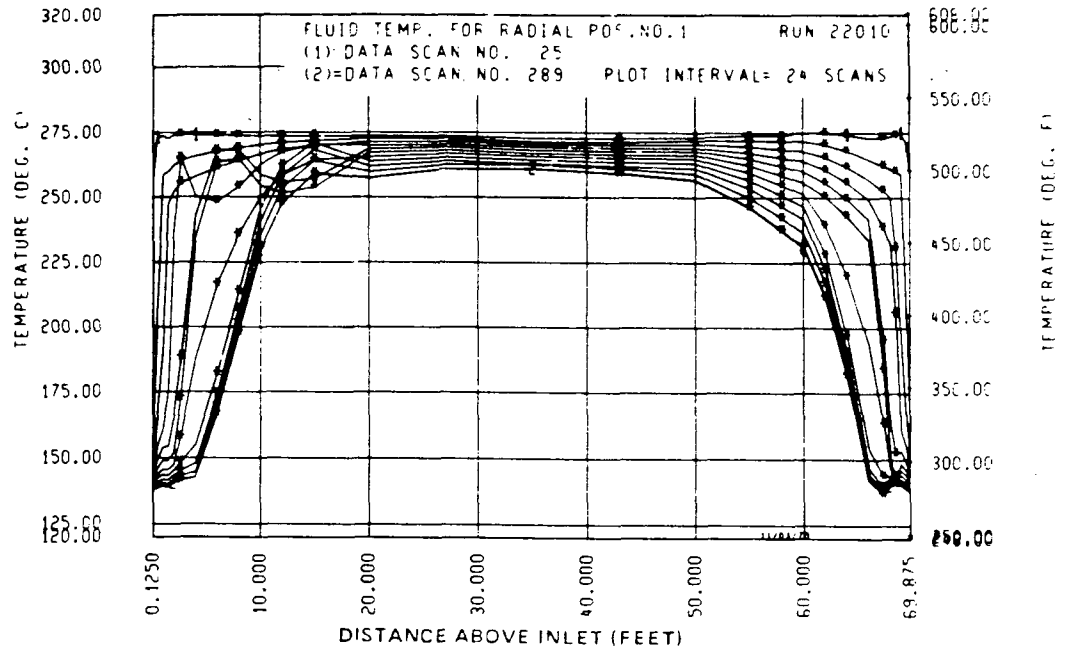
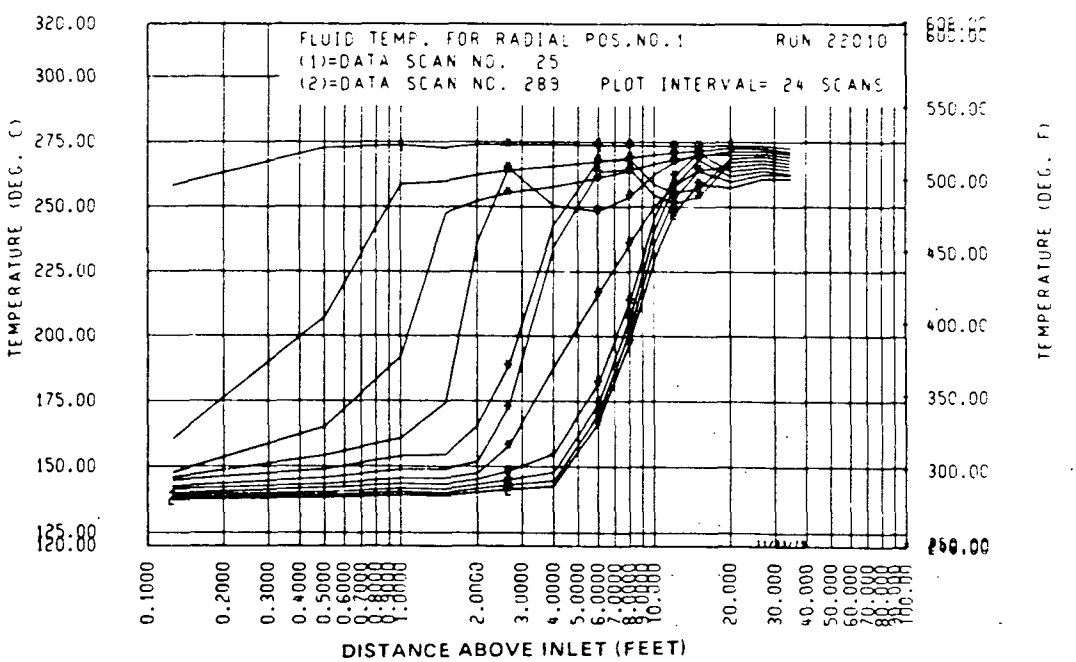


Figure 4-3. Steam Generator Nodalization

15607-42



(a) Linear Plot



(b) Semilogarithmic Plot

Figure 4-4. Linear and Semilogarithmic Plot of SGTEMPS Data (Run 22010)

the bundle temperatures from the SGTEMPS program and calculated the local quality and heat flux, the heat flux integrated over the tube bundle heat transfer area, and the total heat transfer rate integrated over the time interval of the test. The local heat flux was calculated from the secondary side fluid and tube wall temperatures using a natural convection film coefficient from Eckert and Jackson:[1]

$$Nu_s = 0.021\,(Gr \cdot Pr)^{0.40} \tag{4-1}$$

where

Nu_s	=	secondary side Nusselt number
Gr	=	secondary side Grashof number
Pr	=	secondary side Prandtl number

The Grashof number is defined as

$$Gr = \frac{\rho^2 g\, \beta\, (T_f - T_w)\, x^3}{\mu^2}$$

and the Nusselt number is defined as

$$Nu_s = hx/K$$

where

ρ	=	secondary fluid density
g	=	acceleration of gravity
β	=	volume coefficient of expansion
T_f	=	secondary fluid temperature
T_w	=	tube wall temperature
x	=	distance from the leading edge of the boundary layer (figure 4-5)
μ	=	secondary fluid viscosity
h	=	secondary side tube wall film coefficient
K	=	thermal conductivity of secondary water

1. Eckert, E. R. G., and Jackson, T. W., "Analysis of Turbulent Free-Convection Boundary Layer on Flat Plate," NACA-1015, 1951.

The parameter x in the Grashof number is defined as the distance from the leading edge of the boundary layer. On the steam generator inlet side, where the secondary side fluid is being cooled, the boundary layer is assumed to start at the first support plate. On the steam generator outlet side, where the secondary fluid is heated, the boundary layer is assumed to start at the tubesheet. The determination of x is illustrated in figure 4-5.

A comparison of equation (4-1) results with data is shown in figure 4-6.[1] The Grashof numbers for the Eckert and Jackson data range from $10^9 \leq Gr \leq 10^{12}$. The Grashof number can be as large as 10^{15} in the steam generator tests. Therefore, the Eckert and Jackson correlation was extrapolated to these higher Grashof numbers because the correlation does have the proper Grashof number trend. It is to be noted that several different free-convection correlations were examined when comparing the thermocouple bench test data. Because the Eckert and Jackson correlation gave the most consistent results in the evaluation of the data, it was then chosen for evaluating the steam generator secondary side heat transfer.

In the wall heat flux calculation, the measured tube wall temperature was corrected by a linear function of the wall heat flux. The tube wall correction factor was determined from a series of single-phase liquid and steam heat transfer tests that were run during the shakedown test program. In these shakedown tests, the heat flux and tube wall temperature were calculated from the primary and secondary side fluid temperatures. The difference between the calculated and measured tube wall temperature was correlated with the calculated tube wall heat flux.

The correction factor is intended to compensate for local perturbations in the measured wall temperature due to the thermocouple installation method. The tube wall temperature correction factor data from the shakedown test were fit to the linear equation

$$\Delta T = AQ_1 + B \qquad (4\text{-}2)$$

---

1. Eckert, E. R. G., and Jackson, T. W., "Analysis of Turbulent Free-Convection Boundary Layer on Flat Plate," NACA-1015, 1951.

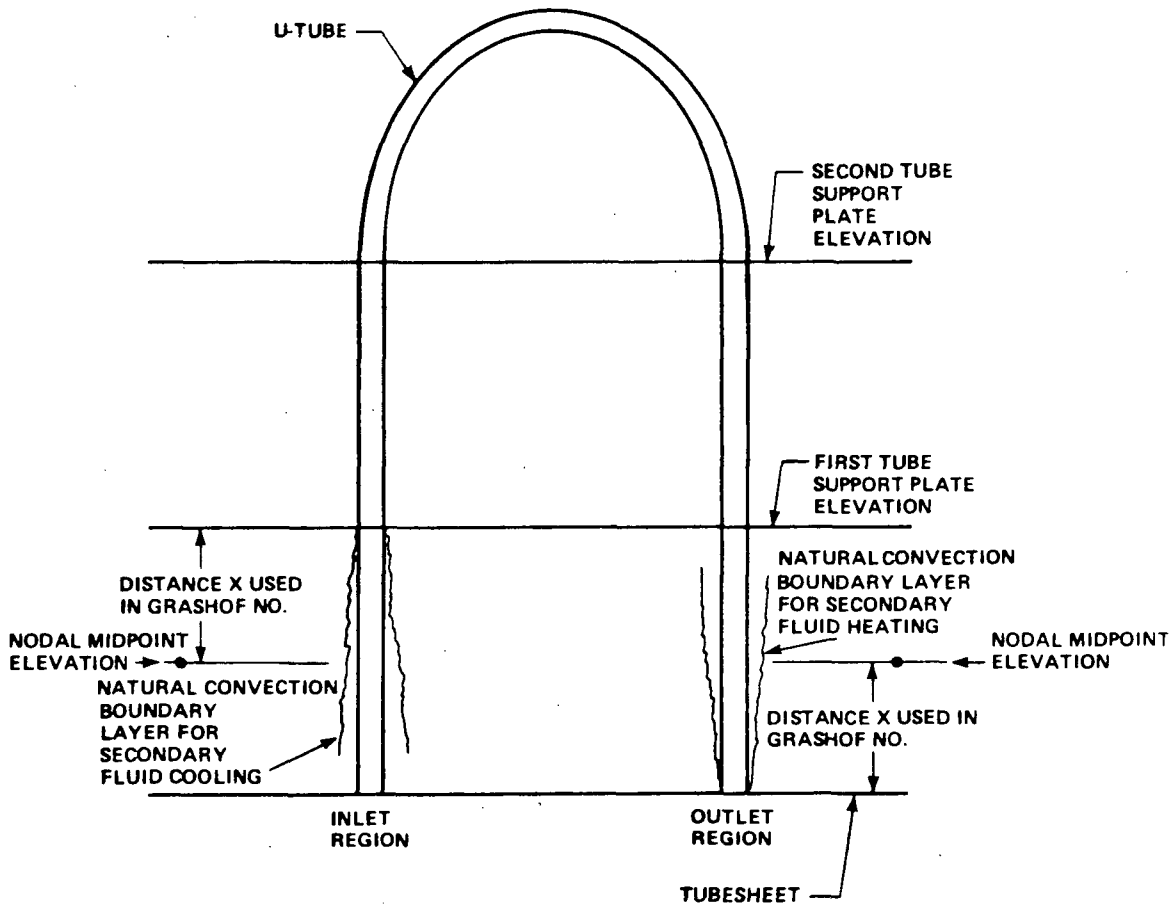


Figure 4-5. Method Used To Determine Length in the Grashof Number

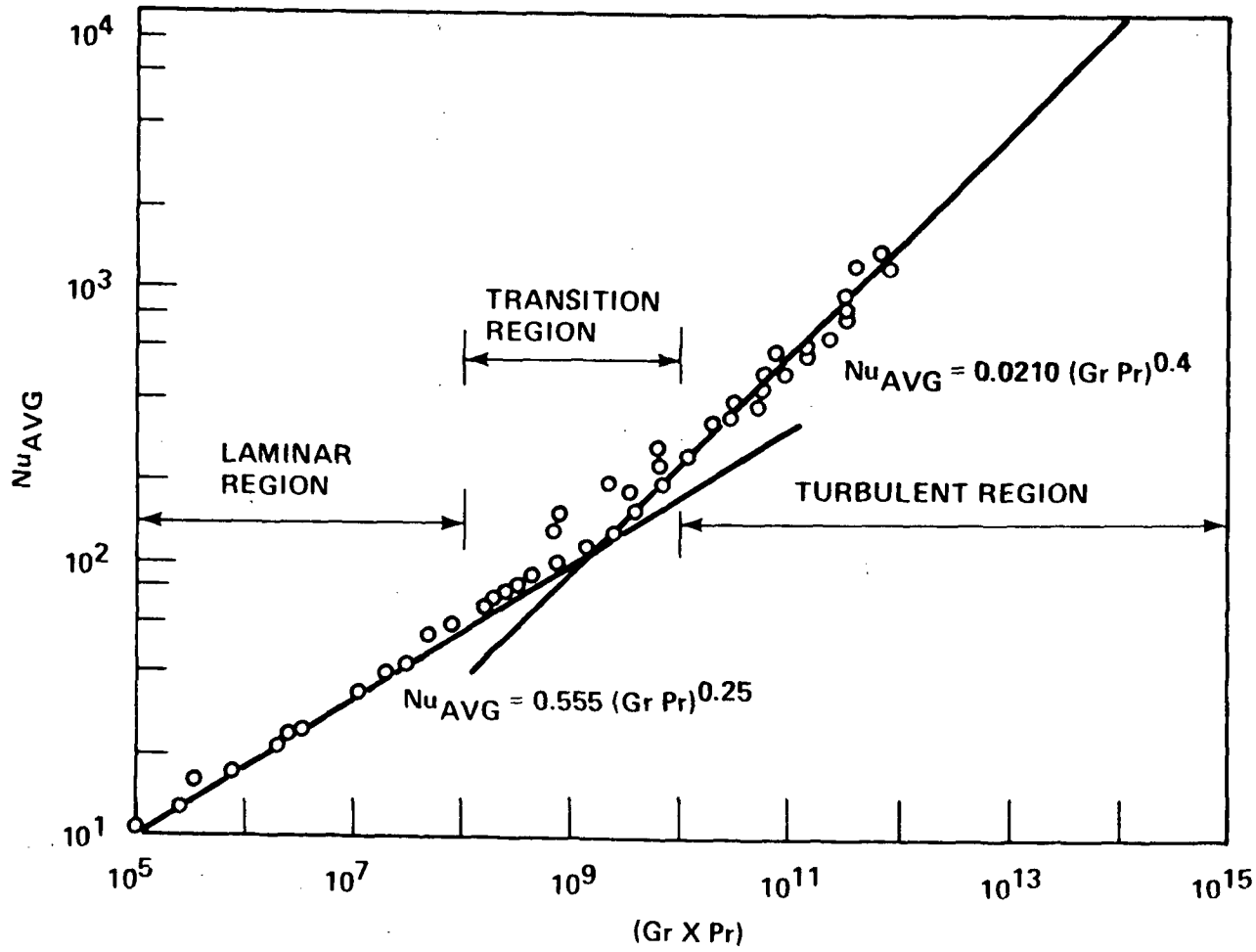


Figure 4-6. Comparison of Nusselt Numbers Calculated by Equation (4-1) With Data

where

ΔT = tube wall temperature correction

Q_l = local tube wall heat flux

Values for A and B are given in table F-4 of the data report.[1]

In the SGFLUX program, the local tube wall heat flux in the two-phase matrix test was calculated from the simultaneous solution of equation (4-2) and the following equation:

$$Q_l = h_s (T_f - T_w + \Delta T) \tag{4-3}$$

where

Q_l	=	tube wall heat flux (calculated)
h_s	=	turbulent free convection film coefficient calculated from equation (4-1)
T_f	=	secondary fluid temperature (measured)
T_w	=	tube wall temperature (measured)
ΔT	=	tube wall temperature correction calculated from equation (4-2)
A and B	=	coefficients in tube wall correction factor equation, determined from single-phase shakedown tests

The solution of equations (4-2) and (4-3) shows that for the case where 1/A is less than h_s, the value of Q_l will be negative for positive values of $(T_f - T_w)$ and B. Since this solution is physically not correct, an alternate solution was used to calculate the heat flux if 1/A was less than h_s. In this case, the primary side flow regime is assumed to be dispersed flow with no liquid film on the walls. The primary side film coefficient was calculated from the Dittus-Boelter correlation. The overall heat transfer coefficient and local heat flux were then calculated from the following equations:

$$\frac{1}{U_{OVERALL}} = \frac{1}{h_s} + \frac{1}{h_t} + \frac{1}{h_p} \tag{4-4}$$

1. Howard, R. C., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task Data Report," NRC/EPRI/Westinghouse-4, January 1980.

$$Q_l = U_{OVERALL} (T_f - T_p) \quad (4\text{-}5)$$

where

$U_{OVERALL}$ = overall heat transfer coefficient
h_s = secondary side turbulent free convection film coefficient
h_t = tube wall equivalent heat transfer coefficient
h_p = primary side turbulent forced convection film coefficient
T_p = primary side temperature

From the measured heat flux in the four instrumented tubes, the total bundle heat transfer rate was calculated by multiplying the instrumented tube heat transfer by a weighting factor, which represented the number of uninstrumented tubes assumed to respond like the instrumented tube. The weighting factors were determined from a series of air/water tests on the inlet plenum. These tests measured the flow distribution of air and water at the tubesheet. The weighting factor represents the number of tubes with inlet flow conditions close to the inlet flow of the instrumented tube. The weighting factors developed from the air/water tests are presented in appendix B of the data report.[1]

The local tube wall heat flux, the primary steam temperature, and the individual tube inlet flow distribution data from the air/water test were combined to calculate local quality in the tubes from a nodal energy balance (figure 4-7). The nodal energy balance was written as

Energy transferred to the node = Energy absorbed by the primary fluid

That is,

Tube wall heat flux - Wall heat stored = Energy absorbed by steam plus energy absorbed by evaporating liquid drops

$$Q_l A_l - M_w C_p \frac{dT_w}{dt} = W_g [H_o - H_i] + W_{fg} [H_o - H_f] \quad (4\text{-}6)$$

1. Howard, R. C., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task Data Report," NRC/EPRI/Westinghouse-4, January 1980.

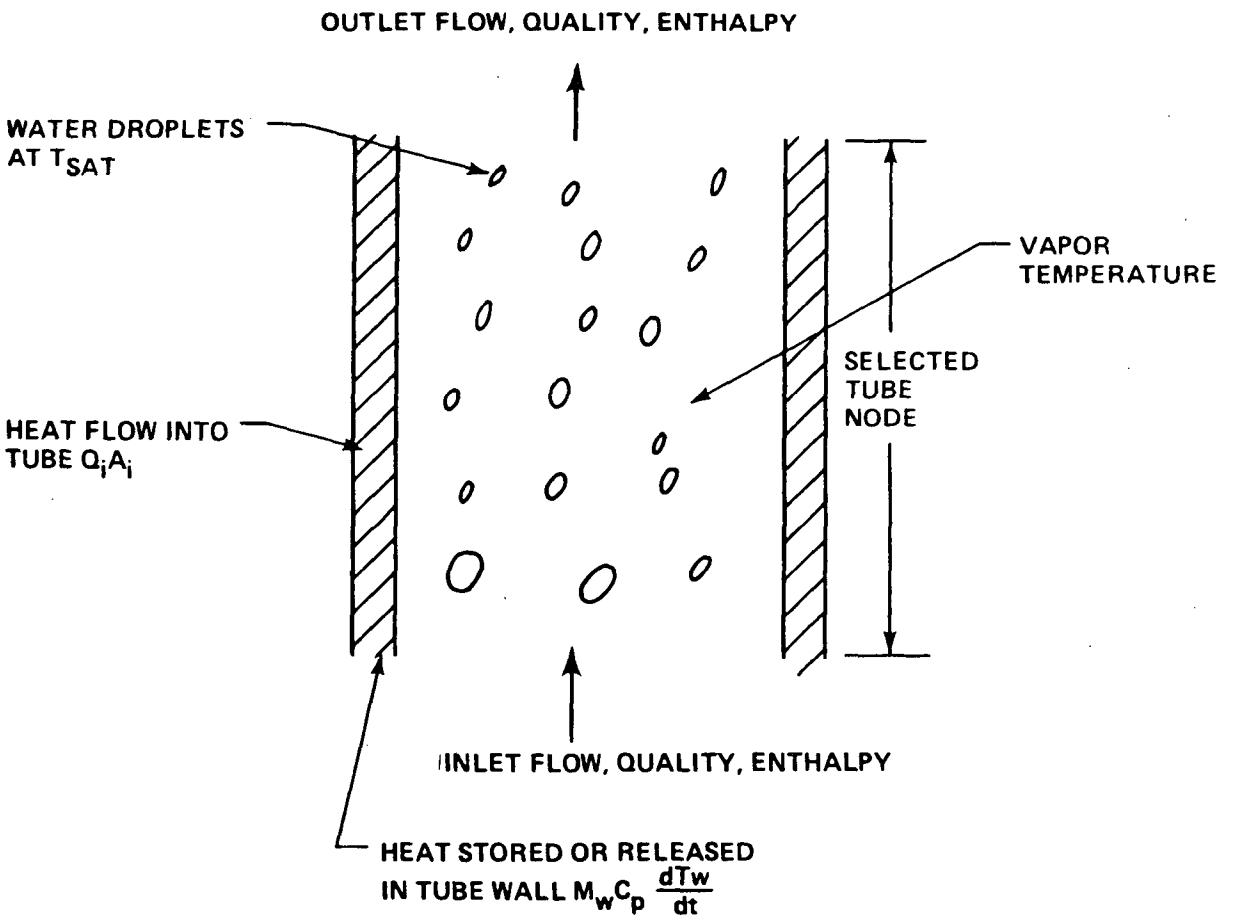


Figure 4-7. Heat Transfer and Quality Calculation for a Single Primary Tube

where

Q_l	=	measured nodal tube wall heat flux
A_l	=	tube wall nodal heat transfer area
M_w	=	tube wall nodal mass
C_p	=	tube wall heat capacity
dT_w/dt	=	rate of increase of tube wall temperature
W_g	=	primary side steam mass flow rate at the entrance to the node
H_o	=	steam enthalpy at the node exit
H_i	=	steam enthalpy at the node entrance
H_f	=	enthalpy of saturated liquid
W_{fg}	=	rate of liquid evaporation in the node

From the steam probe data, the primary steam enthalpy was determined. The rate of change of tube wall temperature was calculated from the tube wall thermocouple data and the tube wall heat flux was calculated from the measured secondary fluid and tube wall thermocouples. The individual tube inlet steam flow was derived from the air/water test data. The remaining unknown in equation (4-6) is W_{fg}, the rate of liquid evaporation in the node. By starting at the first nodal elevation, where the inlet steam mass flow rate was known from the air/water tests, equation (4-6) was used to compute the liquid evaporation in the node. From this calculation the inlet steam flow to the next node could be found and equation (4-6) could again be used to compute the liquid evaporation in the second node. The calculation was continued for all the calculational nodes. From the local nodal steam flow and the total tube mass flow (assumed to be constant), the local quality was found.

Uncertainties in the total bundle heat transfer rate due to measurement error and the additional uncertainty of the tube wall correction factor are discussed in appendix I of the data report.[1] The data show that the uncertainty is relatively small for low flow and high quality experiments, where the tube wall quench front only reaches approximately 1.22 m (4 ft). For lower qualities and higher flows, the quench front

1. Howard, R. C., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task Data Report," NRC/EPRI/Westinghouse-4, January 1980.

advances beyond the 1.22 m (4 ft) elevation into a region of the tube bundle which is not as well instrumented. Therefore, the temperature interpolation/extrapolation methods which are used have greater uncertainty, resulting in larger uncertainties in the calculated energy transfer. It is also to be noted that, since the quality calculation is a step-wise marching approach, errors can accumulate and produce larger errors at the upper regions of the steam generator where there is less instrumentation to correct the calculation.

4-3. SUMMARY OF TEST RESULTS

Table 4-2 presents the actual run conditions for each valid test, and summary test results. Summarized in table 4-2 are the time-averaged test boundary conditions (total inlet flow, quality, and loop pressure) and the test initial conditions (steam generator secondary liquid temperature and level). More detailed test run conditions are presented in appendix H of the task plan.[1]

The data in tables 4-2A and 4-2B were also presented in the data report. However, since the data report was issued, it has been learned that the data in column 12 reporting total energy transport for test runs prior to run 22701 were not based on the current version of the data reduction program SGFLOWS. In the original version of SGFLOWS, the heat loss through the superheater pipe wall was neglected. This assumption tended to overestimate the energy absorbed by the primary flow in the separator and the calculated liquid evaporation in the superheater. Since the amount of liquid evaporated in the superheater is subtracted from the measured loop outlet steam flow to get the steam generator outlet plenum steam flow, overestimation of the liquid evaporation in the superheater will result in underestimation of the steam generator outlet plenum steam flow. This error led directly to an underestimation of the bundle energy transfer. The data presented in tables 4-2A and 4-2B in this report are taken from the current version of SGFLOWS.

---

1. Hochreiter, L. E., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task: Task Plan Report," NRC/EPRI/Westinghouse-2, March 1978.

SECTION 5
DATA ANALYSIS

5-1. INTRODUCTION

In this section, the steam generator test data are explored in depth. Phenomenological reasons are proposed to explain the data trends within a run and the variation in data trends among runs.

The first test run to be analyzed was the reference run, run 22701. Data from this run were evaluated to determine that the loop boundary conditions were properly controlled. The boundary conditions at the steam generator tubesheet were calculated from the loop instrumentation, and the overall bundle heat transfer was calculated from the tubesheet boundary conditions. Reduced data from the tube bundle thermocouples were evaluated to aid in understanding of the radial and axial variation within the tube bundle. The replicate reference runs and the single-parameter variation tests were evaluated by comparing key parameters with those of the reference run.

Test results for each run are presented graphically in appendix H of NRC/EPRI/Westinghouse Report No. 4.[1] Additional information relating to each test is presented in the summary sheets preceding the plots in appendix H of Report No. 4 and in table 4-2 of this report. Summary sheets for the three reference runs and the two quality sensitivity runs are reproduced in tables 5-1 through 5-5. In these tables, the mixer pressure and containment tank pressure are reported as recorded in gage pressure units. Where a conversion from gage to absolute pressure is required, a constant conversion factor of 97.9 kPa (14.2 psi), the mean atmospheric pressure at 300 m (1000 ft), is used. The elevation at the Westinghouse Forest Hills test facility is approximately 300 m (1000 ft) above sea level.

---

1. Howard, R. C., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task Evaluation Report," NRC/EPRI/Westinghouse-4, January 1980.

TABLE 5-1

REFERENCE RUN SUMMARY SHEET

DATE: 4/4/79

A. TIME-AVERAGED RUN CONDITIONS

1. Boiler steam flow [kg/sec (lb/sec)] - 0.179 (0.395)
2. Water flow [kg/sec (lb/sec)] - 0.045 (0.100)
3. Containment tank pressure [kPa (psig)] - 172 (25)
4. Steam temperature [^{o}C (^{o}F)] - 155 (311)
5. Water temperature [^{o}C (^{o}F)] - 122 (251)
6. Mixer pressure [kPa (psig)] - 193 (28)
7. Test time (sec) - 1439.0

B. INITIAL SECONDARY LIQUID LEVEL AND TEMPERATURE

1. Level [m(ft)] - 10.1 (33.1)
2. Initial temperature

Elevation [m(ft)]	Initial Temperature [^{o}C (^{o}F)]
0.00 (0.00)	262 (504)
0.15 (0.50)	271 (520)
0.30 (1.00)	274 (526)
0.46 (1.50)	273 (523)
0.61 (2.00)	273 (524)
1.22 (4.00)	-
3.05 (10.00)	274 (525)
6.09 (20.00)	273 (524)
8.23 (27.00)	-
10.67 (35.00)	273 (524)

TABLE 5-1 (cont)

REFERENCE RUN SUMMARY SHEET

C. MASS BALANCE COMPONENTS

1. Steam probe purge steam [kg (lb)] - 3.19 (7.04)
2. Liquid collection
   (a) Outlet plenum [kg (lb)] - 4.48 (9.87)
   (b) SG collection tank [kg (lb)] - NA
3. Posttest drain from hot leg [kg (lb)] - 1.29 (2.85)

D. FAILED BUNDLE T/Cs[1]

294, 295, 298, 305, 309, 310, 311, 321, 326, 532, 549, 553, 555, 564, 565, 568, 569

E. OVERALL ENERGY EXCHANGE FROM SECONDARY TO PRIMARY FROM BEGINNING OF TEST TO 1.2-METER (4-FOOT) QUENCH TIME

1. From primary side energy balance [kw-sec(Btu)] - 1.13×10^5 (1.08×10^5)
2. From local heat flux ($\int_0^t \int_0^{HTA} \Phi \, da dt$) [kw-sec(Btu)] - 0.960×10^5 (0.914×10^5)
3. Φ = tube wall heat flux (kw/m^2)
   HTA = bundle heat transfer area
   t = integration time limit (900 sec)

---

1. T/Cs are defined as failed based on resistance reading or T/C response.

TABLE 5-2

SUMMARY SHEET FOR REPLICATE OF REFERENCE RUN

(Run 21711)

DATE: 3/14/79

A. TIME-AVERAGED RUN CONDITIONS

1. Boiler steam flow [kg/sec (lb/sec)] - 0.179 (0.395)
2. Water flow [kg/sec (lb/sec)] - 0.045 (0.099)
3. Containment tank pressure [kPa (psig)] - 172 (25)
4. Steam temperature [°C (°F)] - 157 (315)
5. Water temperature [°C (°F)] - 124 (256)
6. Mixer pressure [kPa (psig)] - 193 (28)
7. Test time (sec) - 1439.0

B. INITIAL SECONDARY LIQUID LEVEL AND TEMPERATURE

1. Level [m(ft)] - 9.9 (32.4)
2. Initial temperature

Elevation [m(ft)]	Initial Temperature [°C (°F)]
0.00 (0.00)	260 (500)
0.15 (0.50)	266 (510)
0.30 (1.00)	274 (525)
0.46 (1.50)	271 (520)
0.61 (2.00)	271 (520)
1.22 (4.00)	271 (520)
3.05 (10.00)	271 (520)
6.09 (20.00)	271 (520)
8.23 (27.00)	271 (520)
10.67 (35.00)	271 (520)

TABLE 5-2 (cont)

SUMMARY SHEET FOR REPLICATE OF REFERENCE RUN

(Run 21711)

C. MASS BALANCE COMPONENTS

1. Steam probe purge steam [kg (lb)] - 4.04 (8.91)
2. Liquid collection
   (a) Outlet plenum [kg (lb)] - 2.15 (4.74)
   (b) SG collection tank [kg (lb)] - NA
3. Posttest drain from hot leg [kg (lb)] - 1.33 (2.94)

D. FAILED BUNDLE T/Cs[1]

294, 295, 298, 305, 309, 310, 311, 321, 326, 549, 553, 564, 565, 568

E. OVERALL ENERGY EXCHANGE FROM SECONDARY TO PRIMARY FROM BEGINNING OF TEST TO 1.2-METER (4-FOOT) QUENCH TIME

1. From primary side energy balance [kw-sec(Btu)] - 0.594×10^5 (0.566×10^5)
2. From local heat flux ($\int_0^t \int_0^{HTA} \phi \, da dt$) [kw-sec(Btu)] - 0.678×10^5 (0.646×10^5)
3. ϕ = tube wall heat flux (kw/m^2)
   HTA = bundle heat transfer area
   t = integration time limit (600 sec)

---

1. T/Cs are defined as failed based on resistance reading or T/C response.

TABLE 5-3

SUMMARY SHEET FOR REPLICATE OF REFERENCE RUN

(Run 22010)

DATE: 3/22/79

A. TIME-AVERAGED RUN CONDITIONS

1. Boiler steam flow [kg/sec (lb/sec)] - 0.182 (0.402)
2. Water flow [kg/sec (lb/sec)] - 0.045 (0.100)
3. Containment tank pressure [kPa (psig)] - 172 (25)
4. Steam temperature [^{o}C (^{o}F)] - 154 (309)
5. Water temperature [^{o}C (^{o}F)]- 125 (257)
6. Mixer pressure [kPa (psig)] - 193 (28)
7. Test time (sec) - 1440.0

B. INITIAL SECONDARY LIQUID LEVEL AND TEMPERATURE

1. Level [m(ft)] - 10.2 (33.6)
2. Initial temperature

Elevation [m(ft)]	Initial Temperature [^{o}C (^{o}F)]
0.00 (0.00)	257 (495)
0.15 (0.50)	271 (520)
0.30 (1.00)	274 (525)
0.46 (1.50)	274 (525)
0.61 (2.00)	274 (525)
1.22 (4.00)	274 (525)
3.05 (10.00)	274 (525)
6.09 (20.00)	274 (525)
8.23 (27.00)	273 (524)
10.67 (35.00)	273 (524)

TABLE 5-3 (cont)

SUMMARY SHEET FOR REPLICATE OF REFERENCE RUN

(Run 22010)

C. MASS BALANCE COMPONENTS

1. Steam probe purge steam [kg (lb)] - 4.01 (8.84)
2. Liquid collection
   (a) Outlet plenum [kg (lb)] - 3.18 (7.01)
   (b) SG collection tank [kg (lb)] - NA
3. Posttest drain from hot leg [kg (lb)] - 1.09 (2.40)

D. FAILED BUNDLE T/Cs[1]

294, 295, 305, 309, 310, 311, 326, 532, 553, 564, 565, 568, 569

E. OVERALL ENERGY EXCHANGE FROM SECONDARY TO PRIMARY FROM BEGINNING OF TEST TO 1.2-METER (4-FOOT) QUENCH TIME

1. From primary side energy balance [kw-sec(Btu)] - 0.627×10^5 (0.597×10^5)
2. From local heat flux ($\int_0^t \int_0^{HTA} \phi \, da\,dt$) [kw-sec(Btu)] - 0.613×10^5 (0.584×10^5)
3. ϕ = tube wall heat flux (kw/m^2)
   HTA = bundle heat transfer area
   t = integration time limit (600 sec)

---

1. T/Cs are defined as failed based on resistance reading or T/C response.

TABLE 5-4

SUMMARY SHEET FOR QUALITY SENSITIVITY RUN (Run 23605)

DATE: 4/27/79

A. TIME-AVERAGED RUN CONDITIONS

1. Boiler steam flow [kg/sec (lb/sec)] - 0.111 (0.245)
2. Water flow [kg/sec (lb/sec)] - 0.113 (0.249)
3. Containment tank pressure [kPa (psig)] - 172 (25)
4. Steam temperature [^{o}C (^{o}F)] - 152 (306)
5. Water temperature [^{o}C (^{o}F)]- 126 (258)
6. Mixer pressure [kPa (psig)] - 193 (28)
7. Test time (sec) - 1446.0

B. INITIAL SECONDARY LIQUID LEVEL AND TEMPERATURE

1. Level [m(ft)] - 10.1 (33.3)
2. Initial temperature

Elevation [m(ft)]	Initial Temperature [^{o}C (^{o}F)]
0.00 (0.00)	257 (494)
0.15 (0.50)	266 (510)
0.30 (1.00)	274 (526)
0.46 (1.50)	273 (523)
0.61 (2.00)	272 (521)
1.22 (4.00)	-
3.05 (10.00)	274 (525)
6.09 (20.00)	273 (524)
8.23 (27.00)	-
10.67 (35.00)	273 (524)

TABLE 5-4 (cont)

SUMMARY SHEET FOR QUALITY SENSITIVITY RUN (Run 23605)

C. MASS BALANCE COMPONENTS

1. Steam probe purge steam [kg (lb)] - 6.75 (14.88)
2. Liquid collection
   (a) Outlet plenum [kg (lb)] - 10.06 (22.18)
   (b) SG collection tank [kg (lb)] - NA
3. Posttest drain from hot leg [kg (lb)] - 9.07 (20.0)

D. FAILED BUNDLE T/Cs[1]

287, 294, 295, 298, 305, 308, 309, 310, 311, 326, 517, 518, 520, 521, 524, 531, 532, 533, 549, 553, 555, 564, 565, 568, 569, 570

E. OVERALL ENERGY EXCHANGE FROM SECONDARY TO PRIMARY FROM BEGINNING OF TEST TO 1.2-METER (4-FOOT) QUENCH TIME

1. From primary side energy balance [kw-sec(Btu)] - 0.719×10^5 (0.685×10^5)
2. From local heat flux ($\int_0^t \int_0^{HTA} \phi \, da dt$) [kw-sec(Btu)] - 0.378×10^5 (0.360×10^5)
3. ϕ = tube wall heat flux (kw/m^2)
   HTA = bundle heat transfer area
   t = integration time limit (300 sec)

---

1. T/Cs are defined as failed based on resistance reading or T/C response.

TABLE 5-5

SUMMARY SHEET FOR QUALITY SENSITIVITY RUN (Run 21806)

A. TIME-AVERAGED RUN CONDITIONS

1. Boiler steam flow [kg/sec (lb/sec)] - 0.045 (0.100)
2. Water flow [kg/sec (lb/sec)] - 0.181 (0.400)
3. Containment tank pressure [kPa (psig)] - 172 (25)
4. Steam temperature [^{o}C (^{o}F)] - 148 (299)
5. Water temperature [^{o}C (^{o}F)] - 128 (262)
6. Mixer pressure [kPa (psig)] - 200 (29)
7. Test time (sec) - 1679.0

B. INITIAL SECONDARY LIQUID LEVEL AND TEMPERATURE

1. Level [m(ft)] - 10.0 (32.7)
2. Initial temperature

Elevation [m(ft)]	Initial Temperature [^{o}C (^{o}F)]
0.00 (0.00)	260 (500)
0.15 (0.50)	266 (510)
0.30 (1.00)	268 (515)
0.46 (1.50)	271 (520)
0.61 (2.00)	271 (520)
1.22 (4.00)	271 (520)
3.05 (10.00)	271 (520)
6.09 (20.00)	271 (520)
8.23 (27.00)	271 (520)
10.67 (35.00)	271 (520)

TABLE 5-5 (cont)

SUMMARY SHEET FOR QUALITY SENSITIVITY RUN (Run 21806)

C. MASS BALANCE COMPONENTS

1. Steam probe purge steam [kg (lb)] - 13.09 (28.85)
2. Liquid collection
   (a) Outlet plenum [kg (lb)] - NA
   (b) SG collection tank [kg (lb)] - 65.23 (143.8)
3. Posttest drain from hot leg [kg (lb)] - 17.33 (38.21)

D. FAILED BUNDLE T/Cs[1]

310, 311, 326, 553, 564, 565, 568

E. OVERALL ENERGY EXCHANGE FROM SECONDARY TO PRIMARY FROM BEGINNING OF TEST TO 1.2-METER (4-FOOT) QUENCH TIME

1. From primary side energy balance [kw-sec(Btu)] - 0.752×10^5 (0.716×10^5)
2. From local heat flux ($\int_0^t \int_0^{HTA} \phi \, da dt$) [kw-sec(Btu)] - 0.378×10^5 (0.360×10^5)
3. ϕ = tube wall heat flux (kw/m^2)
   HTA = bundle heat transfer area
   t = integration time limit (300 sec)

---

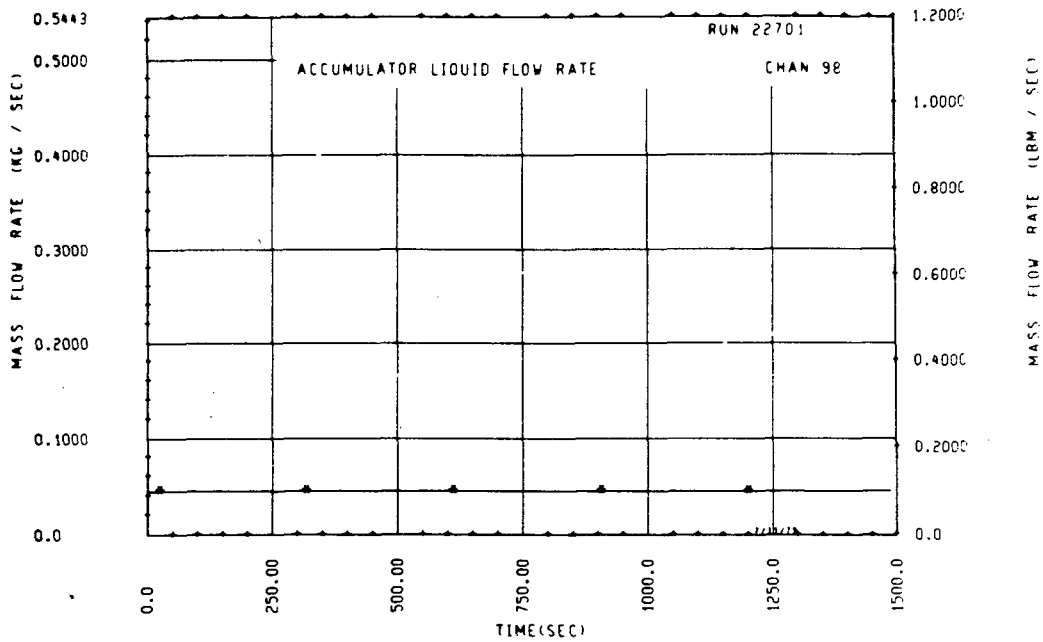
1. T/Cs are defined as failed based on resistance reading or T/C response.

5-2. ANALYSIS OF REFERENCE RUN

Evaluation of the reference run data shows that the boundary condition at the inlet tubesheet quickly reaches steady state. The liquid phase is very nearly completely evaporated in the tubes and the secondary water develops a temperature profile with a steep axial gradient but very little radial gradient. Inside the tubes, a liquid film forms which slowly advances up the tubes in a fashion that is analogous to the conduction-controlled rewetting of a hot fuel rod. The hot secondary fluid provides a source of stored energy which is cooled by the primary side two-phase mixture. The wet/dry interface, which is clearly seen by the tube wall thermocouples, advances at a constant velocity up the inside wall of the tubes. Residual liquid is present at the wet/dry interface. This liquid is dispersed into drops by the boiling at the interface and becomes entrained in the steam flow. Liquid evaporation occurs in the liquid film below the wet/dry interface and in the dispersed droplets above the wet/dry interface. The tube wall heat flux reaches a maximum at the wet/dry interface. The heat flux magnitude is consistent with the assumptions of single-phase forced convection above the interface with entrained droplets, two-phase forced convection below the interface, and critical heat flux at the interface, as shown in the following discussion.

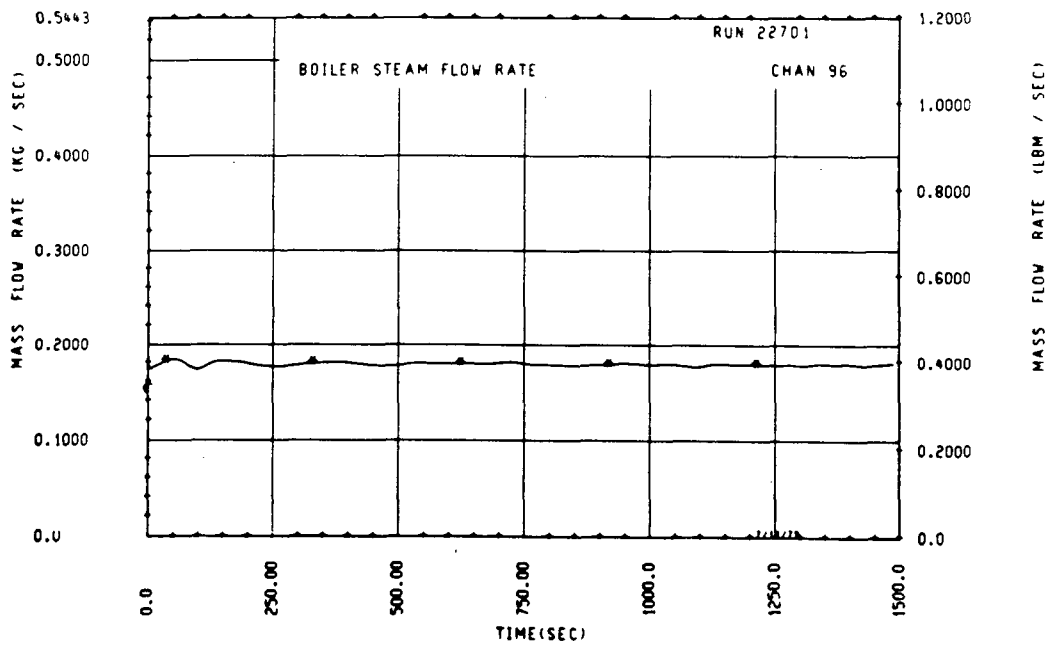
In the following discussion, the controlled test parameters are evaluated. The reference run data are reproduced in figures 5-1 through 5-31.

Figures 5-1 through 5-3 and figures 5-14 through 5-16 illustrate reference test data reduced by the SGFLOWS data reduction program. The mass flow rates in figures 5-1 through 5-3 are reduced from volumetric flow rate data. From the mass flow rate data calculated for the inlet and outlet steam generator plenums, the inlet and outlet plenum quality was calculated (figures 5-15 and 5-16) and from the mass flows and enthalpy, the overall bundle energy flow (figure 5-14) was calculated. The SGLOWS-reduced data are indicated by an asterisk at 300-second intervals on the plotted data line. Figure 5-10 plots the outlet plenum temperature measured by a thermocople in the outlet plenum, and figure 5-12 plots the steam temperature downstream of the superheater in the exhaust line, as measured by a resistance temperature detector (RTD). The steam temperatures in figure 5-12 are higher than those in figure 5-10 because of the superheater. The test was terminated at 1500 seconds.



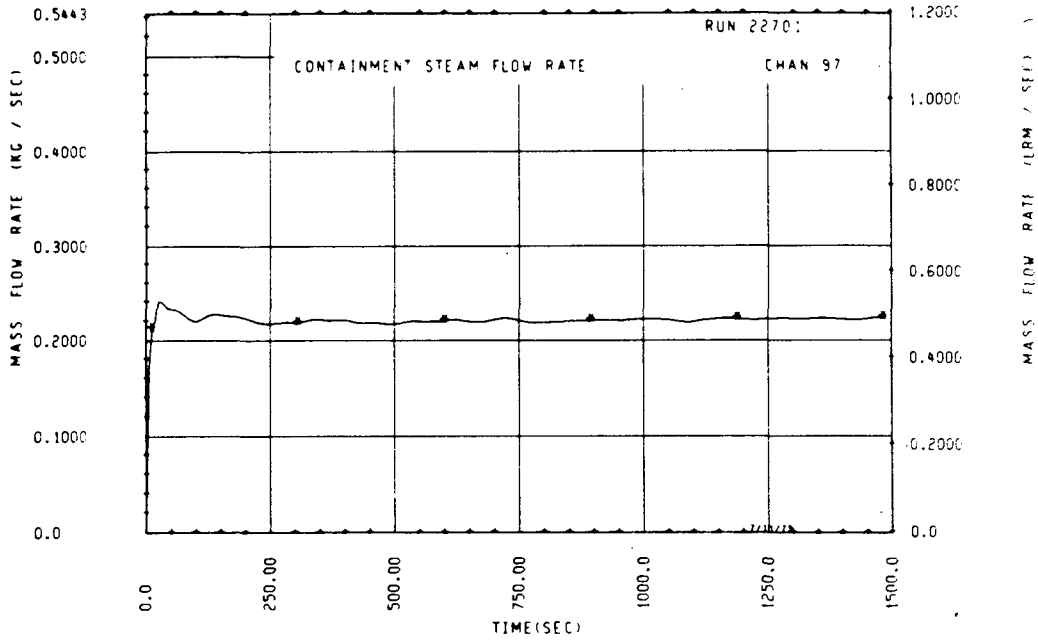
* SGFLOWS REDUCED DATA

Figure 5-1. Accumulator Liquid Flow Rate Versus Time, Reference Run



* SGFLOWS REDUCED DATA

Figure 5-2. Boiler Steam Flow Rate Versus Time, Reference Run



* SGFLOWS REDUCED DATA

Figure 5-3. Containment Steam Flow Rate Versus Time, Reference Run

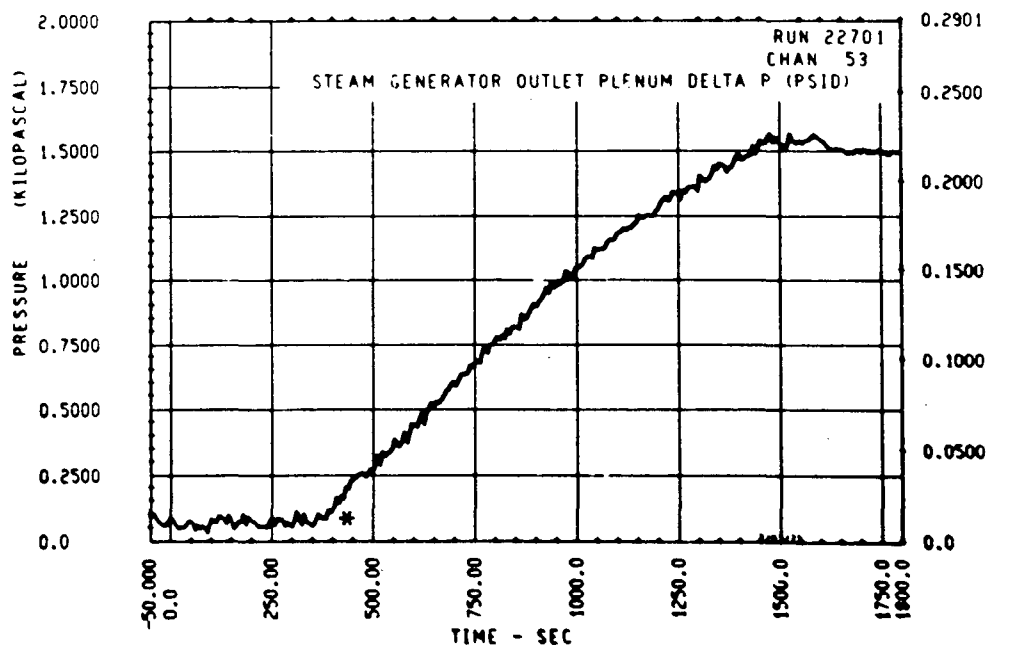


Figure 5-4. Outlet Plenum Differential Pressure Versus Time, Reference Run

*Response lag due to liquid collection below the lower pressure tap

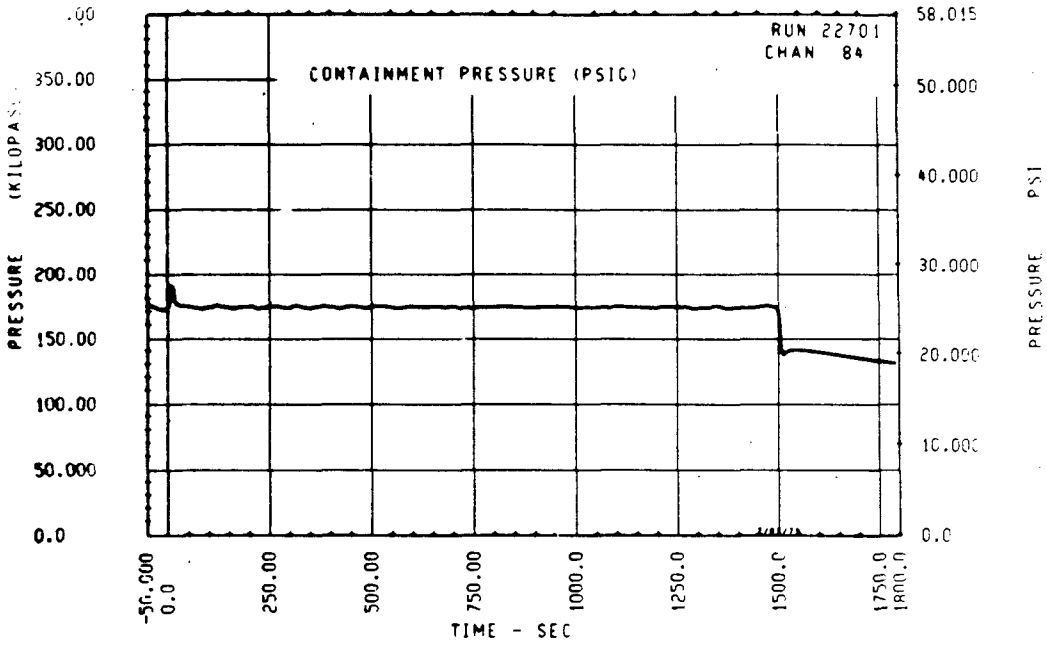


Figure 5-5. Containment Tank Pressure Versus Time, Reference Run

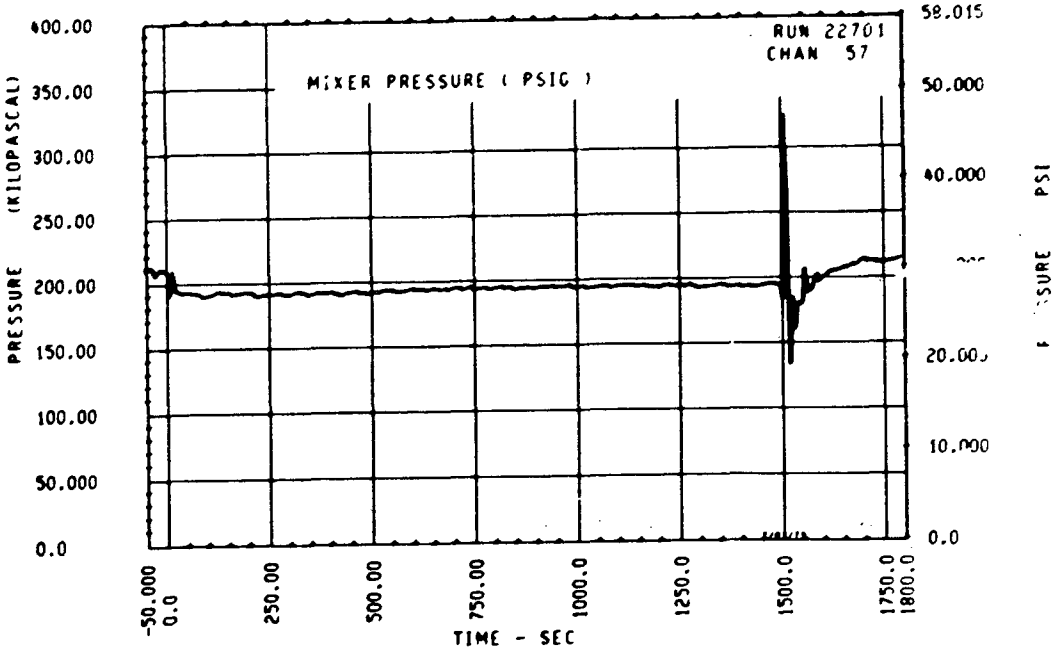


Figure 5-6. Mixer Pressure Versus Time, Reference Run

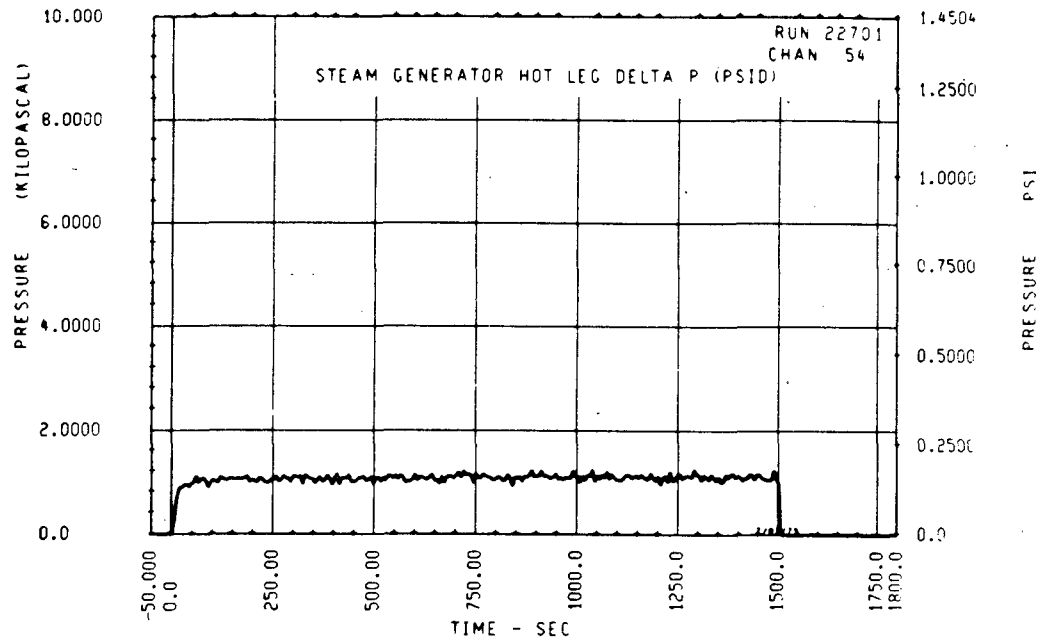


Figure 5-7. Hot Leg Differential Pressure Versus Time, Reference Run

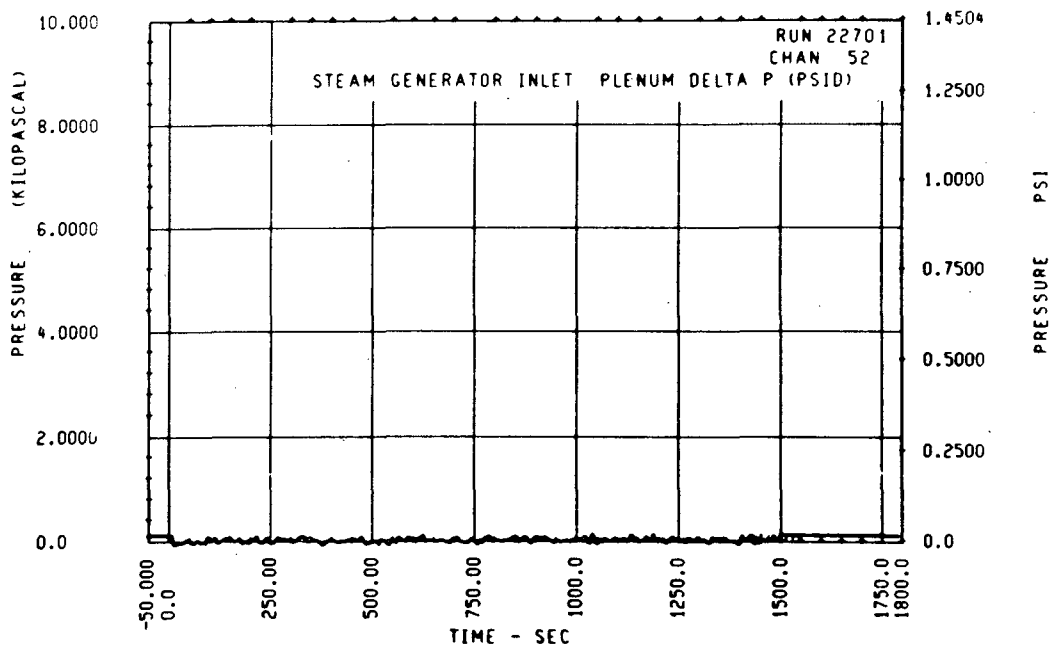


Figure 5-8. Inlet Plenum Differential Pressure Versus Time, Reference Run

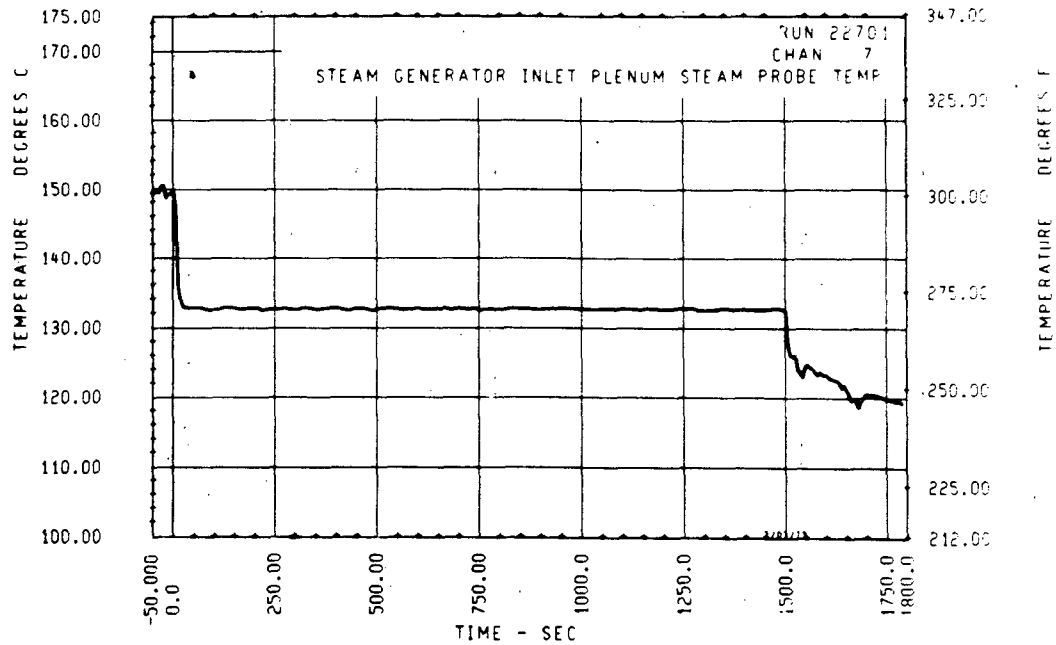


Figure 5-9. Inlet Plenum Steam Probe Temperature Versus Time, Reference Run

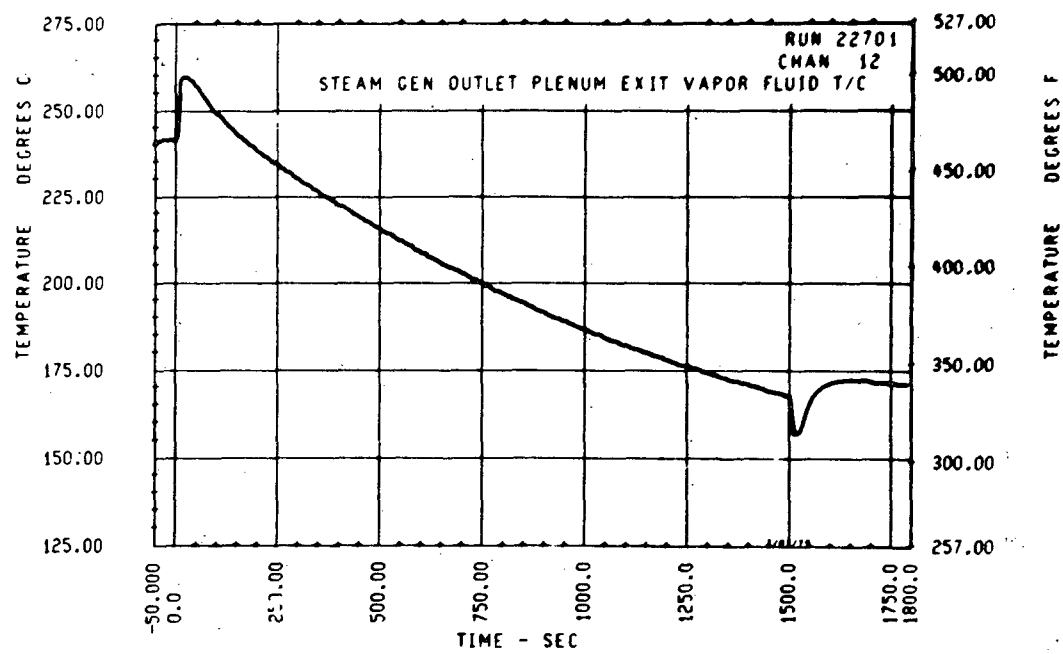


Figure 5-10. Outlet Plenum Exit Vapor Temperature Versus Time, Reference Run

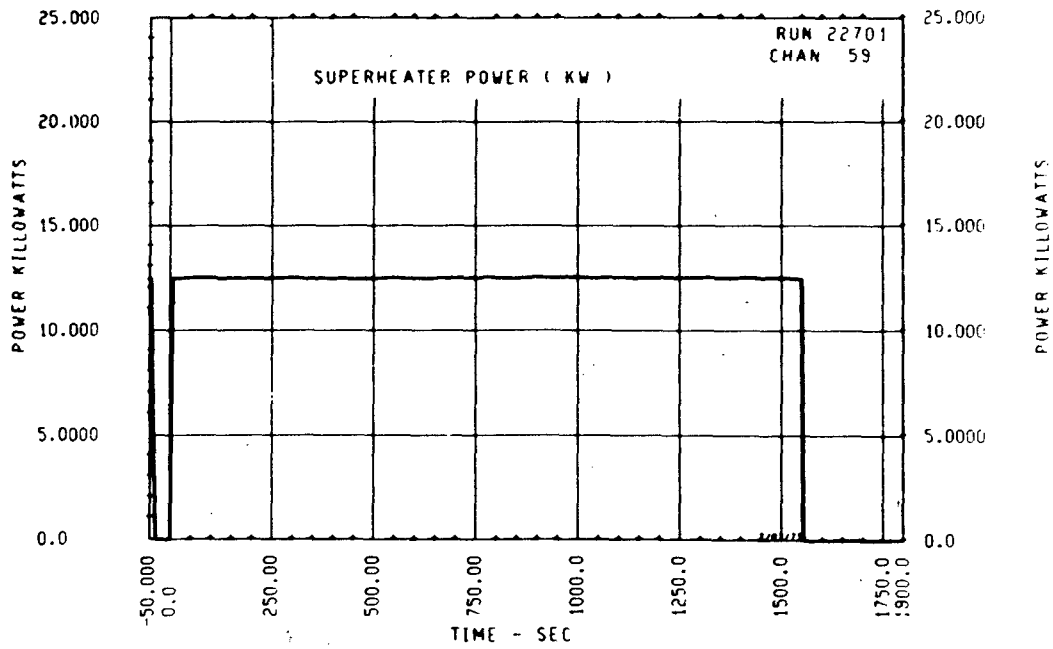


Figure 5-11. Superheater Power Versus Time, Reference Run

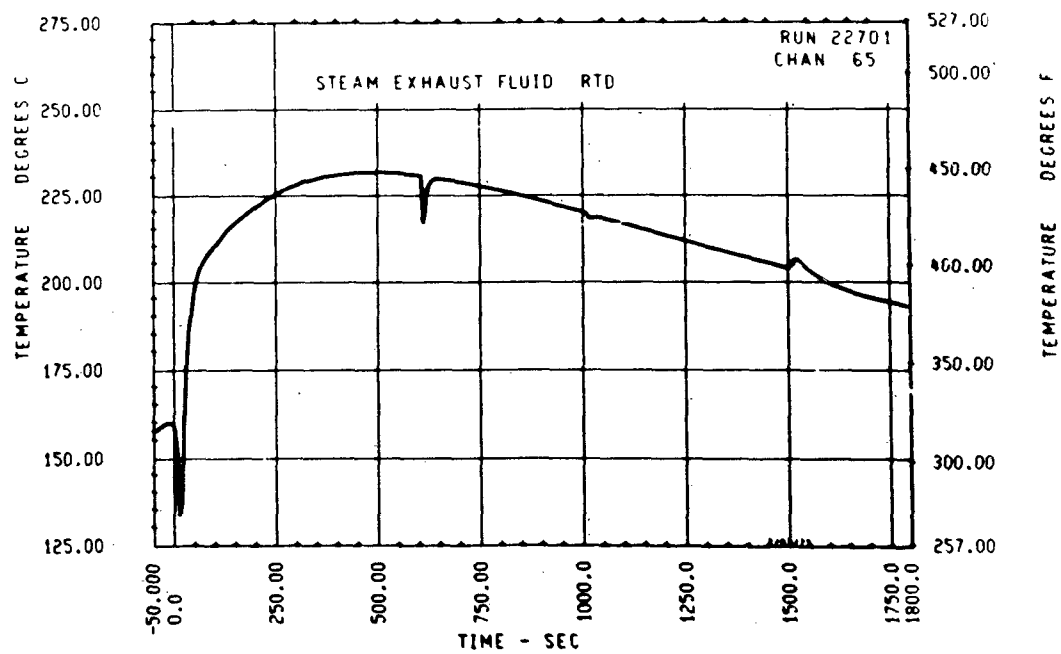


Figure 5-12. Superheater Exhaust Fluid Temperature Versus Time, Reference Run

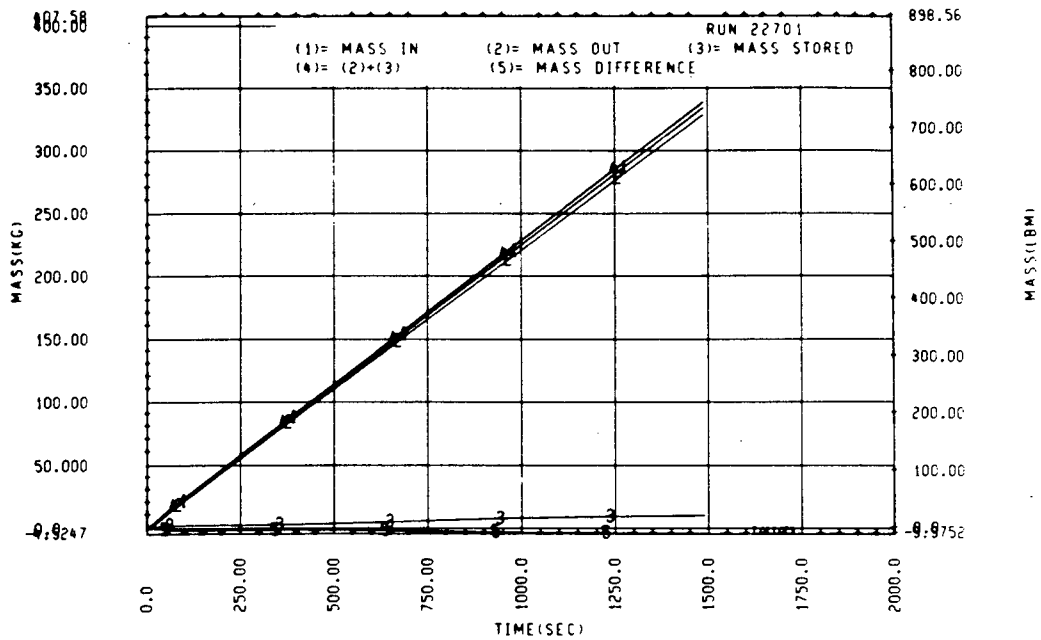
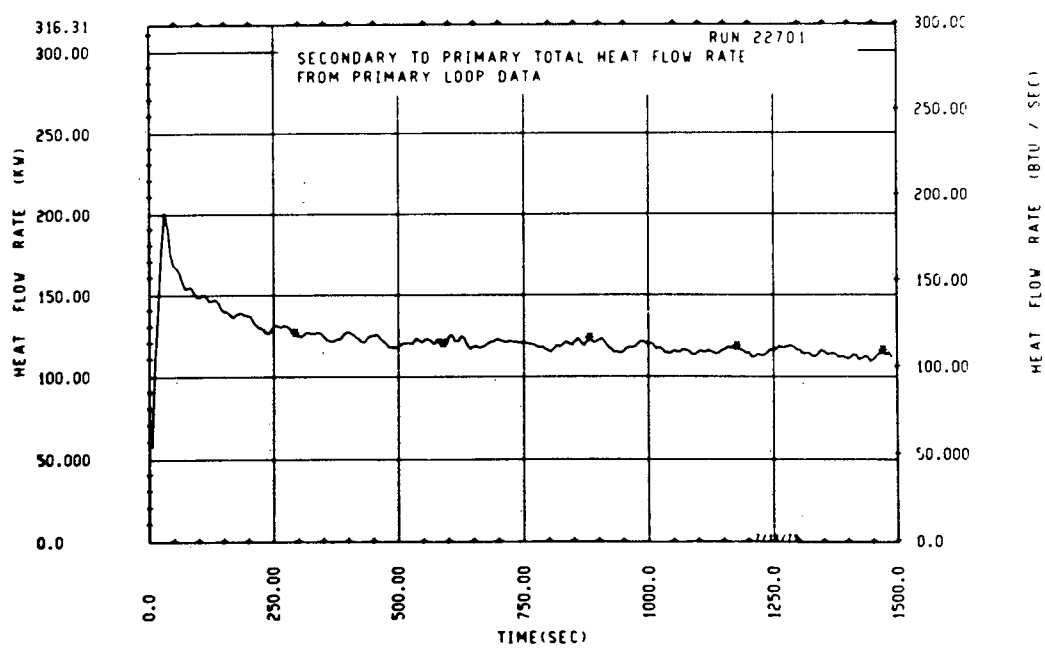
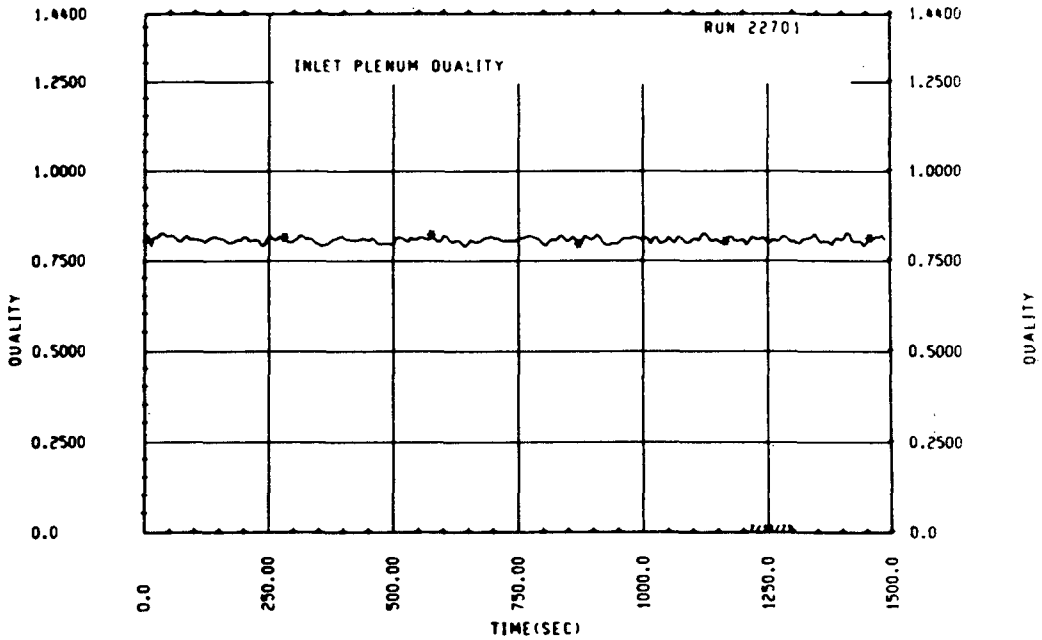


Figure 5-13. Mass Balance Versus Time, Reference Run



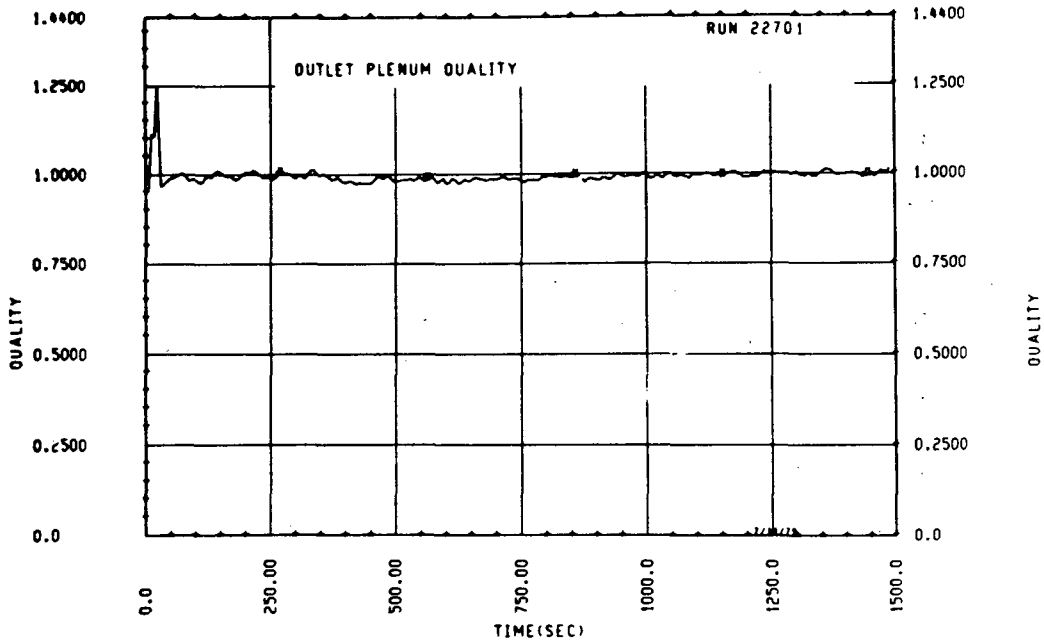
• SGFLOWS REDUCED DATA

Figure 5-14. Secondary to Primary Heat Flow Rate Versus Time, Reference Run



* SGFLOWS REDUCED DATA

Figure 5-15. Inlet Plenum Quality Versus Time, Reference Run



* SGFLOWS REDUCED DATA

Figure 5-16. Outlet Plenum Quality Versus Time, Reference Run

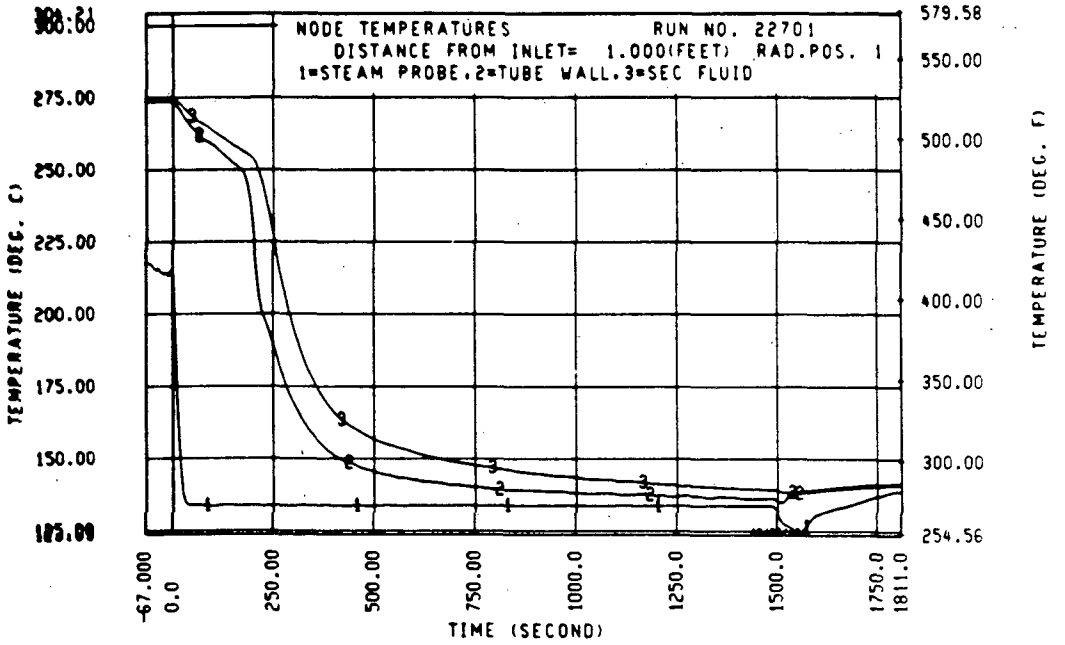


Figure 5-17. Nodal Temperatures, Reference Run, 0.30 m (1 ft) Elevation, Radial Position 1

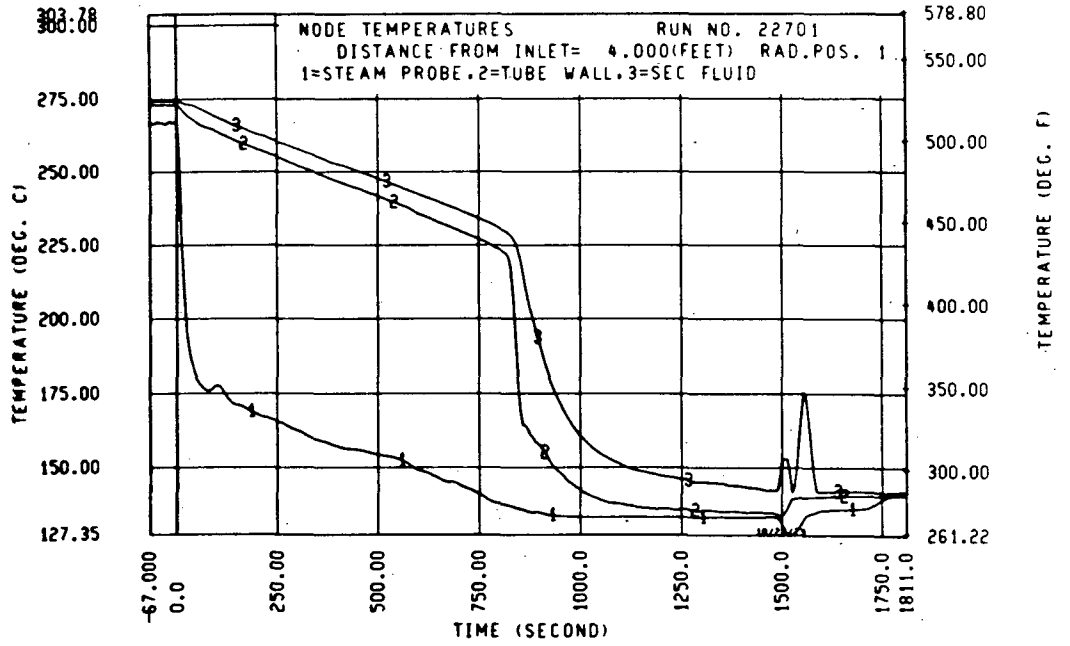


Figure 5-18. Nodal Temperatures, Reference Run, 1.22 m (4 ft) Elevation, Radial Position 1

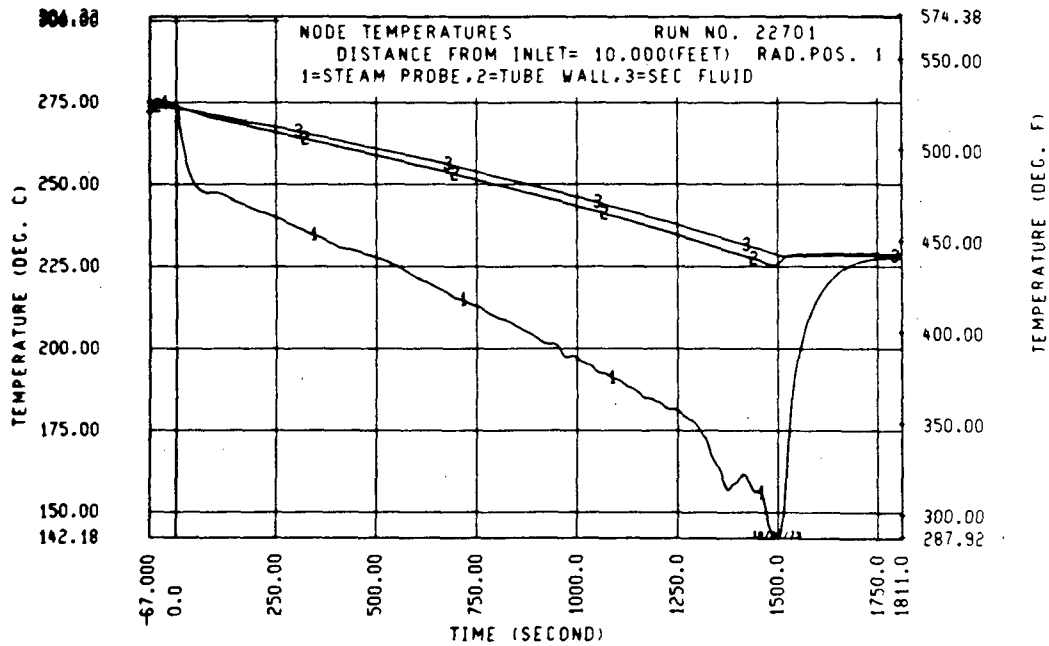


Figure 5-19. Nodal Temperatures, Reference Run, 3.0 m (10 ft) Elevation, Radial Position 1

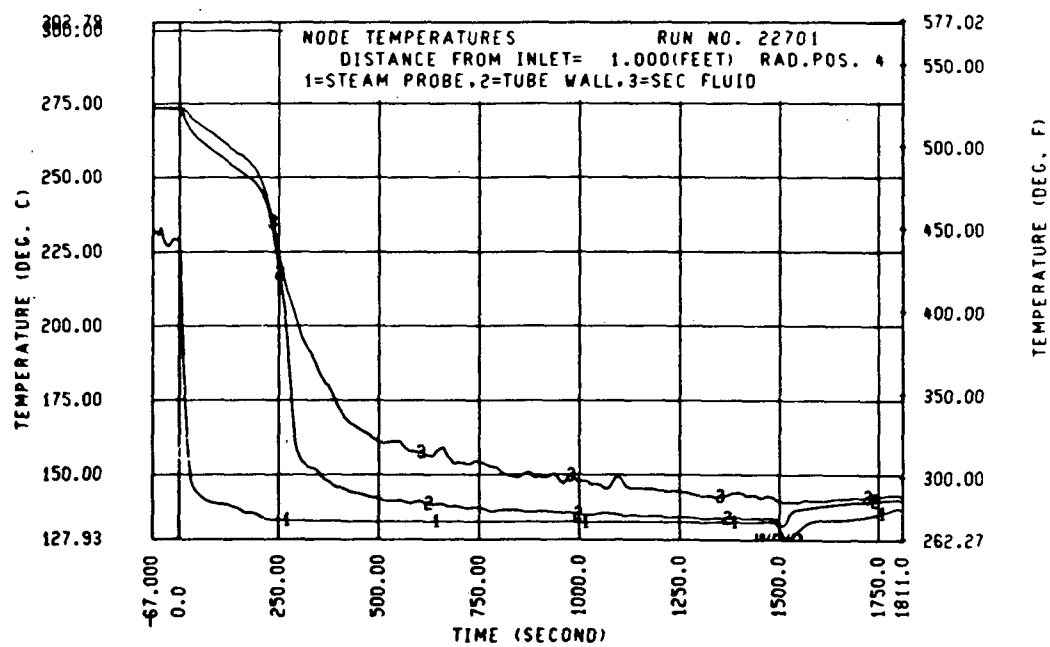


Figure 5-20. Nodal Temperatures, Reference Run, 0.30 m (1 ft) Elevation, Radial Position 4

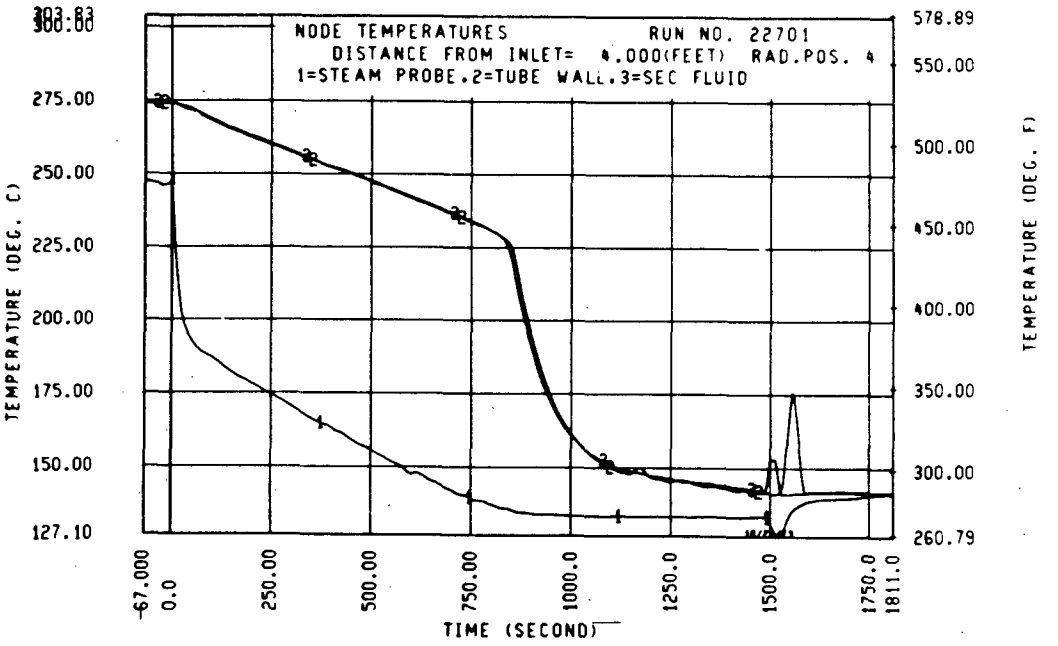


Figure 5-21. Nodal Temperatures, Reference Run, 1.22 m (4 ft) Elevation, Radial Position 4

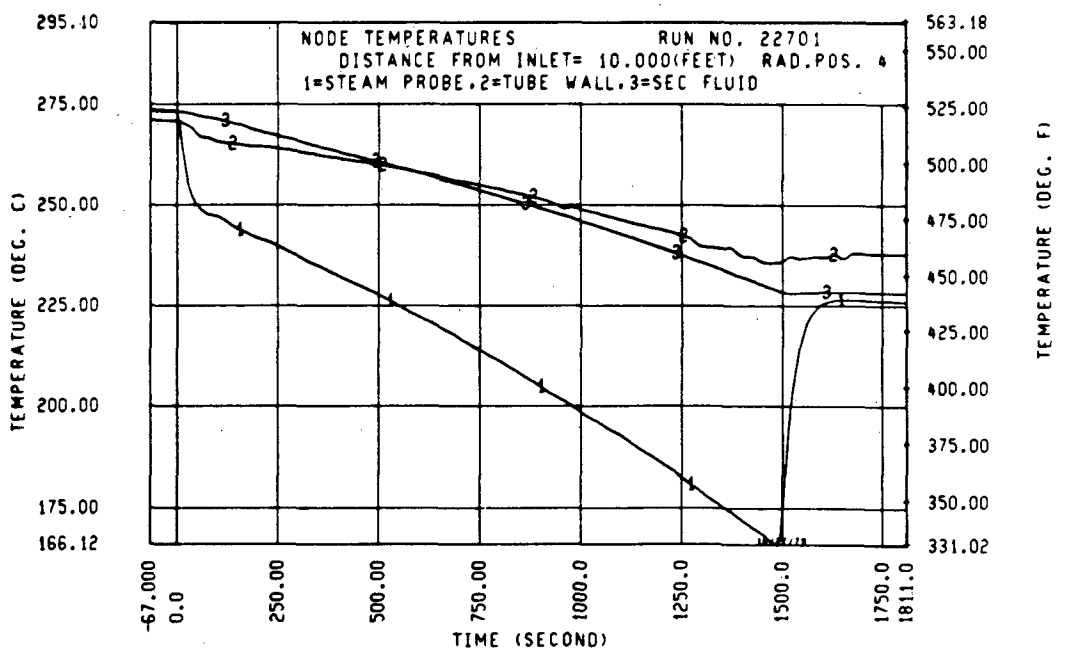


Figure 5-22. Nodal Temperatures, Reference Run, 3.0 m (10 ft) Elevation, Radial Position 4

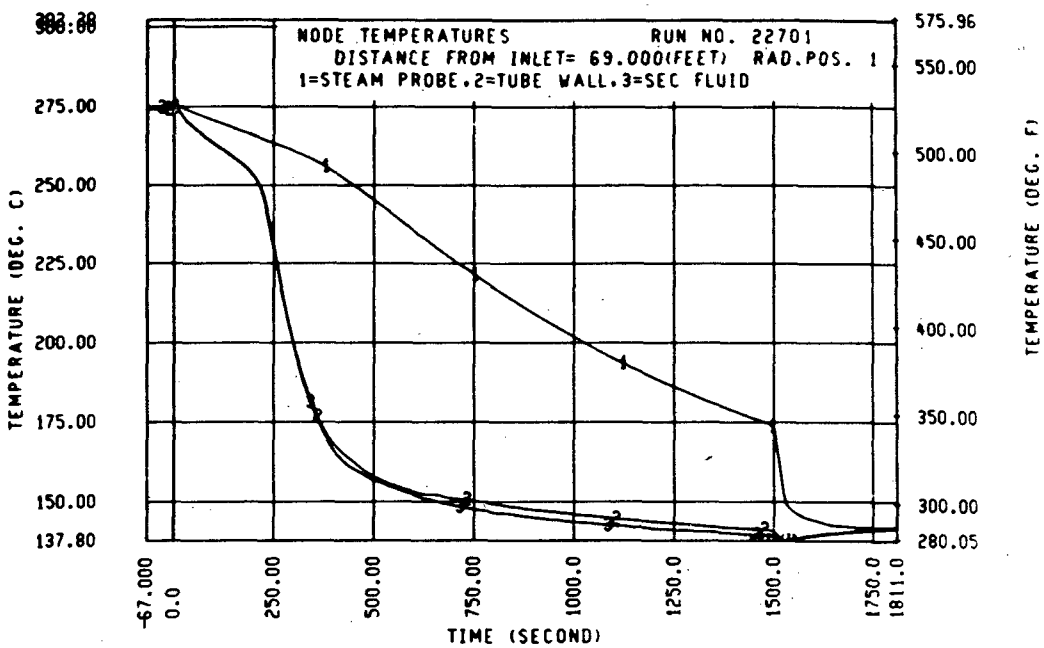


Figure 5-23. Nodal Temperatures, Reference Run, 21.0 m (69 ft) Elevation, Radial Position 1

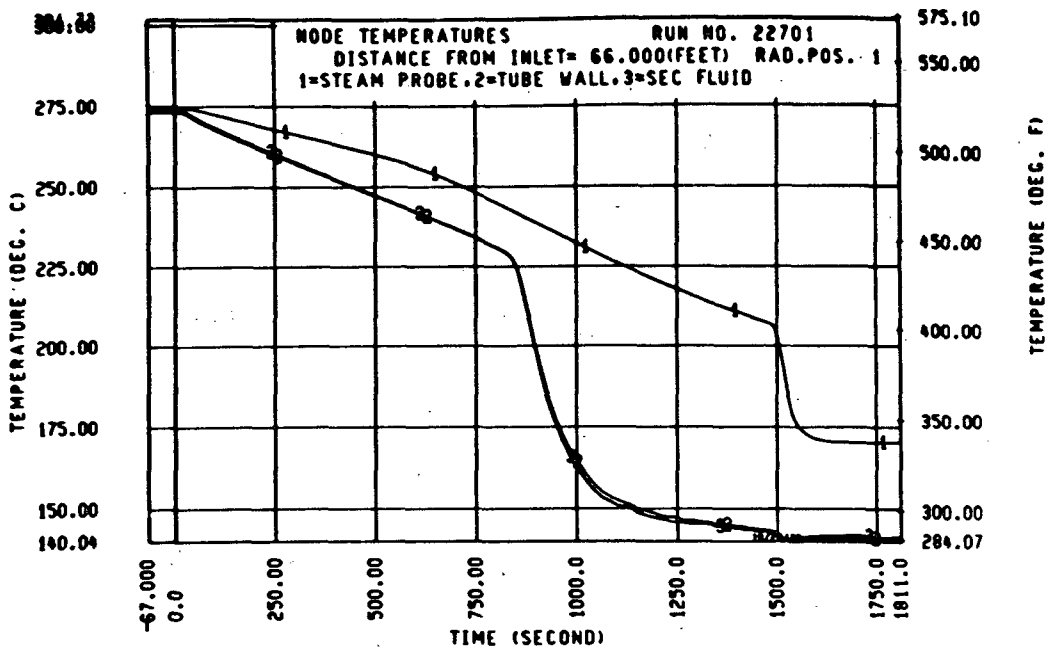


Figure 5-24. Nodal Temperatures, Reference Run, 20.1 m (66 ft) Elevation, Radial Position 1

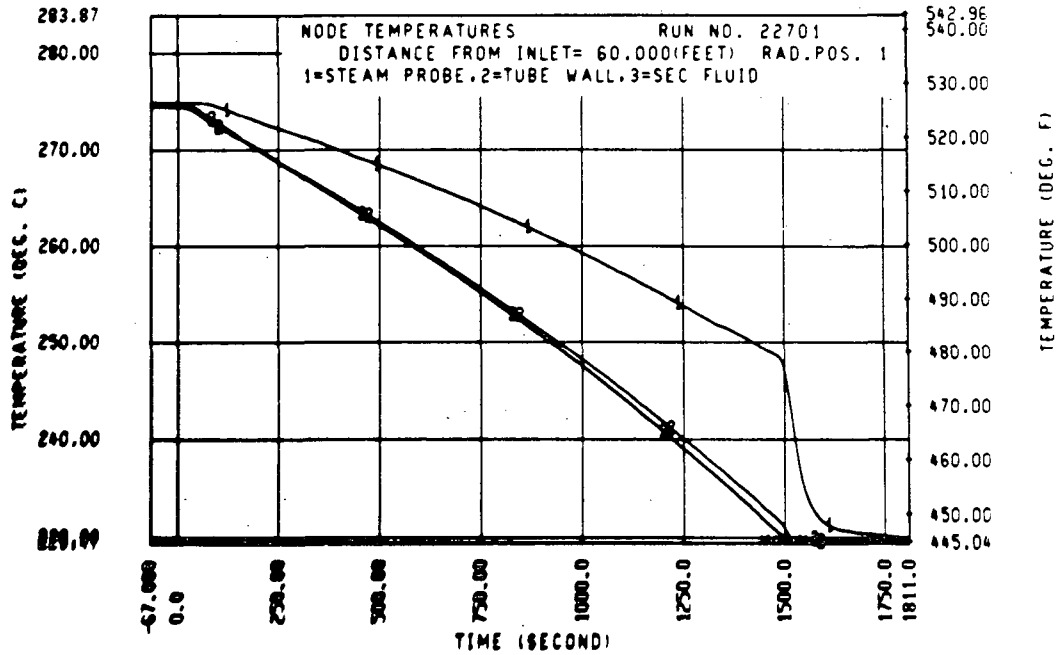


Figure 5-25. Nodal Temperatures, Reference Run, 18.3 m (60 ft) Elevation, Radial Position 1

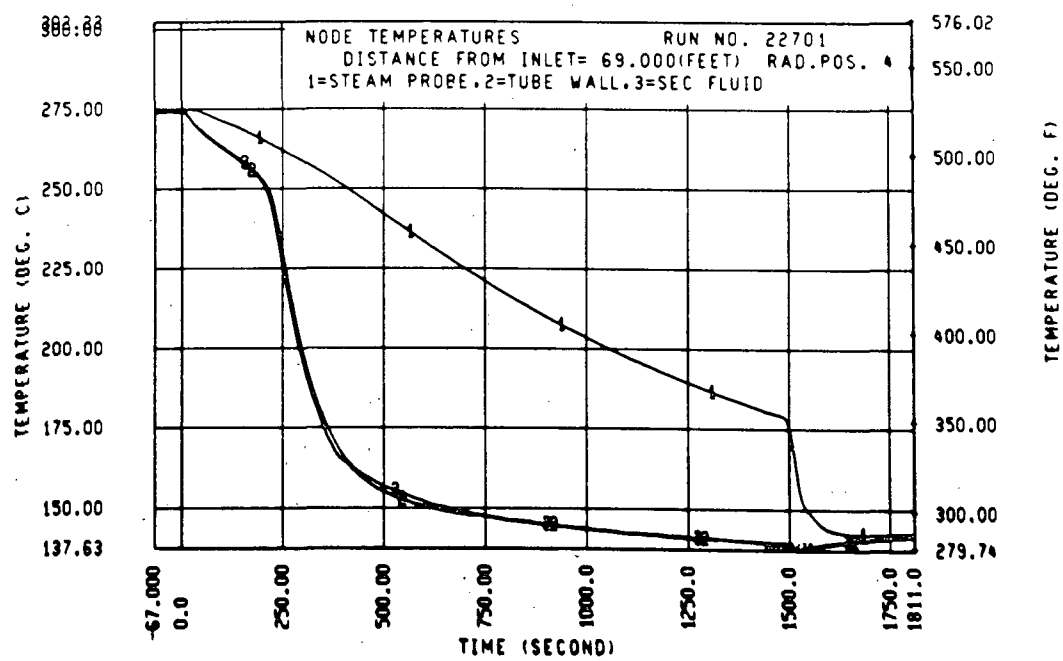


Figure 5-26. Nodal Temperatures, Reference Run, 21.0 m (69 ft) Elevation, Radial Position 4

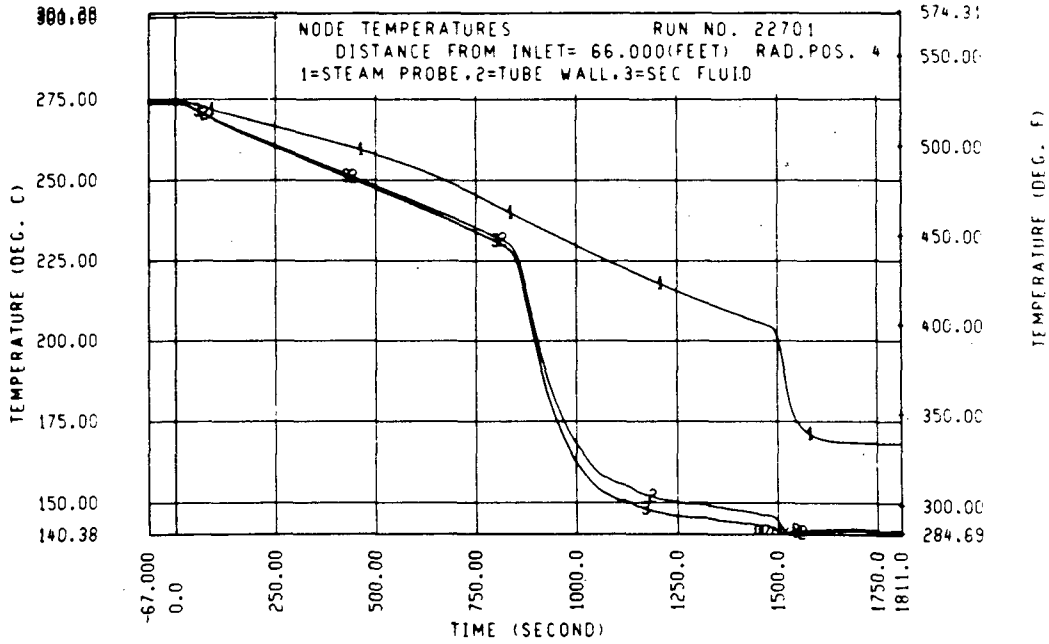


Figure 5-27. Nodal Temperatures, Reference Run, 20.1 m (66 ft) Elevation, Radial Position 4

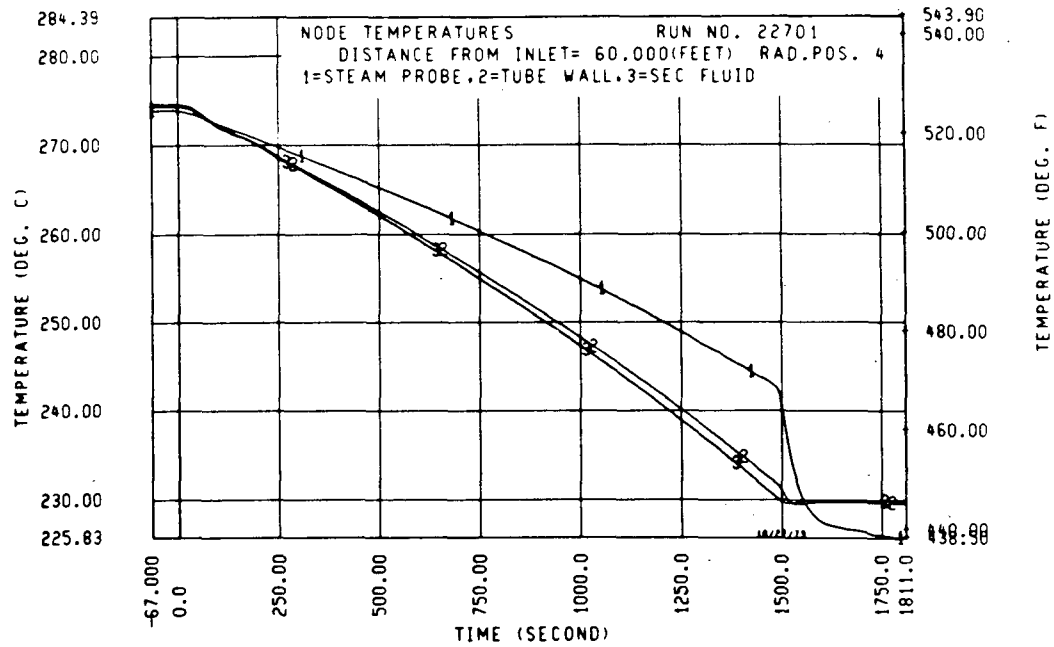


Figure 5-28. Nodal Temperatures, Reference Run, 18.3 m (60 ft) Elevation, Radial Position 4

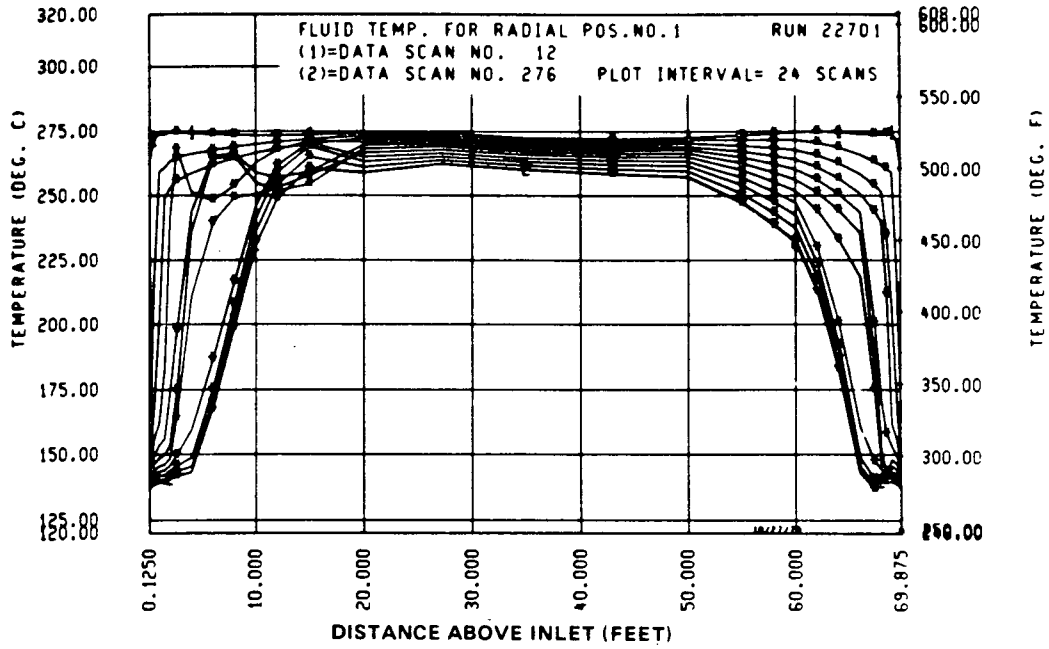


Figure 5-29. Fluid Temperature Versus Distance Above Inlet, Reference Run

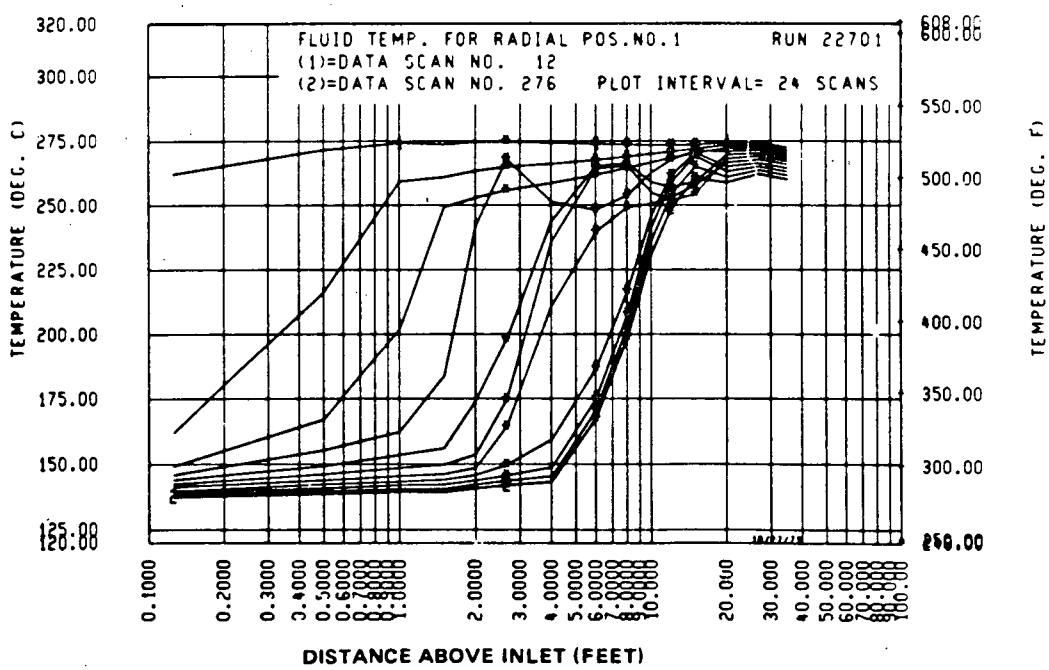


Figure 5-30. Fluid Temperature Versus Distance Above Inlet, Reference Run (Semilogarithmic Plot)

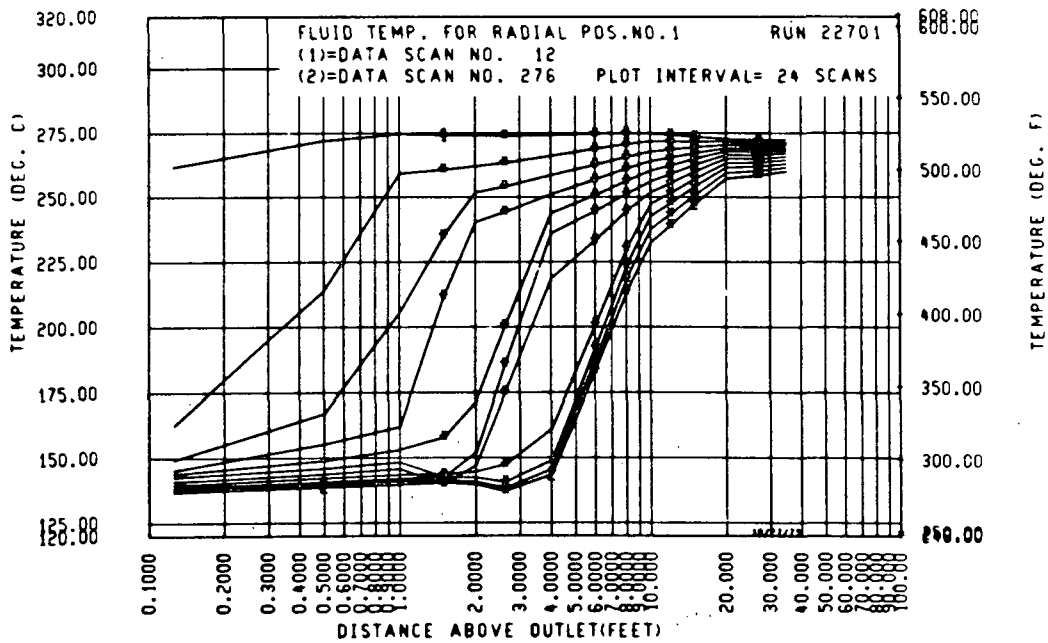


Figure 5-31. Fluid Temperature Versus Distance Above Outlet, Reference Run (Semilogarithmic Plot)

Figures 5-29 through 5-31 illustrate plots of the secondary fluid temperature spatial variation. On these plots, an asterisk represents nodal temperatures that were interpolated from measured temperatures in adjacent nodes. The bundle nodalization is illustrated in figure 4-3. The fluid temperature plots illustrate how the temperature changes with time in a parametric fashion. In the computer-generated plots, the temperature distribution plot was recreated at an interval calculated by dividing the time by 11. The nearest integer number of scans to this interval times the scan time (6 seconds) is the time interval between plots on figures 5-29 through 5-31. The scan interval between plots is stated in the title of the temperature distribution plots. The scan number associated with the start of the test and the end of the test is also stated in the title block.

The reference run computer plots indicate that the three controlled variables, loop pressure (figure 5-5), steam flow (figure 5-2), and water flow (figure 5-1), were well behaved during the test interval. The slight pressure spike at time zero in figure 5-5 is due to the step change in loop flow that occurred when the loop isolation valve SV-2 was opened to begin the test. The valve switching transient at the beginning of the test caused a slight shift in the loop pressure at the spray nozzle (figure 5-6) and a slight steam flow oscillation which decayed with time (figure 5-2).

The above evaluation demonstrates that the test requirement of constant loop boundary conditions was achieved in the test loop. The boundary conditions at the tubesheet in the inlet plenum can be calculated by subtracting the mass storage in the hot leg pipe and inlet plenum from the loop inlet boundary conditions.

To record these mass accumulation terms, D/P cells were installed on the inlet plenum and on the hot leg vertical rise. The hot leg D/P cell also includes the inlet plenum vertical rise.

The inlet plenum D/P cell plot (figure 5-8) indicates a slightly negative pressure drop (that is, a pressure increase) in the inlet plenum. The pressure rise was caused by the steam deceleration from the inlet nozzle velocity to the inlet plenum velocity. This effect is clearly shown in the single-phase steam run (page 22920-6 in Report No. 4.)

The smaller pressure rise in the two-phase conditions of the reference run indicates that some of the pressure increase was cancelled by the liquid being stored in the inlet plenum. The inlet plenum liquid storage can be estimated by subtracting the inlet plenum ΔP, run 22920, from that of run 22701. This ΔP was approximately 0.003 MPa (0.04 psi), which implies that the mass of liquid stored in the inlet plenum was 0.599 kg (1.32 lb).

The liquid stored in the hot leg vertical rise is equal to the channel 54 ΔP, run 22701, minus that of run 22920, minus the inlet plenum ΔP. The net hot leg ΔP was 0.006 MPa (0.09 psi) minus 0.003 MPa (0.04 psi), or 0.003 MPa (0.05 psi), and the implied mass of liquid stored in the hot leg is 0.14 kg (0.3 lb).

In the reference run, the hot leg and inlet plenum D/P cells indicate a total liquid storage of 0.73 kg (1.6 lb). Additional sources of liquid storage are the horizontal run of the hot leg from the spray nozzle to the bend radius in the inlet line and the liquid storage in the tube bundle above the tubesheet. Although D/P probes were installed in the tube inlet region, their response was unreliable, as discussed in appendix I of Report No. 4.

At the end of each test, the hot leg was drained into a weigh tank. For the reference run, 1.29 kg (2.85 lb) of water was collected. This liquid collection is consistent with the liquid accumulation calculated from the D/P cells. At the reference run liquid flow rate of 0.045 kg (0.10 lb/sec), the hot leg and inlet plenum liquid storage will reach equilibrium within 30 seconds. The shape of the D/P data from the hot leg and inlet plenum show that the D/P cells reached equilibrium relatively quickly; for test times greater than 30 seconds, the measured liquid injection flow rate can be assumed to be the liquid flow rate at the tubesheet in the inlet plenum.

The automated data reduction program SGFLOWS converted the hot leg and inlet plenum D/P data directly to a liquid mass; it neglected pressure drop components due to friction and momentum effects. Because the inlet plenum and hot leg liquid storage was small, these simplifying assumptions do not lead to large errors. The quality at the inlet plenum tubesheet as calculated by SGFLOWS is shown in figure 5-15.

At the tubesheet in the outlet plenum, the liquid mass flow rate was calculated directly from the rate of increase of the outlet plenum liquid collection. The steam mass flow was measured downstream of the loop moisture separator and superheater. The steam flow rate at the outlet plenum upstream of the superheater was calculated from an energy balance on the moisture separator and superheater.

The liquid flow rate leaving the steam generator was collected in the outlet plenum itself or in the collection tank below the outlet plenum. For the reference run, the outlet plenum was used and the D/P response is shown in figure 5-4. The delayed response in figure 5-4 is due to the storage volume below the lower tap having to fill before the D/P signal responds. For the outlet plenum, the volume below the lower tap held 1.5 kg (3.3 lb) of water. Since the D/P cell responded at 350 seconds, the average liquid collection rate over this interval was 0.004 kg/sec (0.009 lb/sec). The slope of the outlet plenum liquid collection D/P signal after 350 seconds was 1.6 Pa/sec (2.3 x 10^{-4} psi/sec), which corresponds to a liquid accumulation rate of 0.004 kg/sec (0.009 lb/sec). This rate demonstrates that the liquid collection rate was continuous over the test interval.

The steam generator outlet plenum nozzle was constructed to act like a moisture separator, so that any residual moisture in the outlet plenum steam would stay in the outlet plenum. However, to provide for possible moisture in the exhaust steam, a commercial moisture separator was installed in the exhaust line and an electric resistance superheater was installed downstream of the moisture separator. The temperature response of the steam leaving the superheater (figure 5-12) indicates generally dry steam, although the one negative temperature spike at 600 seconds was probably caused by a liquid drop striking the RTD. The data recorded to measure the entrained liquid in the exhaust line included readings from the D/P cell on the moisture separator collection tank, the power to the superheater, and fluid and wall thermocouples.

From the following mass and energy balance around the loop separator and superheater, the amount of liquid evaporated by the superheater is calculated:

$$Q_{in} - MC_P \frac{dT}{dt} = W_{g_o} h_{g_o} - (W_{g_{in}} h_{g_{in}} + W_{f_{in}} h_f) \qquad (5\text{-}1)$$

$$W_{g_o} = W_{g_{in}} + W_{f_{in}} \tag{5-2}$$

where

Q_{in} = net superheater power (total input power - heat loss to ambient)

M = mass of steam separator and superheater loop piping

C_p = pipe wall heat capacity

dT/dt = rate of change of pipe and superheater wall temperature

W_{g_o} = exhaust steam mass flow rate

h_{g_o} = steam enthalpy at superheater exit

$h_{g_{in}}$ = steam enthalpy in the outlet plenum

h_f = enthalpy of saturated liquid

$W_{g_{in}}$ = steam flow rate into the superheater

$W_{f_{in}}$ = liquid flow rate into the superheater

The two unknowns in these equations are $W_{g_{in}}$ and $W_{f_{in}}$. The solution for $W_{f_{in}}$ shows that a negligible amount of liquid was evaporated by the superheater. The loop separator liquid collection tank also accumulated a negligible amount of liquid.

A summary of the measured mass flow rates in the test loop is presented in table 5-6. Table 5-6 presents the liquid flow rate to the spray nozzle as measured by the turbine meter and calculated from the rate of change of the accumulator level D/P transducer. The rate calculated from the accumulator D/P serves as a check on the turbine meter reading. The most accurate flow rate indication is from the turbine meter. The test data show that after a brief transient within the first minute of the test, the steam generator inlet boundary conditions were constant. At the bundle exit, a small amount of liquid migrated to the outlet plenum even though the outlet plenum steam temperature was close to 260° C (500° F) at the beginning of the test. The shape of the outlet plenum liquid collection D/P curve shows that the rate of liquid collection was at a maximum at time zero and slowly decreased during the test. From the initial outlet plenum liquid collection rate, the outlet plenum nonequilibrium quality was calculated to be 98.1 percent at time zero, increasing with time.

TABLE 5-7

STEAM GENERATOR SEPARATE EFFECTS TEST REFERENCE RUN DATA

Time (sec)	Depletion Rate: Accumulator Tank Readings [kg/sec (lbm/sec)]	Depletion Rate: Turbine Readings [kg/sec (lbm/sec)]	Accumulation Rate: Hot Leg Pipe [kg/sec (lbm/sec)]	Accumulation Rate: Inlet Plenum [kg/sec (lbm/sec)]	Tube Bundle [kg/sec (lbm/sec)]	Outlet Plenum [kg/sec (lbm/sec)]	Entrained Liquid in Separator Flow [a] [kg/sec (lbm/sec)]
0.0	0.000 (0.000)	0.0454 (0.100)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	-0.002 (-0.005)
60.0	-0.0526 (-0.116)	0.0454 (0.100)	0.001 (0.003)	-0.001 (-0.003)	0.016 (0.036)	-0.002 (-0.005)	0.002 (0.004)
120.0	-0.0553 (-0.122)	0.0454 (0.100)	0.001 (0.002)	-0.003 (-0.006)	0.001 (0.003)	0.001 (0.002)	0.001 (0.002)
180.0	-0.0676 (-0.149)	0.0454 (0.100)	0.000 (0.000)	-0.001 (-0.003)	0.002 (0.005)	0.001 (0.003)	0.0005 (0.001)
240.0	-0.0313 (-0.069)	0.0454 (0.100)	0.000 (0.000)	-0.0005 (-0.001)	0.001 (0.002)	0.003 (0.006)	0.0005 (0.001)
300.0	-0.0630 (-0.139)	0.0454 (0.100)	0.001 (0.002)	-0.004 (-0.008)	0.001 (0.003)	0.003 (0.006)	0.0005 (0.001)
360.0	-0.0730 (-0.161)	0.0454 (0.100)	0.0005 (0.001)	-0.004 (-0.008)	0.003 (0.006)	0.003 (0.007)	0.000 (0.000)
420.0	-0.0553 (-0.122)	0.0454 (0.100)	-0.0005 (-0.001)	-0.001 (-0.003)	0.001 (0.003)	0.004 (0.008)	0.000 (0.000)
480.0	-0.0367 (-0.081)	0.0454 (0.100)	0.0005 (0.001)	-0.004 (-0.009)	0.001 (0.003)	0.001 (0.003)	-0.0005 (-0.001)
540.0	-0.0594 (-0.131)	0.0454 (0.100)	0.001 (0.002)	-0.001 (-0.002)	0.0068 (0.015)	0.004 (0.009)	-0.0005 (-0.001)
600.0	-0.0458 (-0.101)	0.0454 (0.100)	0.001 (0.003)	-0.002 (-0.004)	0.004 (0.009)	0.0054 (0.012)	-0.0005 (-0.001)
660.0	-0.0499 (-0.110)	0.0454 (0.100)	-0.001 (-0.002)	0.0005 (0.001)	0.0054 (0.012)	0.002 (0.005)	-0.001 (-0.002)
720.0	-0.0395 (-0.087)	0.0454 (0.100)	0.001 (0.002)	-0.0054 (-0.012)	0.002 (0.005)	0.004 (0.008)	-0.001 (-0.002)
780.0	-0.0717 (-0.158)	0.0454 (0.100)	-0.001 (-0.003)	0.0050 (0.011)	0.0077 (0.017)	0.0050 (0.011)	-0.001 (-0.002)
840.0	-0.0349 (-0.077)	0.0454 (0.100)	-0.001 (-0.002)	0.0054 (0.012)	0.0045 (0.010	0.003 (0.006)	-0.001 (-0.003)
900.0	-0.0458 (-0.101)	0.0454 (0.100)	-0.001 (-0.003)	0.0077 (0.017)	0.0054 (0.012)	0.004 (0.008)	-0.001 (-0.003)
960.0	-0.0499 (-0.110)	0.0454 (0.100)	-0.001 (-0.003)	0.002 (0.005)	0.0082 (0.018)	0.004 (0.009)	-0.001 (-0.003)
1020.0	-0.0200 (-0.044)	0.0454 (0.100)	0.002 (0.004)	-0.0059 (-0.013)	-0.002 (-0.004)	0.004 (0.009)	-0.002 (-0.004)
1080.0	-0.0522 (-0.115)	0.0454 (0.100)	0.000 (0.000)	0.001 (0.003)	0.002 (0.005)	0.004 (0.008)	-0.002 (-0.004)
1139.0	-0.0381 (-0.084)	0.0454 (0.100)	-0.001 (-0.002)	0.001 (0.003)	0.003 (0.006)	0.0045 (0.010)	-0.002 (-0.004)
1200.0	-0.0590 (-0.130)	0.0454 (0.100)	-0.001 (-0.002)	-0.002 (-0.005)	0.000 (0.000)	0.0059 (0.013)	-0.002 (-0.005)
1260.0	-0.0404 (-0.089)	0.0454 (0.100)	0.001 (0.002)	-0.001 (-0.003)	0.002 (0.005)	0.001 (0.002)	-0.002 (-0.004)
1319.0	-0.0639 (-0.141)	0.0454 (0.100)	0.0005 (0.001)	-0.0005 (-0.001)	-0.001 (-0.003)	0.001 (0.002)	-0.002 (-0.005)
1380.0	-0.0390 (-0.086)	0.0454 (0.100)	0.001 (0.003)	-0.0045 (-0.010)	0.003 (0.006)	0.004 (0.009)	-0.002 (-0.005)
1439.0	-0.0590 (-0.130)	0.0454 (0.100)	0.003 (0.006)	-0.013 (-0.029)	0.002 (0.004)	0.0059 (0.013)	-0.002 (-0.005)

a. Entrained liquid downstream of loop moisture separator, based on superheater energy balance. See discussion in paragraph 5-3.

From the calculated mass flow rates and measured temperatures in the inlet and outlet plenums, the overall energy exchange rate in the tube bundle was calculated. The results of this calculation are presented graphically in figure 5-14. This plot shows that the maximum energy exchange rate occurred at the beginning of the transient. The rate then gradually approached a constant value.

The initial peak in the total heat flow rate plot in figure 5-14 is due to the initial flow transient caused by the loop flow and pressure controllers. After the first minute, this transient had decayed and the change in the heat flow rate was due to changing conditions in the tube bundle. The heat flow transient decayed from a peak of 158 kw (150 Btu/sec) at 60 seconds to a value of about 116 kw (110 Btu/sec) at the end of the test, with a very small change over most of the test time interval. The heat flow rate has two components. The first contribution to heat flow comes from the evaporation of the liquid-phase primary side flow. The remaining contribution comes from the superheat absorbed by the primary side vapor flow.

The maximum energy exchange rate would consist of complete evaporation of the liquid phase plus superheating of the steam phase to the highest outlet plenum measured temperature. For the reference run parameters, complete evaporation of the liquid phase would require 0.45 kg/sec times 2.17 J/kg (0.10 lb/sec times 934 Btu/lb), or 98.4 kw (93.4 Btu/sec). To superheat the steam to 260°C (500°F) would require 0.23 kg/sec times 2.44 x 10^{6} J/kg (0.5 lb/sec times 105 Btu/lb), or 55.3 kw (52.5 Btu/sec). These two heat flux components sum to 154 kw (146 Btu/sec). To account for the measured liquid flow in the outlet plenum of approximately 0.005 kg/sec (0.01 lb/sec), the above heat rate should be reduced by approximately 9.8 kw (9.3 Btu/sec).

Over the course of the transient, the superheat component continually decreased, as shown by the outlet plenum temperature plot (figure 5-10). The heat flow rate plot (figure 5-14) is flatter than the temperature plot because some of the loss in the superheat component was compensated for by an increase in the liquid evaporation. The increased liquid evaporation late in the test is inferred from lower outlet plenum liquid collection rate, which is reflected in the smaller slope of the liquid collection D/P cell in the outlet plenum.

A check on the heat flow rate can be performed by comparing the heat flow integrated over the test time with the change in the tube bundle stored energy. From the plot of temperature versus distance from the tube bundle inlet (figure 5-29), the average bundle temperature at the end of the test is calculated to be 228°C (443°F). The initial bundle fluid temperature and level (table 5-1) are 274°C (525°F) and 10.1 m (33.1 ft). The steam generator metal mass used in the energy storage calculation is the mass above the tubesheet, which is calculated to be 3400 kg (7500 lb) of metal. The heat capacity of the metal is 418 J/kg-°C (0.10 Btu/lb-°F). The calculated change in the stored energy of the bundle water and metal over the time interval of the test (1500 seconds) is 1.6×10^8 J (151,800 Btu). Based on a uniform rate of energy transfer, the heat transfer rate is 106.7 kw (101.2 Btu/sec). This heat transfer rate is in reasonable agreement with the heat transfer rate calculated from the primary side mass flows and temperatures.

To further investigate the heat transfer process in the steam generator tube bundle, the local tube wall heat flux was studied. The data reduction program SGFLUX was used to calculate the local tube wall heat flux, as described in paragraph 4-3. Selected plots of the local heat flux variation with time at several axial and radial positions in the lower inlet region of the tube bundle are shown in figures 5-32 through 5-41.

The general shape of all of the local heat flux plots is similar. These plots show that the heat flux was initially small [approximately 11 kw/m^2 (1 Btu/sec-ft^2)] and changed slowly with time. As time increased, the heat flux underwent a sudden increase to a peak of approximately 170 to 340 kw/m^2 (15 to 30 Btu/sec-ft^2). The heat flux began to decay from the peak immediately and asymptotically approached zero as time increased.

Comparison of the local heat flux plots with the local temperature versus time plots (figures 5-17 through 5-22) permits correlation of the local heat fluxes with the local temperatures. This comparison shows that the low heat flux region at the beginning of the test corresponds to a region of high tube wall temperature. Typically in this zone the tube wall is above 232°C (450°F), or about 100°C (180°F) above the saturation temperature of 130°C (257°F) at 0.28 MPa (40 psia). At the time of the sharp rise in local heat flux, the tube wall temperature was undergoing a rapid cooldown. The

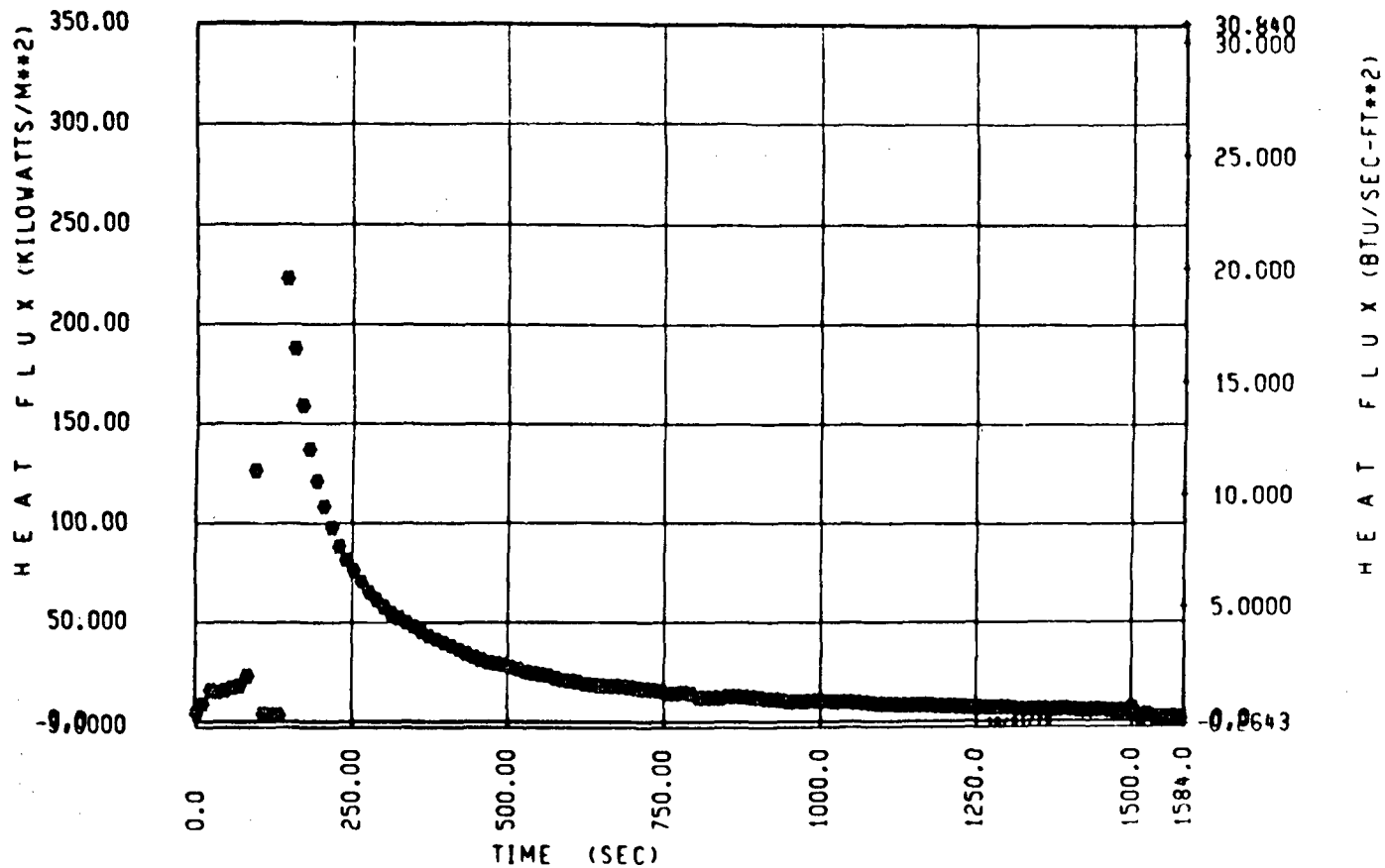


Figure 5-32. Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 1

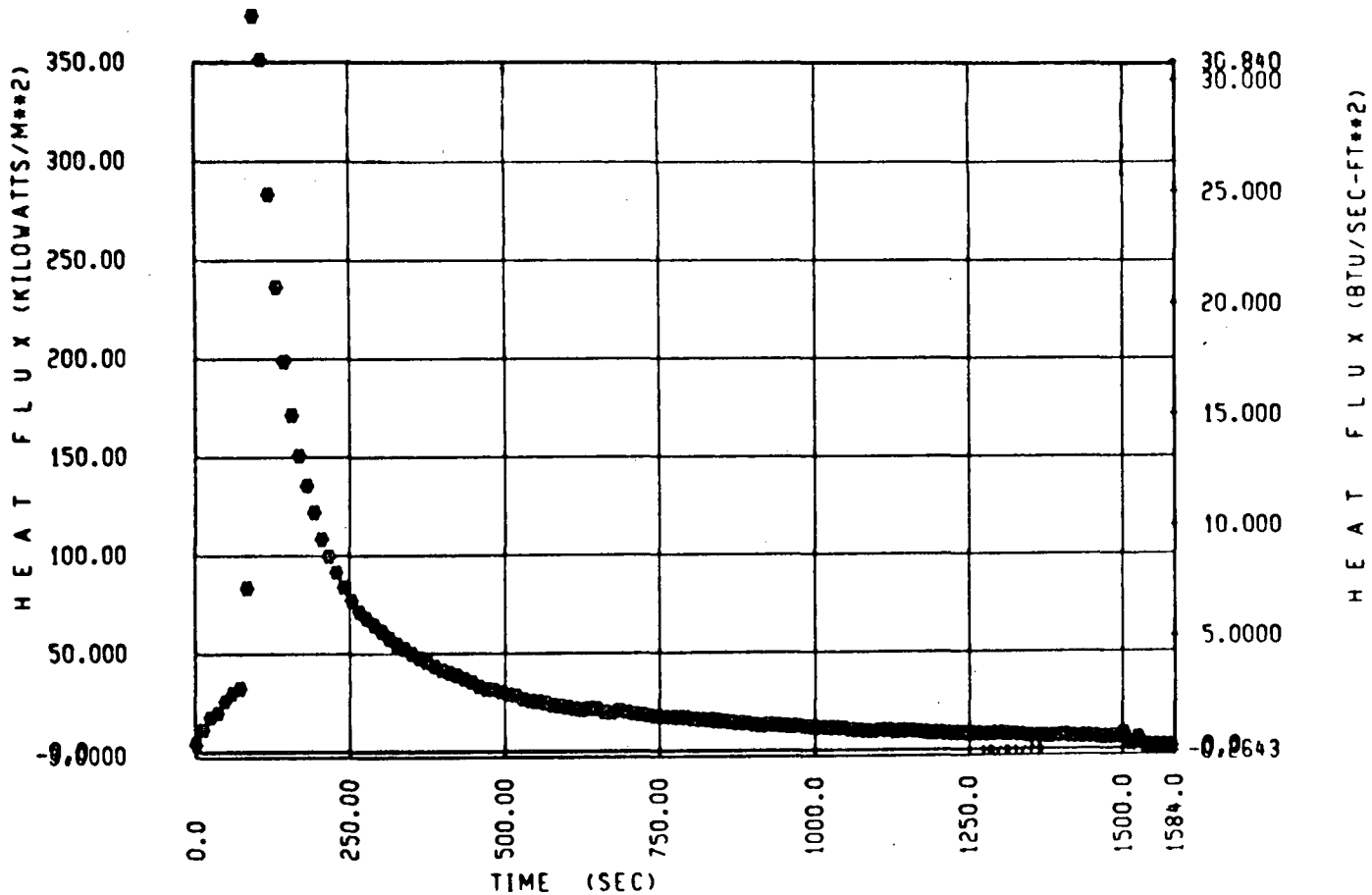


Figure 5-33. Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 2

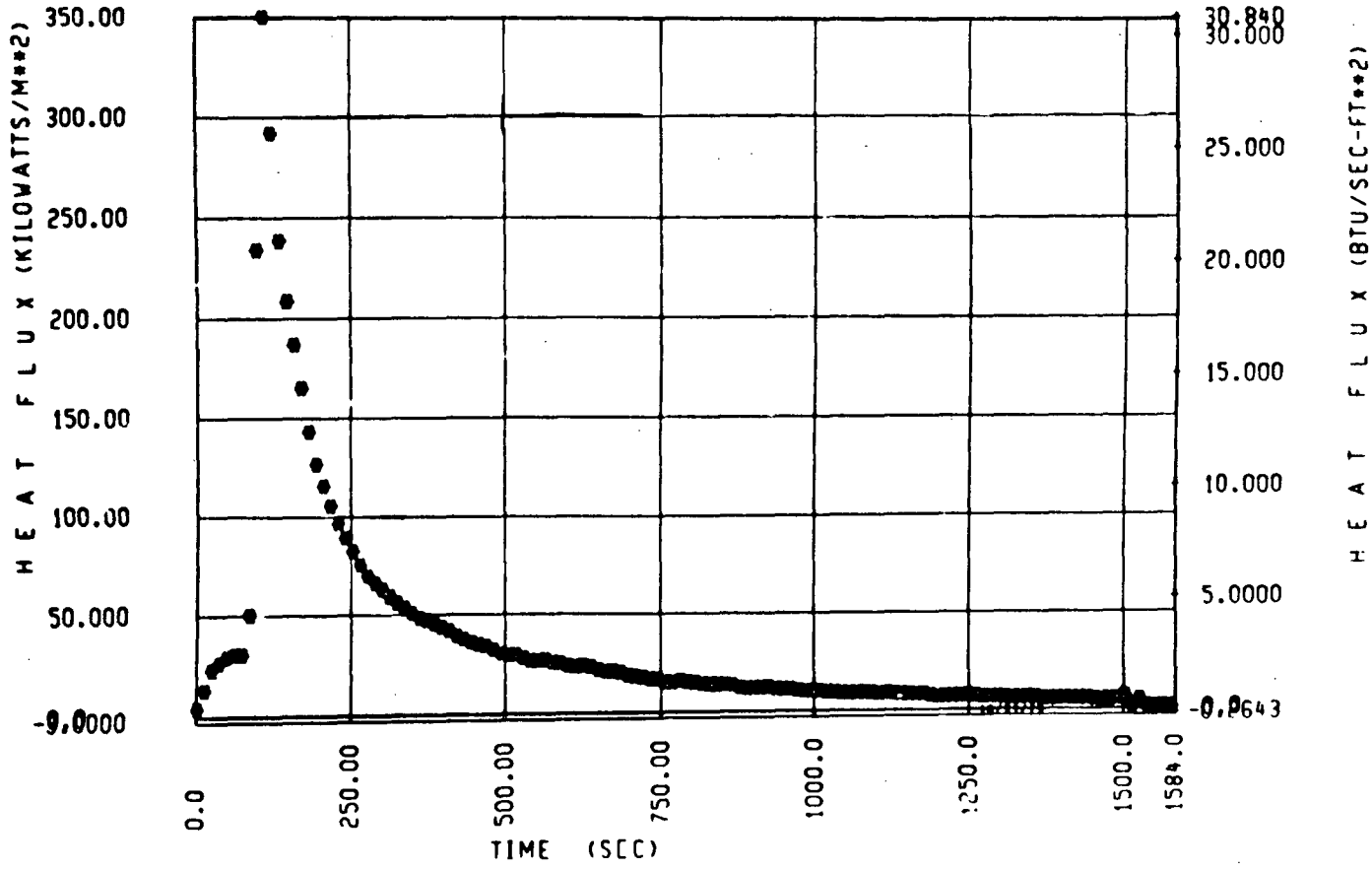


Figure 5-34. Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 3

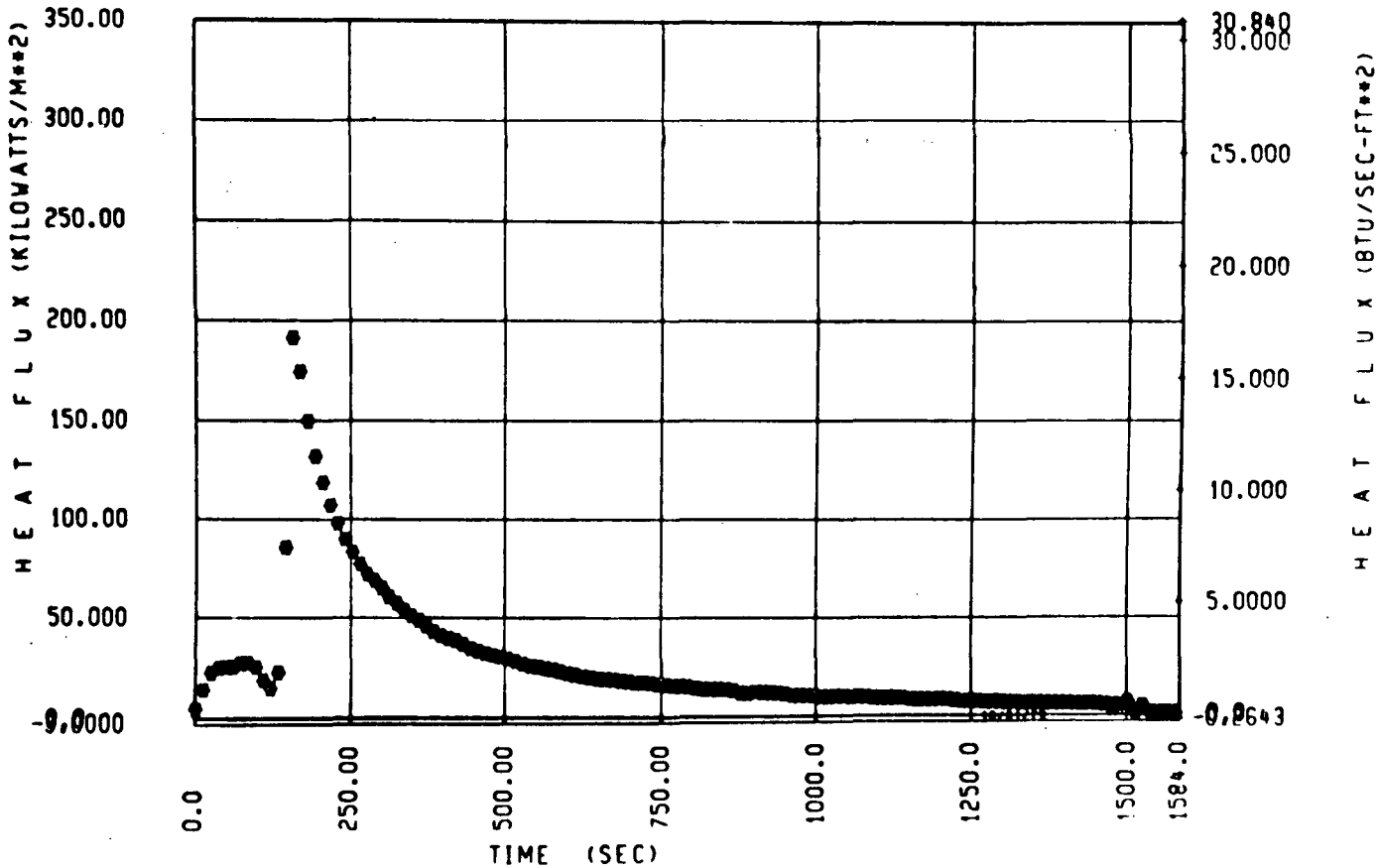


Figure 5-35. Tube Wall Heat Flux, 0.15 m (0.5 ft) Elevation, Radial Position 4

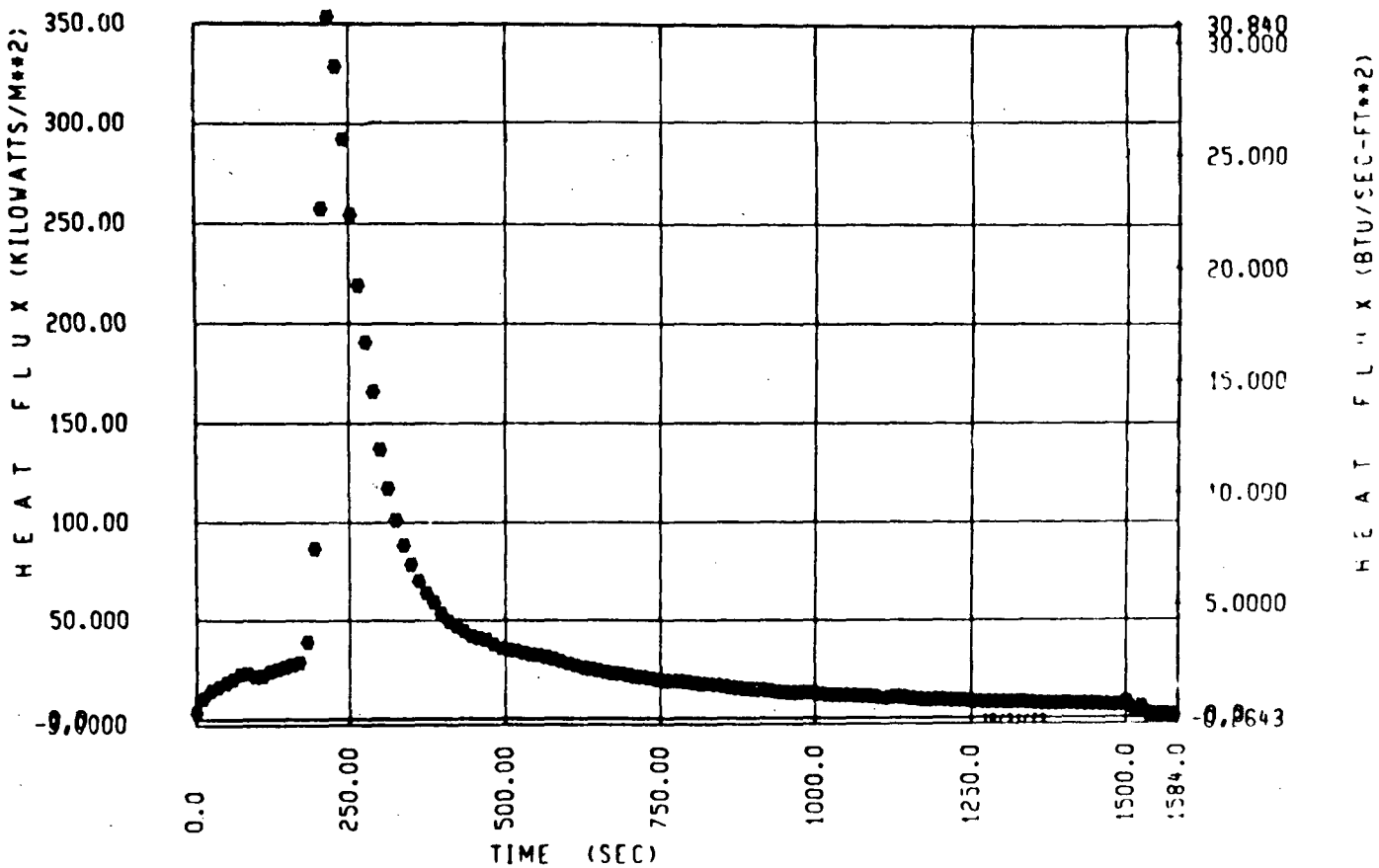


Figure 5-36. Tube Wall Heat Flux, 0.30 m (1 ft) Elevation, Radial Position 1

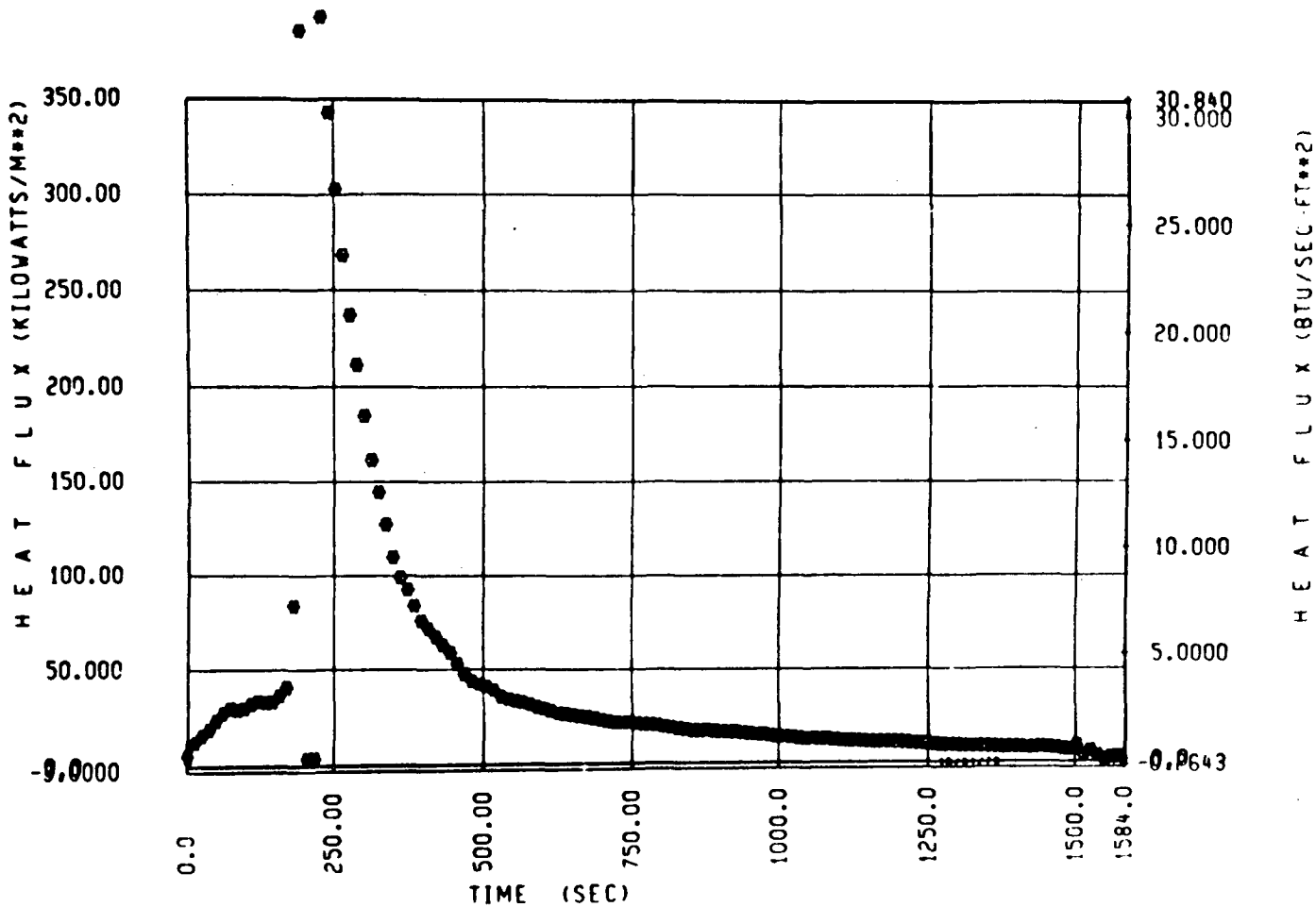


Figure 5-37. Tube Wall Heat Flux, 0.30 m (1 ft) Elevation, Radial Position 2

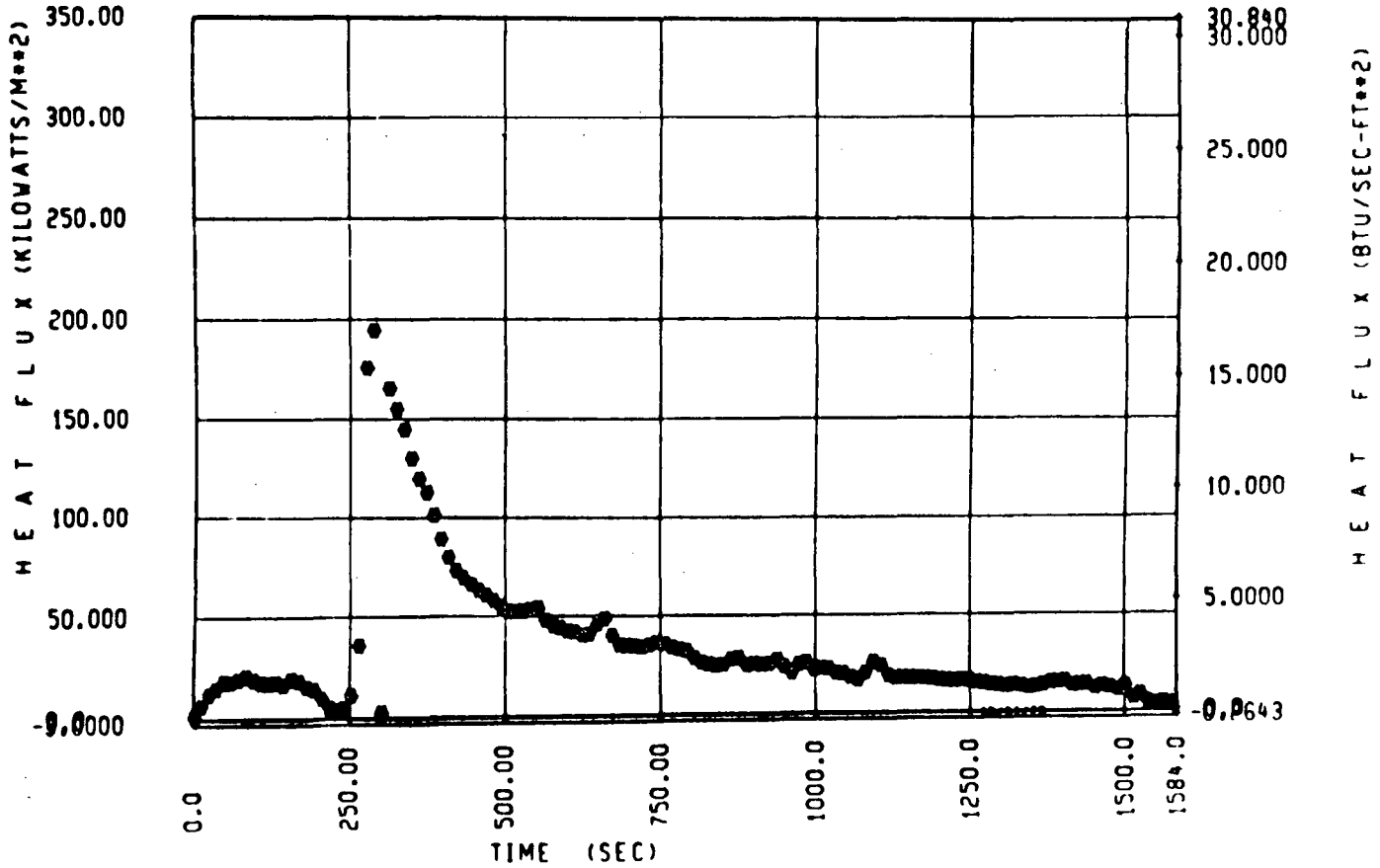


Figure 5-38. Tube Wall Heat FLux, 0.30 m (1 ft) Elevation, Radial Position 4

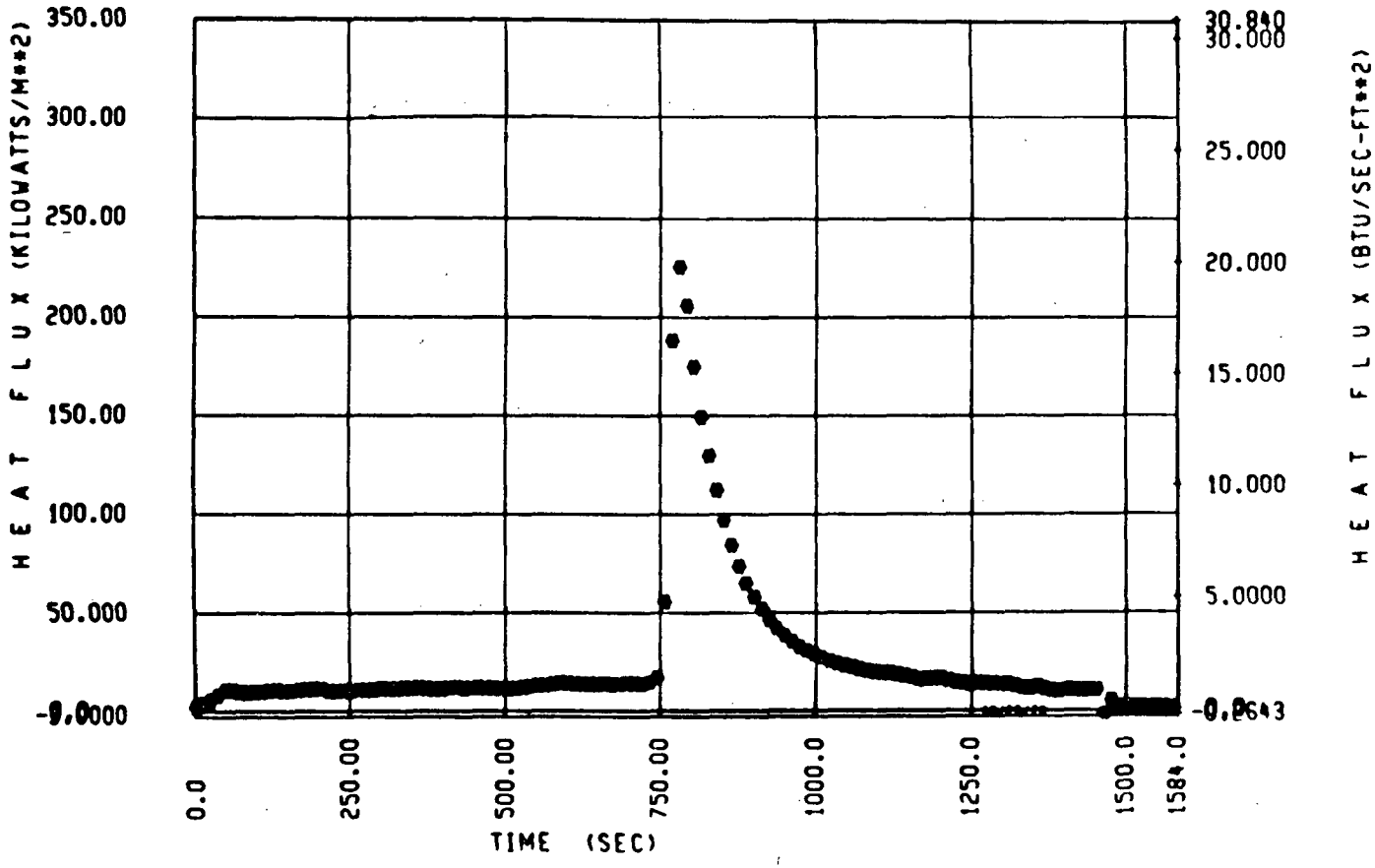


Figure 5-39. Tube Wall Heat Flux, 1.22 m (4 ft) Elevation, Radial Position 1

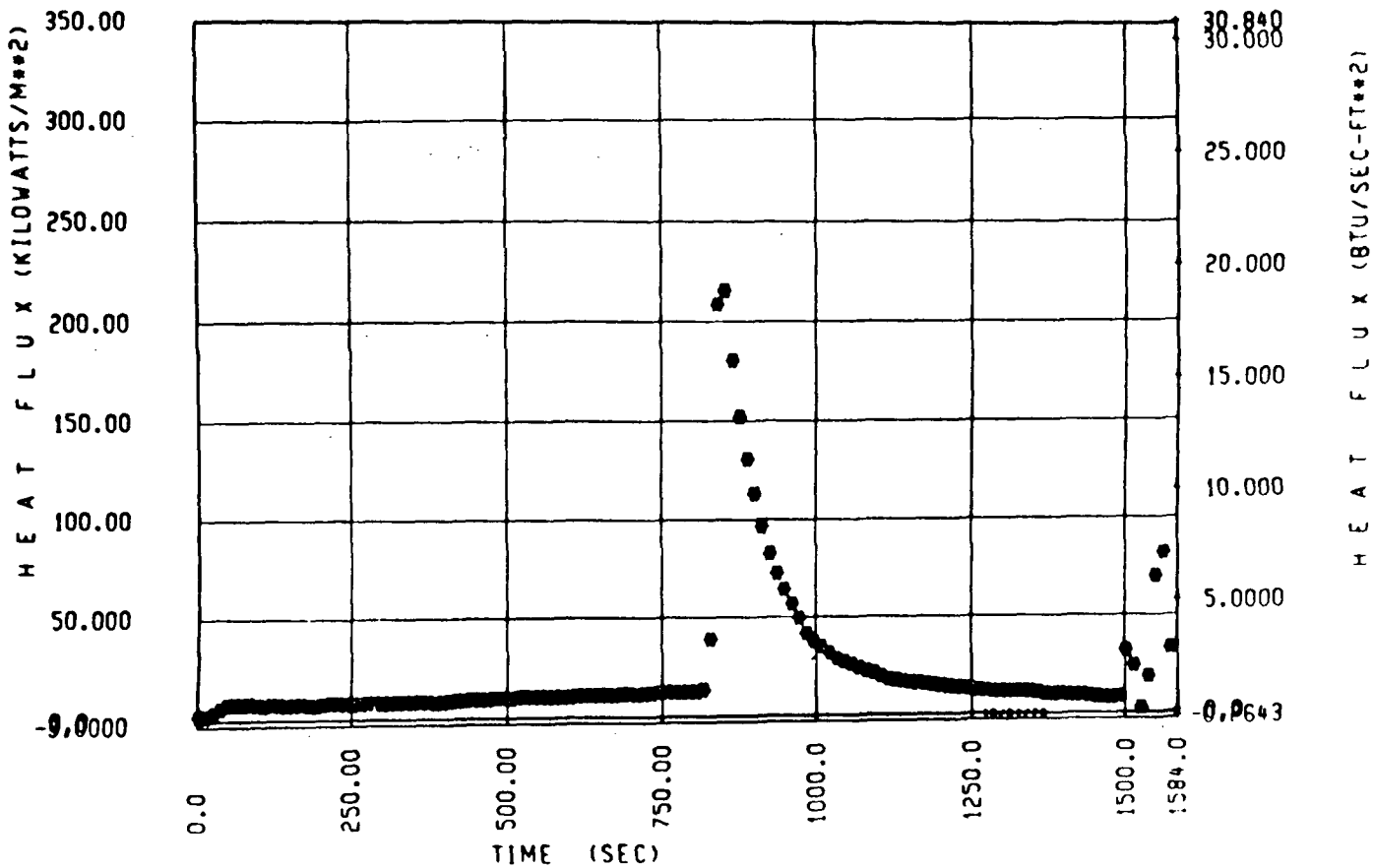


Figure 5-40. Tube Wall Heat Flux, 1.22 m (4 ft) Elevation, Radial Position 2

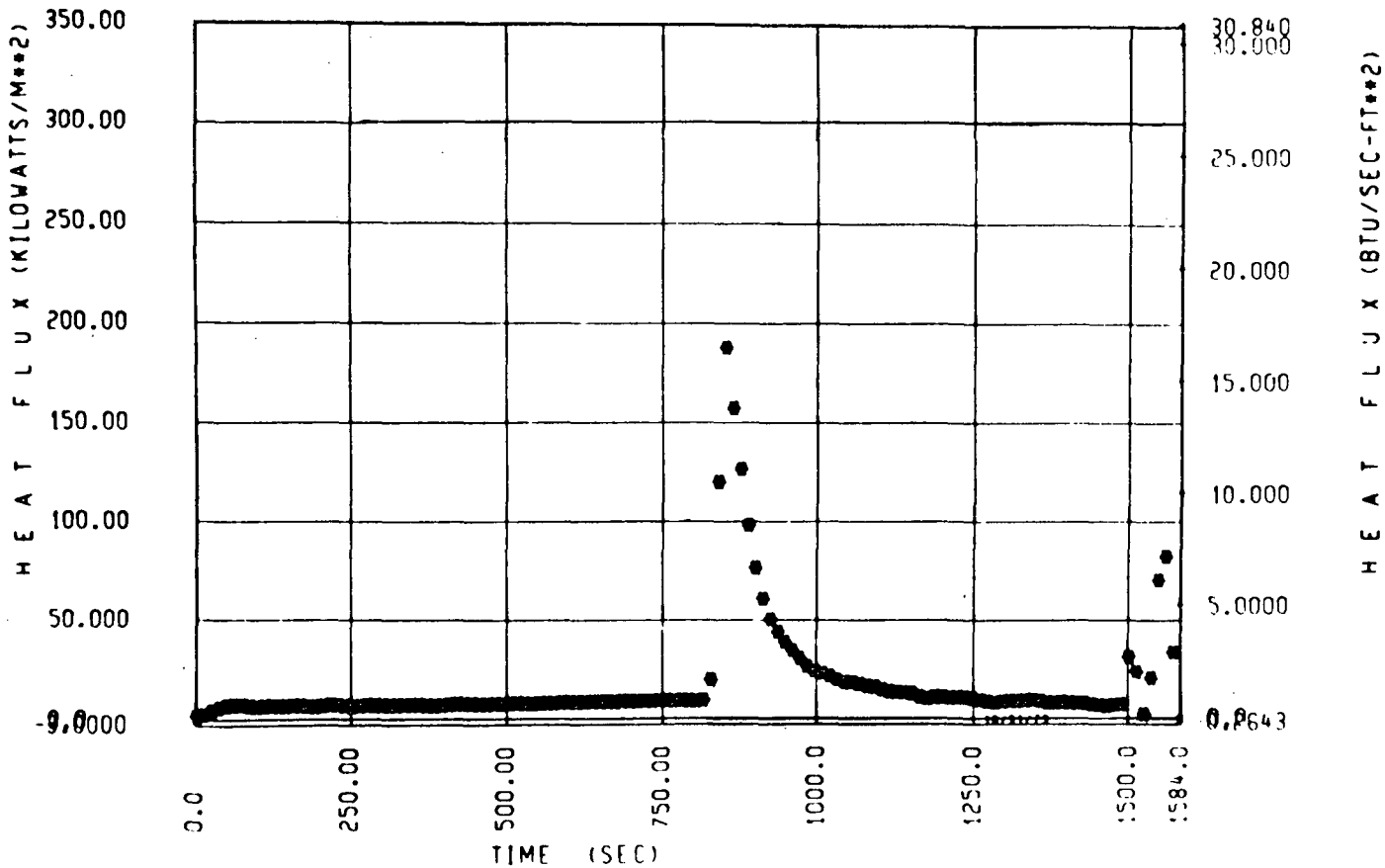


Figure 5-41. Tube Wall Heat Flux, 1.22 m (4 ft) Elevation, Radial Position 3

rapid tube wall temperature decrease caused the secondary fluid temperature cooldown to accelerate, but the secondary fluid cooldown rate did not match the tube wall cooldown rate. At a tube wall temperature generally within 56°C (100°F) of saturation, the rapid tube wall cooldown changed to a slower cooldown rate and the tube wall temperature asymptotically approached saturation temperature. The secondary fluid cooldown followed the tube wall temperature decay and asymptotically approached saturation temperature also.

The primary side steam probe data show that, at elevations as low as 1.22 m (4 ft) from the tube bundle entrance, significant superheating of the steam phase did occur. The amount of steam-phase superheat at a given elevation in the inlet region decreased with time; at the point of most rapid decline of the tube wall temperature the steam temperature was close to saturation.

The temperature versus time plots in figures 5-17 through 5-28 show that, in the outlet side of the tube bundle, the secondary fluid temperatures followed very closely the inlet side thermocouples at the same elevations. As the fluid in the outlet region cooled down, the steam-phase temperature remained high, and the direction of heat transfer was from the primary side steam back into the cooler secondary side water. The magnitude of this heat flow was too small to be accurately measured with the thermocouples on the tube wall.

The analysis of the temperature and local heat flux plots indicates that the primary side film coefficient was undergoing a transition from a dry to a wet condition, by a surface liquid film which formed at the tube entrance and slowly climbed up the inside of the tube wall. The initial heat flux response, with high wall temperature and low rate of heat transfer, corresponds to the time before the liquid film reached that local elevation. The region of rapidly decreasing wall temperature and rising heat flux corresponds to the transition boiling heat transfer regime, where the liquid film established itself on the inside surface of the tube. The decay in heat flux and wall temperature following the wetting of the tube corresponds to the two-phase forced convection heat transfer regime, with a relatively high primary side film coefficient and tube wall heat fluxes that were less than the critical heat flux. In this mode, the tube bundle cooldown continued until secondary temperatures approached the primary side steam temperature.

The time of rapid tube wall temperature decrease (figures 5-17, 5-18, and 5-20) is defined as the quench time for that location. The quench times for the four instrumented radial locations in the inlet region of the tube bundle are plotted in figure 5-42. The plot shows that the quench front advances in tube positions 1, 2, and 3 at about the same rate; the quench front in tube position 4 lagged the other tubes by about 50 seconds in time. Alternatively, using a quench velocity of 1.22 m/850 sec or 1.4 mm/sec (4 ft/850 sec or 0.0047 ft/sec), at a given time, the quench elevation in tube position 4 was about 1.4 x 50 or 70 mm (0.0047 x 50/12 or 2.8 in.) below the quench elevation in the other tubes. Since the conditions on the secondary side of the tube bundle had no significant radial variation, the quench time variation between tube position 4 and the other three instrumented tubes was due to local differences at the tube entrance.

To measure local differences in the tube inlet conditions, a series of air/water tests were run on the inlet plenum. In these tests the volumetric flow rate of air equalled the volumetric flow rate of steam. Local measurements of the air and water flow rates at each tube entrance were made. The results of these tests are presented in appendix B of NRC/EPRI/Westinghouse Report No. 4. The simulated reference test showed that the air flow rate in each tube was equal; the water flow rate was highest in tube position 1 and got successively smaller in tube positions 2, 3, and 4. The normalized liquid flow rates were 1.77 in position 1, 1.18 in position 2, 0.75 in position 3 and 0.68 in position 4.

Despite the wide variation in the liquid flow rate entering the tubes, the radial variation in the local heat flux was nearly uniform in positions 1 through 3, and lower in position 4. The most striking similarity in the local heat flux plots is the closeness of the peak heat flux in different tubes at the same elevation. This phenomenon suggests that the local peak heat flux was being limited by a factor common to all the tubes, rather than by the quality level in the tubes.

In the heat transfer regime below the critical heat flux limit, the limiting factor in determining the maximum local tube wall heat flux is the secondary to primary fluid temperature difference. Since there was little radial variation in the secondary fluid temperature, in the absence of a critical heat flux limit, tubes with different primary side qualities could have the same peak heat flux levels. To estimate the magnitude of

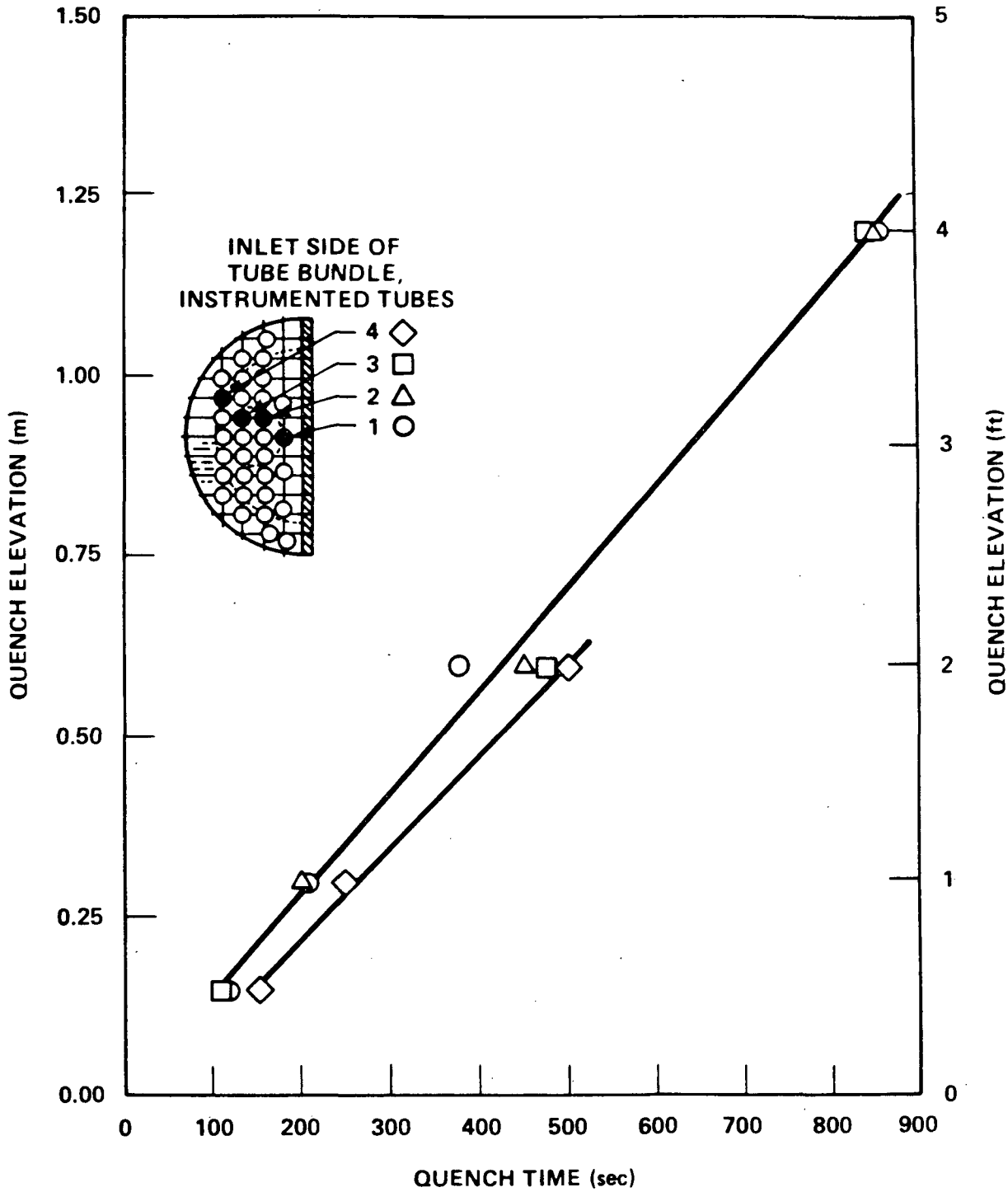


Figure 5-42. Quench Elevation Versus Quench Time

the limiting local heat flux based on a secondary to primary temperature difference of 232°C-130°C (450°F-267°F), or 102°C (183°F), assume a secondary side film coefficient of 4 kw/m^2-°C (0.2 Btu/sec-ft^2-°F) and a primary side film coefficient of 20 kw/m^2-°C (1.0 Btu/sec-ft^2-°F). These film coefficients are based on free convection in the tube bundle secondary and two-phase forced convection in the primary side of the tube. From the above set of assumptions, the estimated peak local heat flux is 346 kw/m^2 (30.5 Btu/sec-ft^2).

The peak heat fluxes shown in figures 5-32 through 5-41, except for figure 5-33, are all at or below 350 kw/m^2 (30.8 Btu/sec-ft^2). This suggests that the mechanism responsible for the magnitude of the flux peak is the secondary to primary temperature difference in those cases with flux peaks close to 350 kw/m^2 (30.8 Btu/sec-ft^2).

In the radial positions with local peak heat fluxes much lower than the above, critical heat flux limits which are dependent on local conditions in the tube are likely to be responsible for the flux limit.

Figure 5-43 illustrates the effect of variable tube inlet quality, assuming that a local-condition critical heat flux limit is applicable and the temperature difference driving the heat flux increases without bound as the elevation increases. The typical tube wall heat flux illustrated in figure 5-43 rose very sharply as it approached the quench front elevation. The wall heat flux slope near the quench elevation was caused by the very steep axial temperature gradient in the secondary fluid at the quench front elevation. Plots of the fluid temperature (figures 5-29 and 5-30) show how the axial temperature profile varied parametrically with time.

Also plotted in figure 5-43 are the critical heat flux limits (CHF) from a local-condition CHF correlation,[1] assuming three tube inlet qualities - 80 percent, 86 percent, and 67 percent. The intersection of the three CHF lines with the tube wall heat flux curves illustrates that tubes with the lowest inlet quality may have the highest peak heat flux, and the tubes with the highest inlet quality may have the lowest peak heat flux.

---

1. Collier, J. G., Convective Boiling and Condensation, McGraw-Hill, New York, 1972.

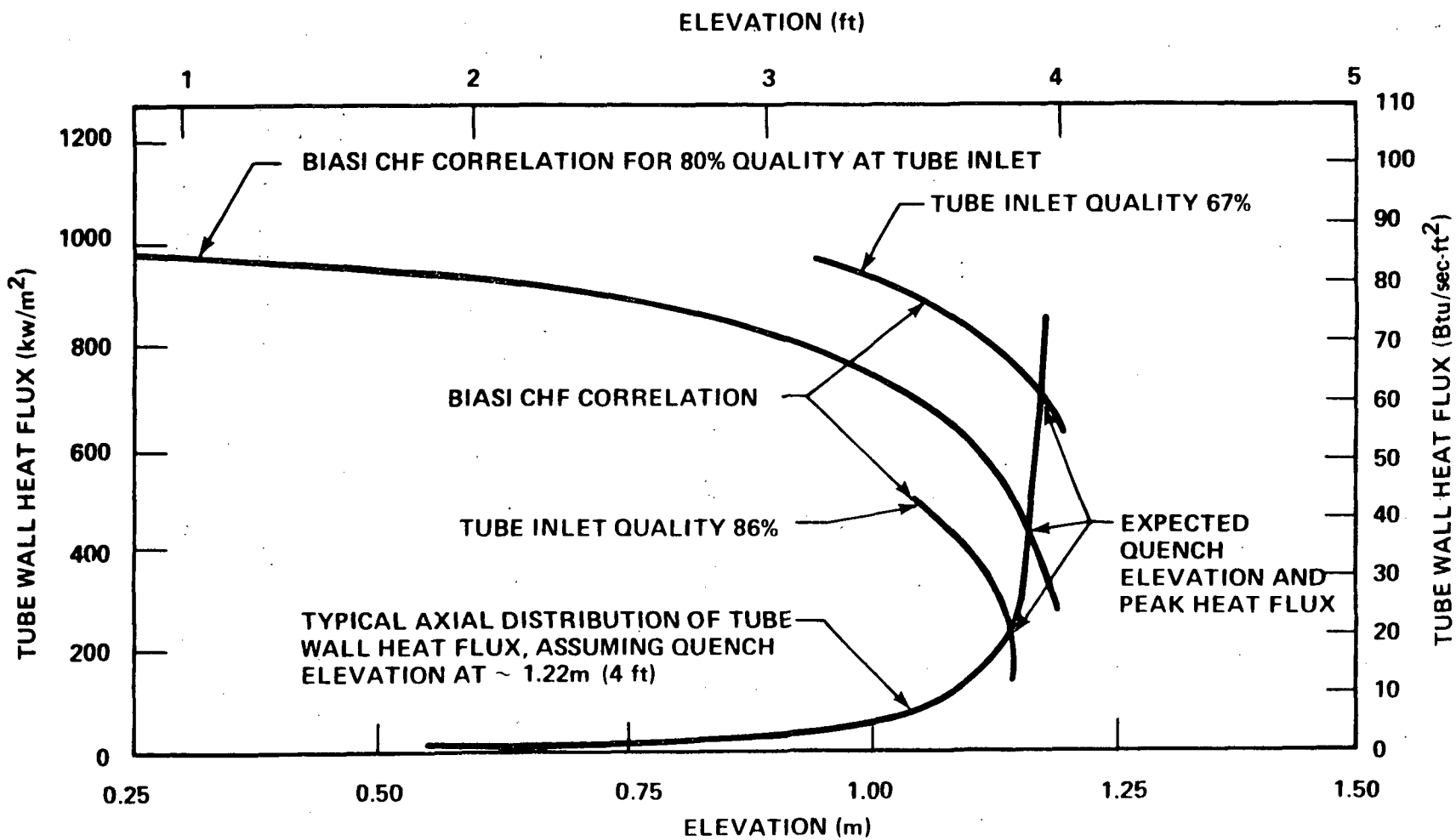


Figure 5-43. Typical Tube Wall Heat Flux Versus Elevation Near Quench Elevation

16817-3

The local heat flux variation between tube 4 and the other tubes illustrated in figures 5-32 through 5-41 is consistent with the expected heat flux results, based on tube 4 having a higher quality and thus a CHF limit lower than the other tubes. The flux peaks in radial positions 1, 2, and 3 were apparently limited by the overall secondary to primary temperature difference; in radial position 4, the higher inlet quality led to critical heat flux limits that were lower than the limits based on overall temperature difference.

The peak heat flux can be used to calculate the local quality using the local-condition CHF correlation. For example, at the 1.22 m (4 ft) elevation, the peak heat flux was approximately 230 kw/m^2 (20 Btu/sec-ft^2), and the local-condition critical heat flux correlation of Biasi[1] shows that a local quality of 95.6 percent will yield a critical heat flux of 230 kw/m^2 (20 Btu/sec-ft^2) at the reference test conditions. For a peak heat flux of 340 kw/m^2 (30 Btu/sec-ft^2), the local quality is 93.4 percent. Therefore relatively large differences in the peak heat flux can be caused by very small changes in quality, when the local quality is close to 1.0.

From the transient local heat flux plots in figures 5-32 through 5-41 and the tube wall temperature data recorded during the test, plots of local tube wall heat flux versus local tube wall superheat were constructed (figures 5-44 and 5-45). This type of plot, generally referred to as a boiling curve, illustrates the nucleate boiling and transition boiling heat transfer regimes. On these plots, the cluster of points at the highest wall superheat represents the dry wall heat transfer. The data in figures 5-44 and 5-45 are segregated based on the peak heat flux value. Figure 5-44 contains all the data with flux peaks close to 230 kw/m^2 (20 Btu/sec-ft^2) and figure 5-45 contains all the data with flux peaks close to 340 kw/m^2 (30 Btu/sec-ft^2).

In the above discussion of the local heat flux data, the assumption is made that radial variation in the secondary fluid temperature is small. Figures 5-46 through 5-49 are isometric plots of the secondary fluid temperatures. These plots, constructed from the measured and interpolated nodal temperatures reduced by the SGTEMPS data reduction program, illustrate the temperature distribution in the radial and axial directions

---

1. Collier, J. G., Convective Boiling and Condensation, McGraw-Hill, New York, 1972.

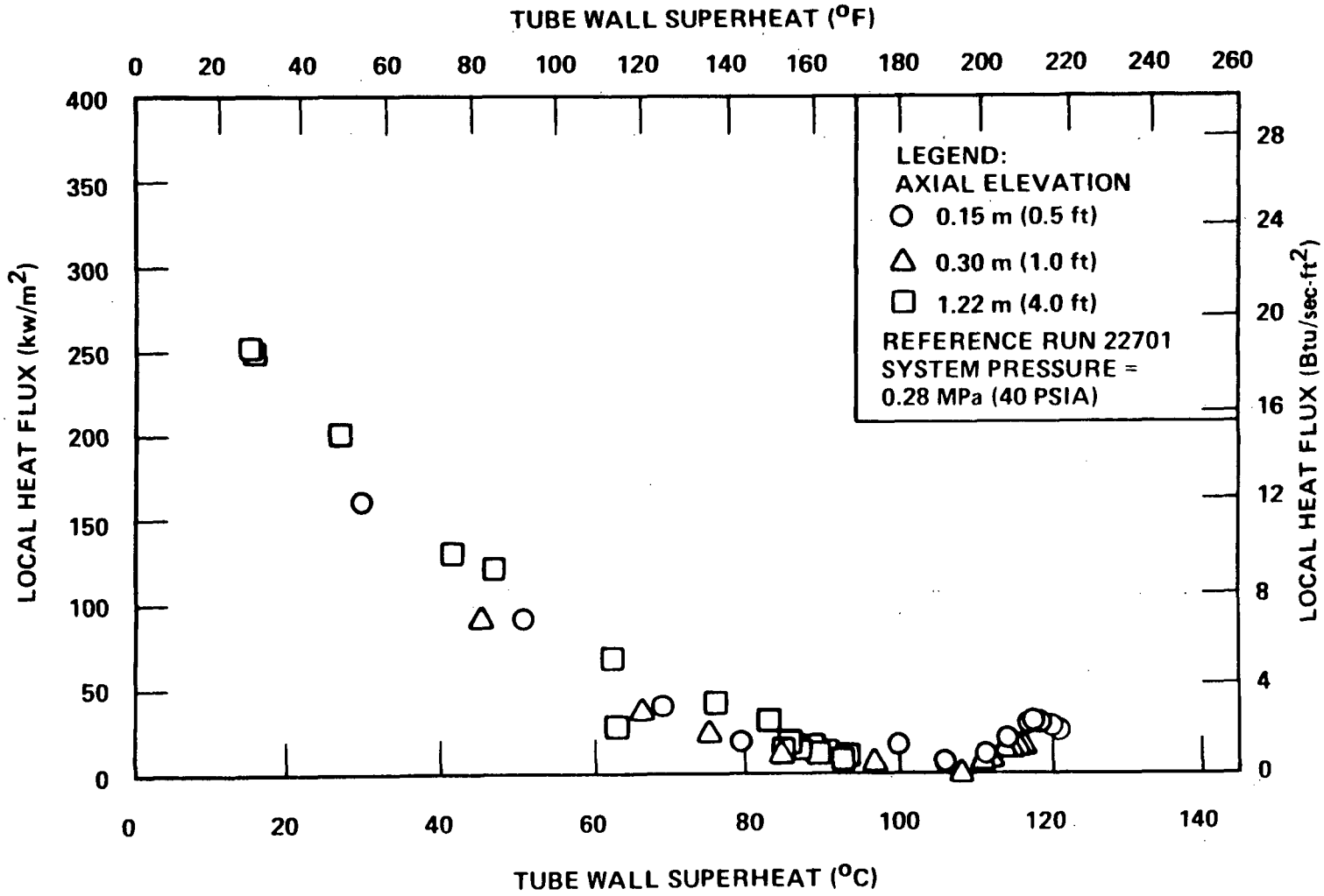


Figure 5-44. Boiling Curve for Nodes With Maximum Heat Flux ≈227 kw/m^2 (20 Btu/sec-ft^2)

16817-4

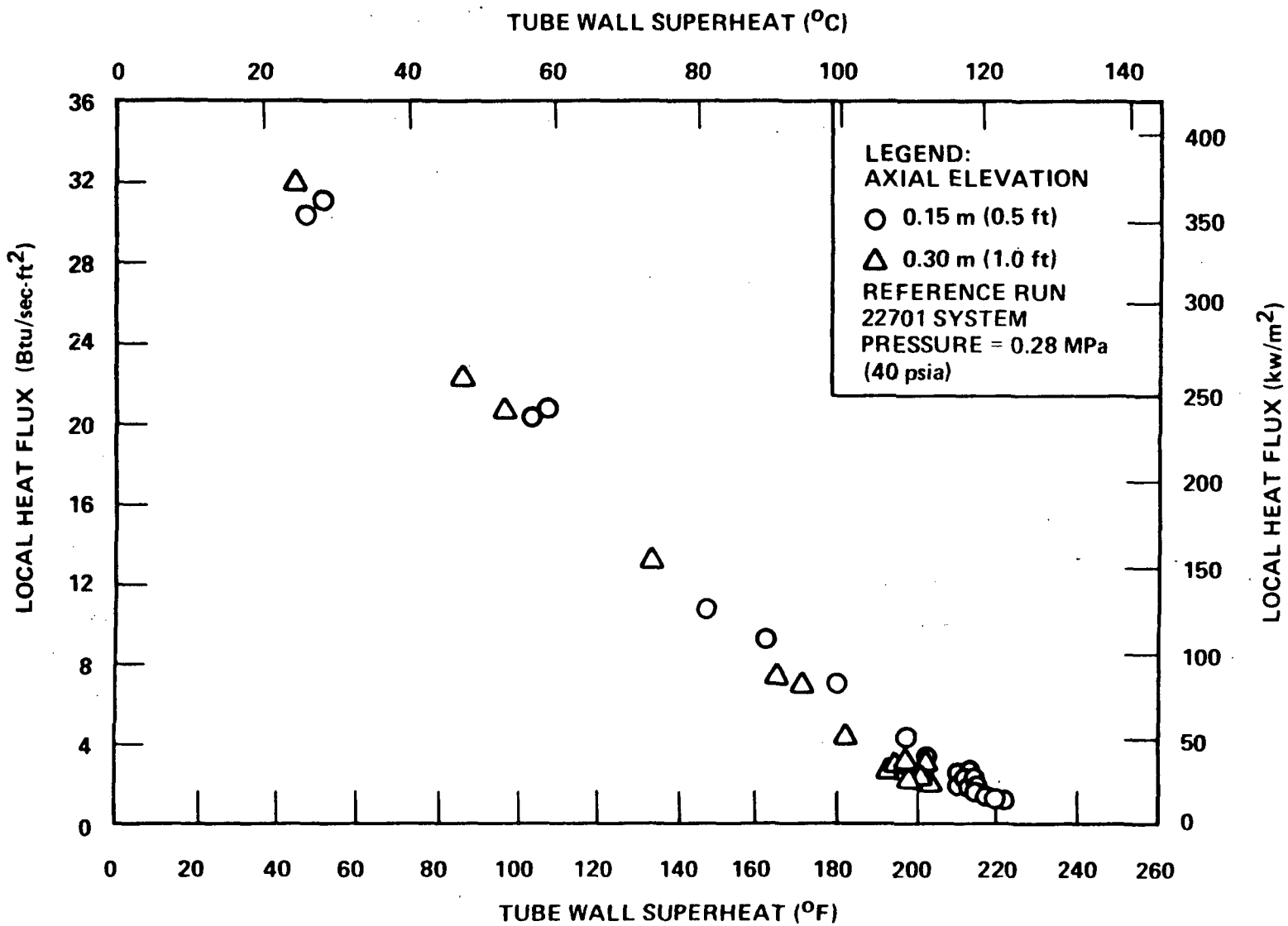


Figure 5-45. Boiling Curve for Nodes With Maximum Heat Flux ≈340 kw/m^2 (30 Btu/sec-ft^2)

16817-9

simultaneously. The plots were drawn from data taken at 3, 6, 12, and 18 minutes into the transient. They show that the temperature change in the four outlet tube positions followed very closely the temperature change in the four inlet tube positions. The principal temperature variation is in the axial direction; only slight temperature differences occurred radially.

The above evaluation of the reference run data shows that the loop boundary conditions were well behaved and that conditions at the inlet plenum tubesheet reached equilibrium very quickly. Virtually all of the liquid phase was evaporated in the tube bundle; however, trace amounts of liquid were detected in the outlet plenum. As the secondary water cooled, a temperature distribution developed in which large axial gradients were present but the radial gradients were very small.

The local tube wall heat flux data indicate that the wall heat flux peaks at the time the wall quenches. This quench front slowly moves up each tube at the same velocity, with tubes with the lowest inlet quality leading the quench front and tubes with the highest inlet quality lagging the quench front.

5-3. EVALUATION OF REPLICATE RUNS

The reference run (22701) test parameters were repeated in runs 21711 and 22010. Test run summary data are presented in tables 5-2 and 5-3. Generally, the replicate run data followed very closely the parameter trends in the reference run. The local composite plots of primary side steam probe, tube wall, and secondary fluid temperatures for the two replicate runs are presented in figures 5-50 through 5-73. These local temperatures are virtually identical to the corresponding reference run temperature transients shown in figures 5-17 through 5-28.

However, two of the parameters that did change significantly between the replicate runs were the overall energy exchange and the liquid collected in the outlet plenum. The total energy exchange as recorded in table 4-2 varies from 164 mw-sec (155,000 Btu) in run 22010 to 177 mw-sec (168,000 Btu) in run 22701. The table 4-2 data also include the mass balance error in each run. In run 22701, the mass balance error was -1.1 percent; in the replicate runs, the largest mass balance error was only -0.2 percent

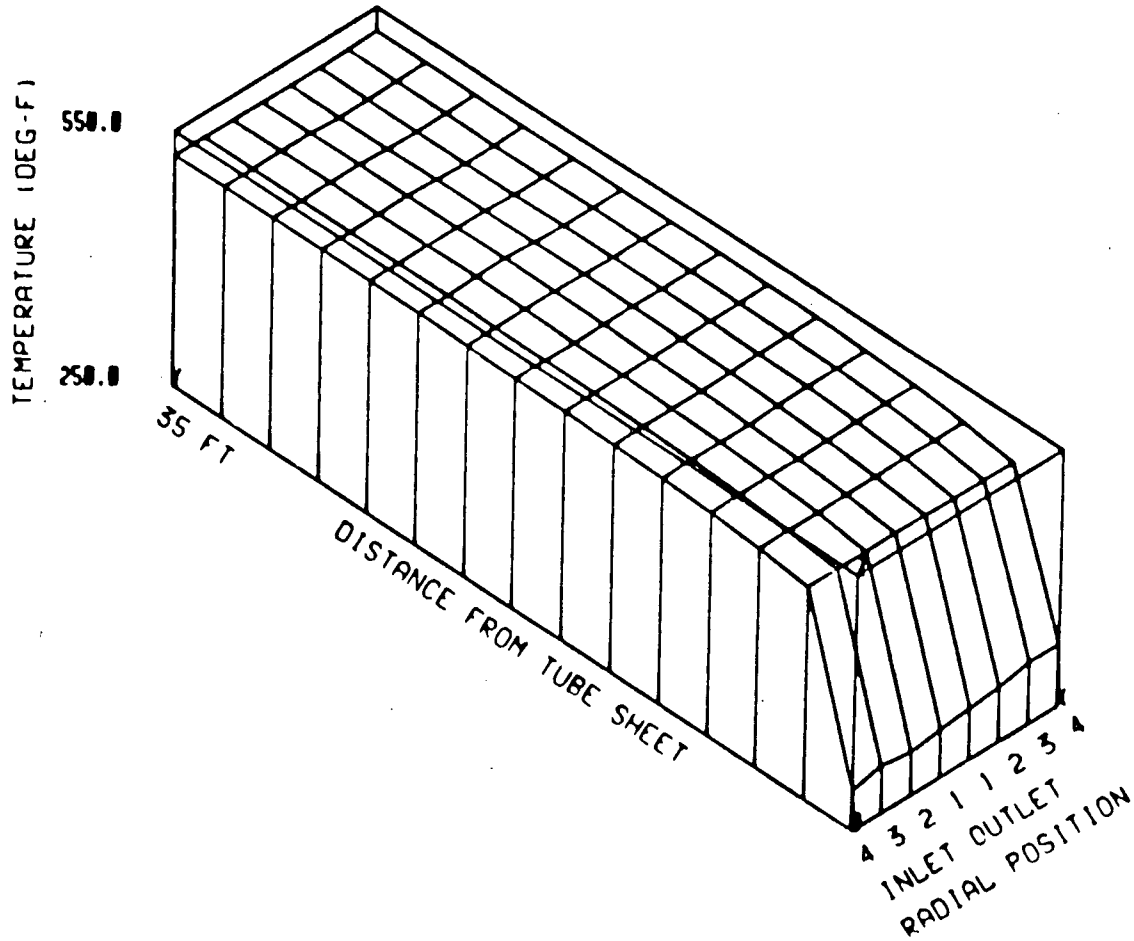


Figure 5-46. Isometric Plot of Secondary Fluid Temperatures at 3.4 Minutes Into Transient, Reference Run

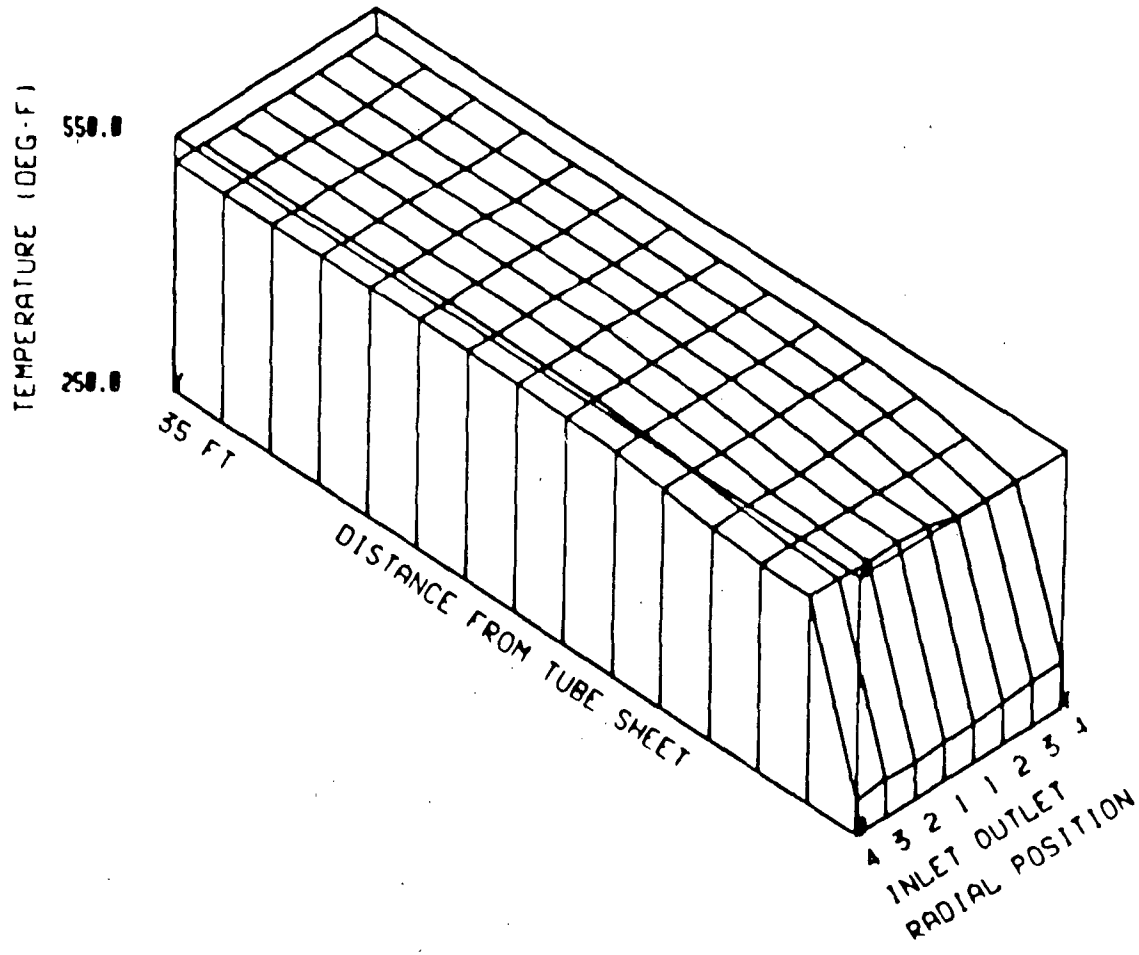


Figure 5-47. Isometric Plot of Secondary Fluid Temperatures at 6.1 Minutes Into Transient, Reference Run

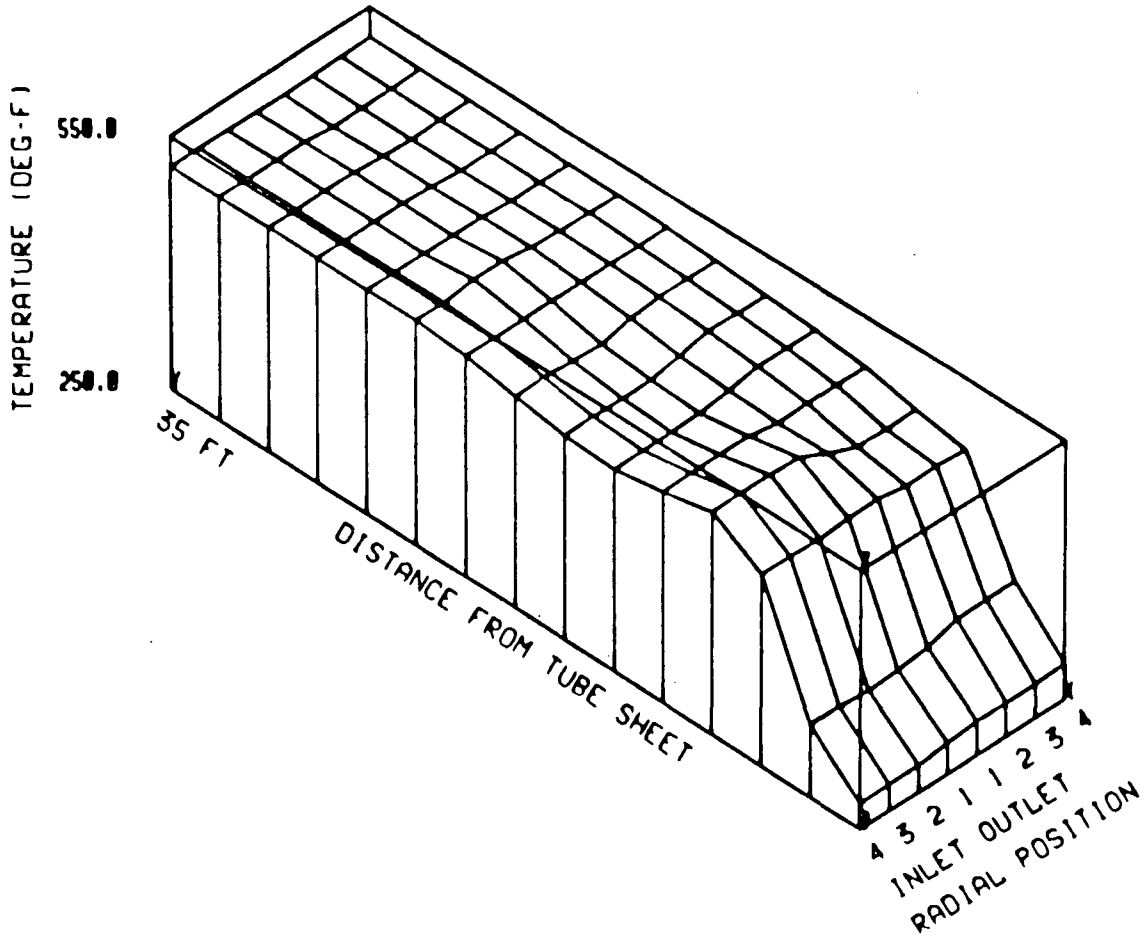


Figure 5-48. Isometric Plot of Secondary Fluid Temperatures at 12.1 Minutes Into Transient, Reference Run

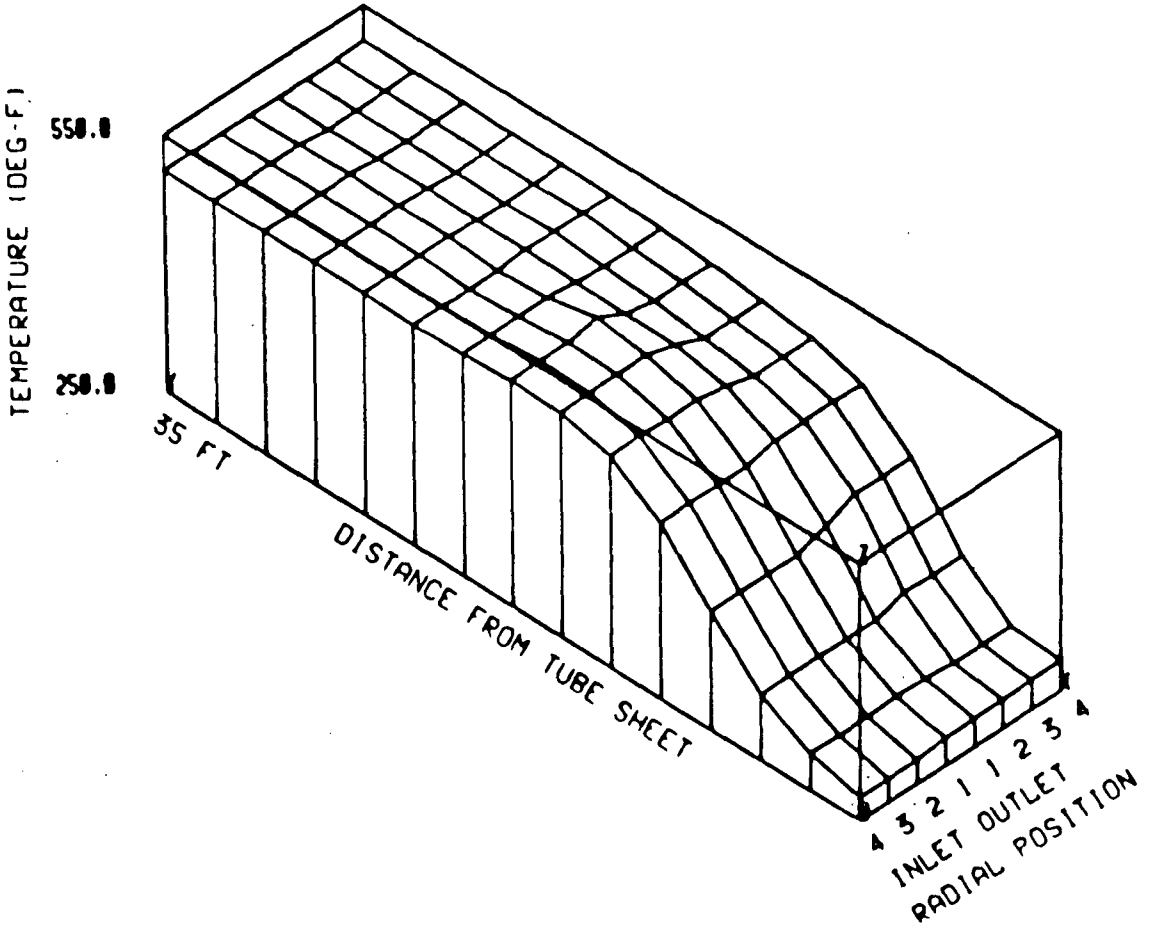


Figure 5-49. Isometric Plot of Secondary Fluid Temperatures at 18.0 Minutes Into Transient, Reference Run

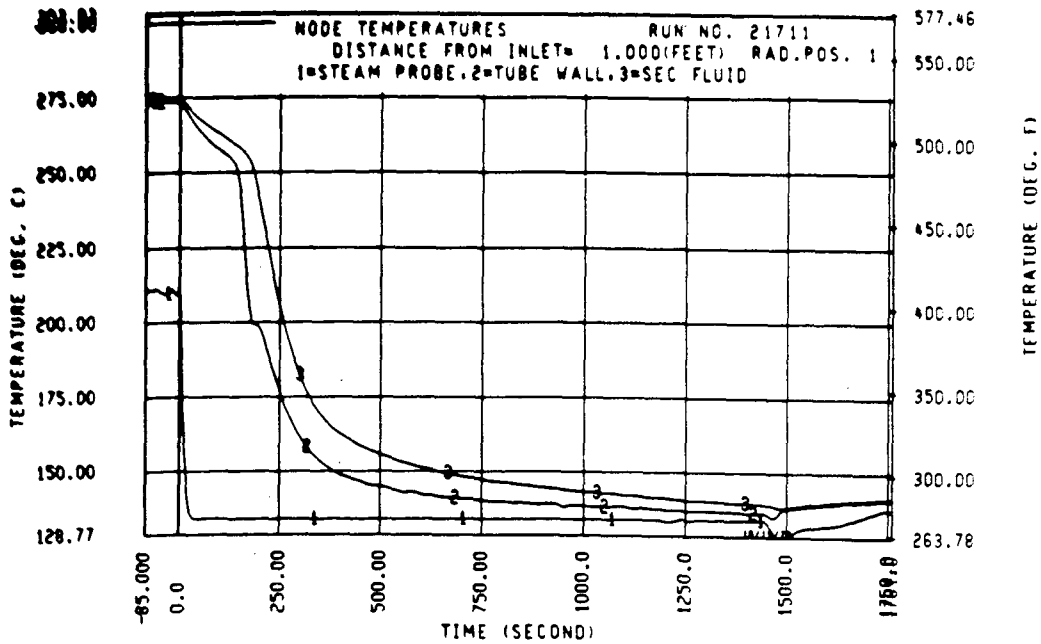


Figure 5-50. Nodal Temperatures, Replicate Run 21711, 0.30 m (1 ft) Elevation, Radial Position 1

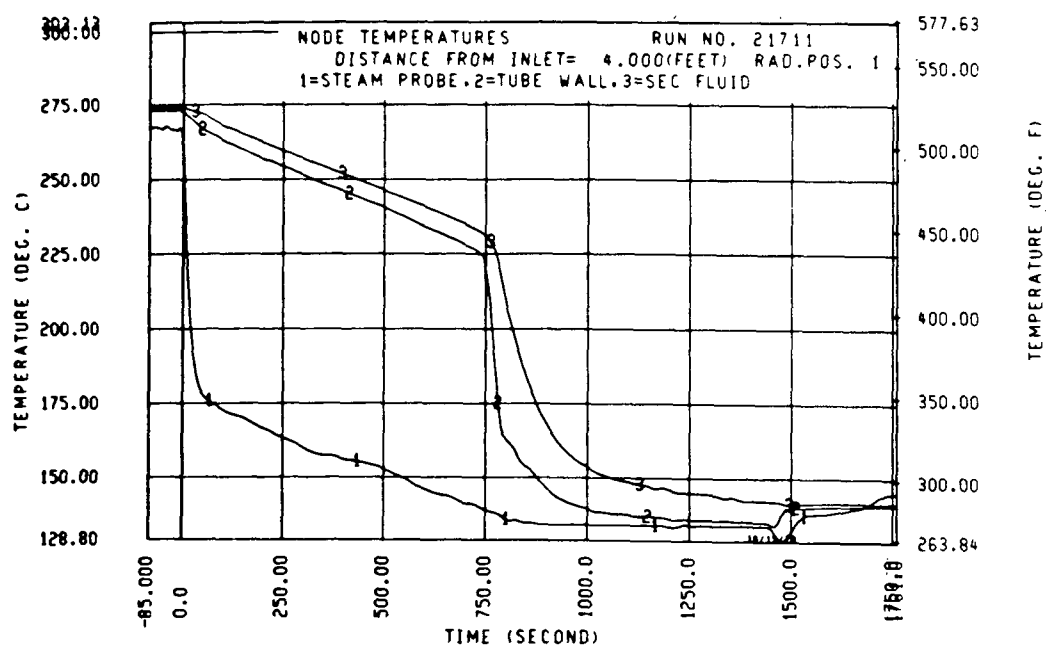


Figure 5-51. Nodal Temperatures, Replicate Run 21711, 1.22 m (4 ft) Elevation, Radial Position 1

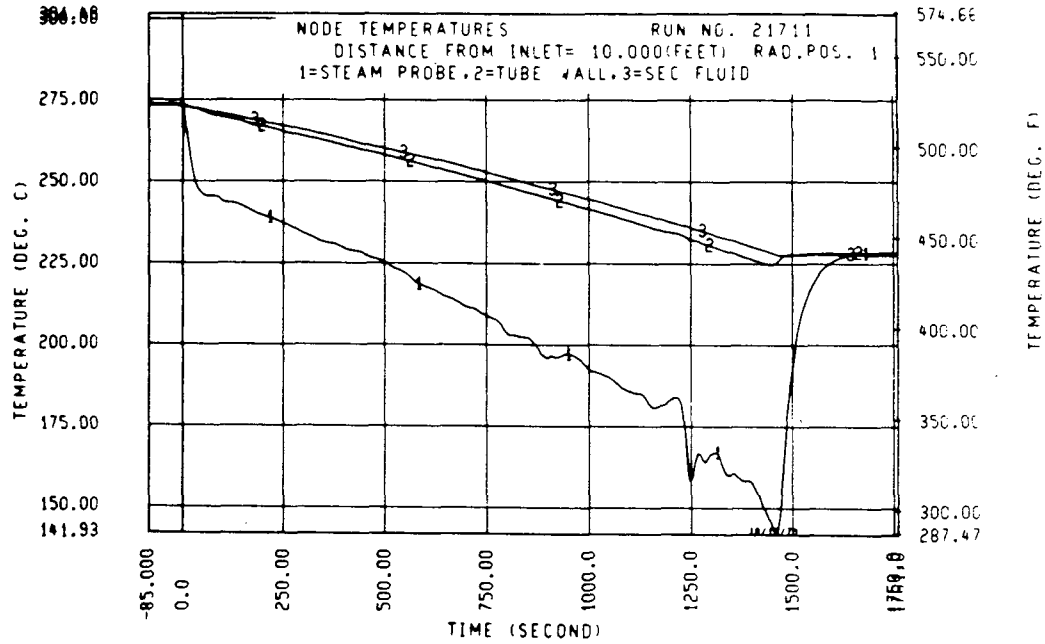


Figure 5-52. Nodal Temperatures, Replicate Run 21711, 3.05 m (10 ft) Elevation, Radial Position 1

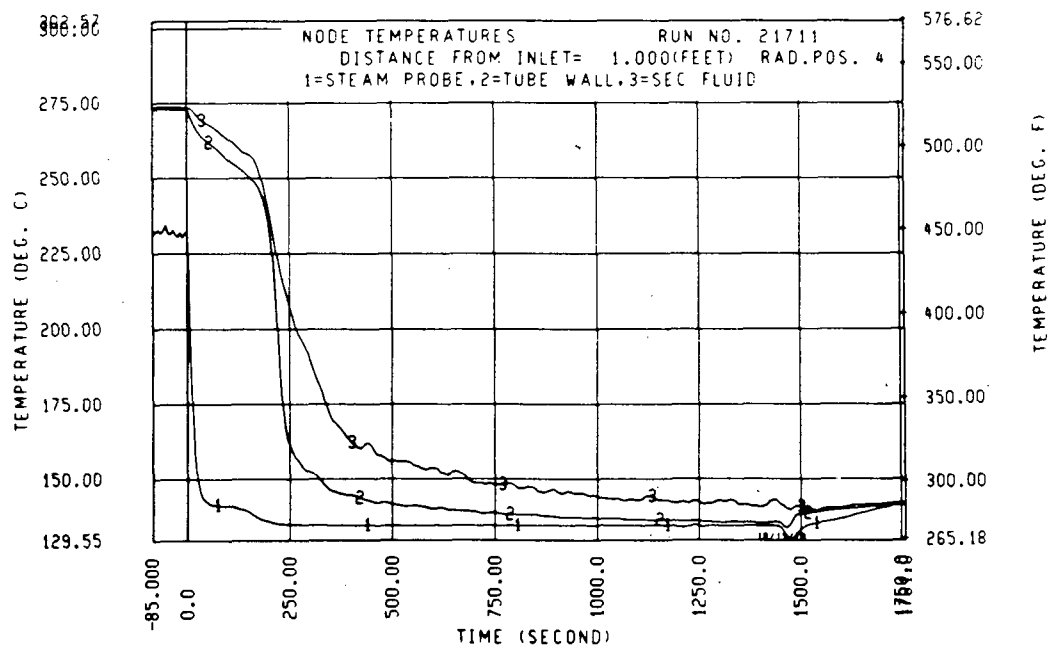


Figure 5-53. Nodal Temperatures, Replicate Run 21711, 0.30 m (1 ft) Elevation, Radial Position 4

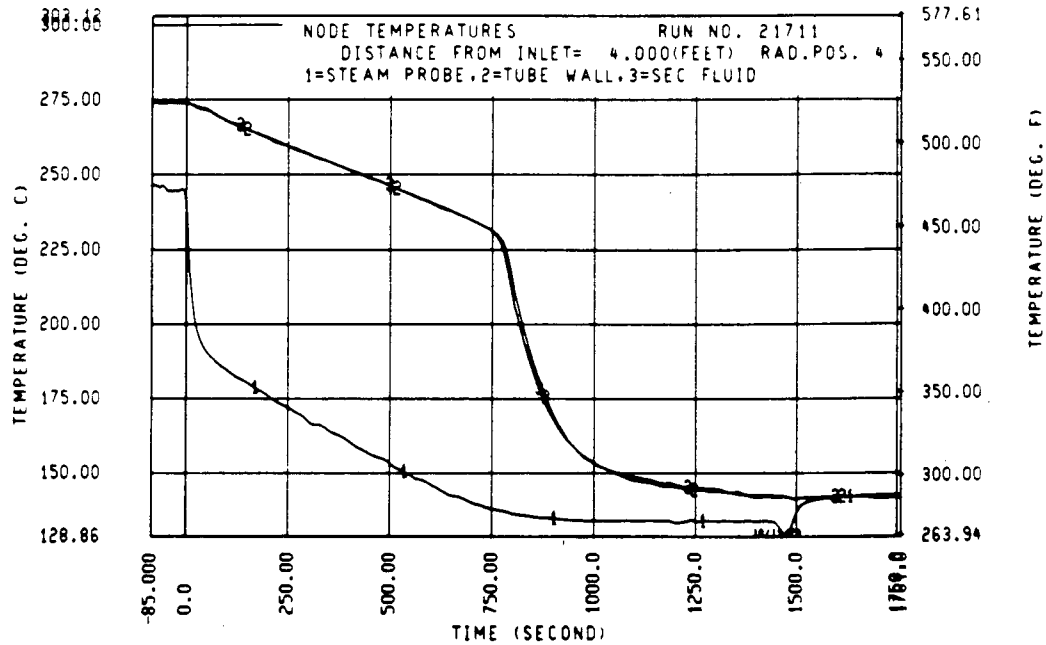


Figure 5-54. Nodal Temperatures, Replicate Run 21711, 1.22 m (4 ft) Elevation, Radial Position 4

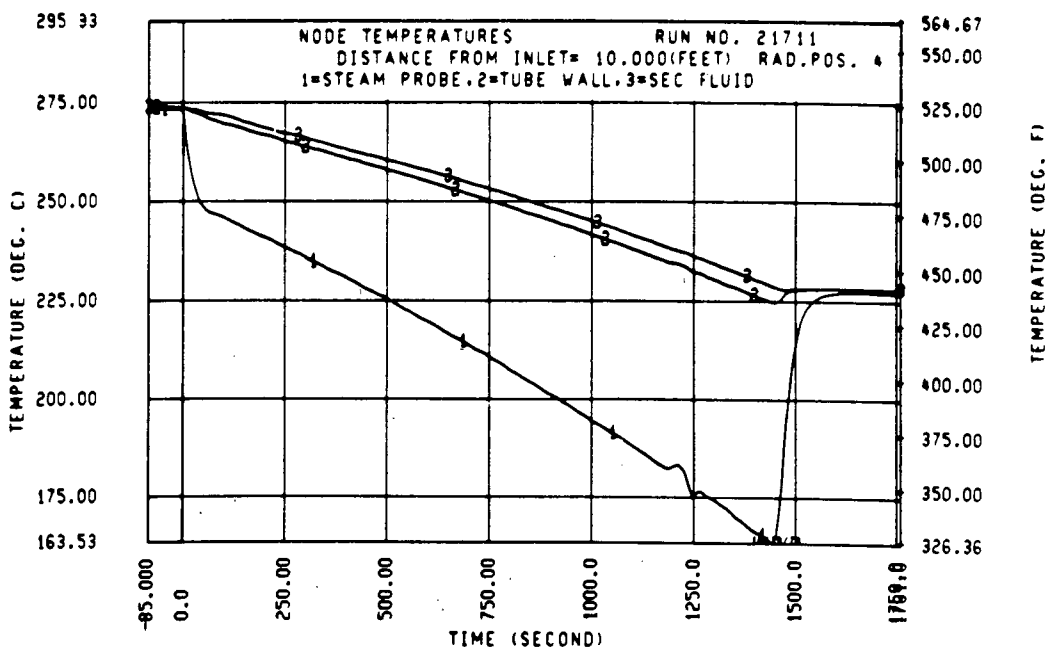


Figure 5-55. Nodal Temperatures, Replicate Run 21711, 3.05 m (10 ft) Elevation, Radial Position 4

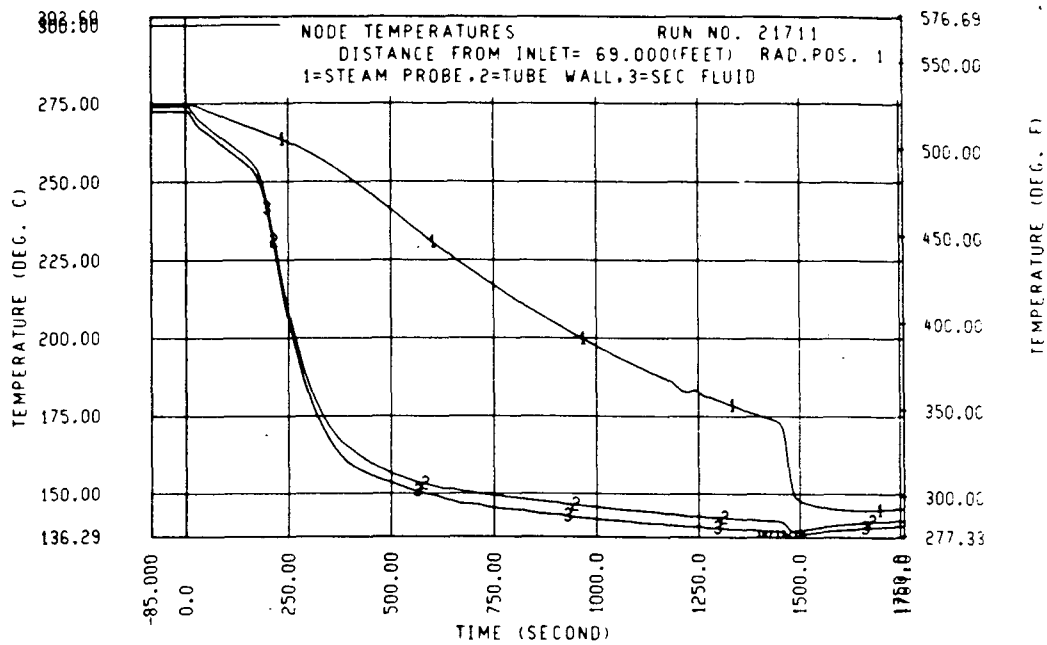


Figure 5-56. Nodal Temperatures, Replicate Run 21711, 21.0 m (69 ft) Elevation, Radial Position 1

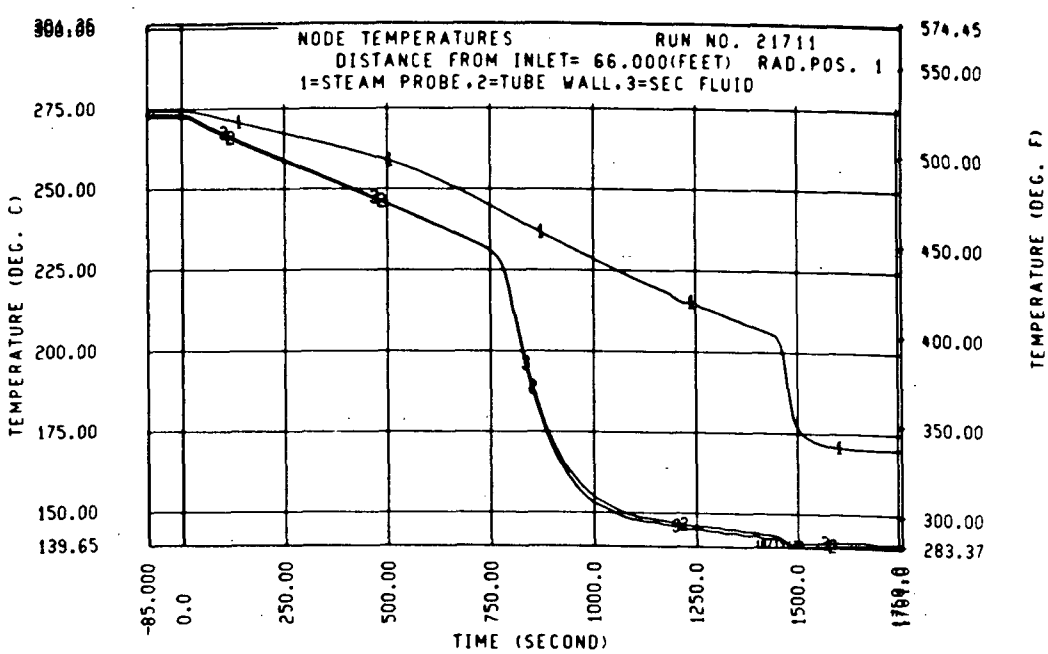


Figure 5-57. Nodal Temperatures, Replicate Run 21711, 20.1 m (66 ft) Elevation, Radial Position 1

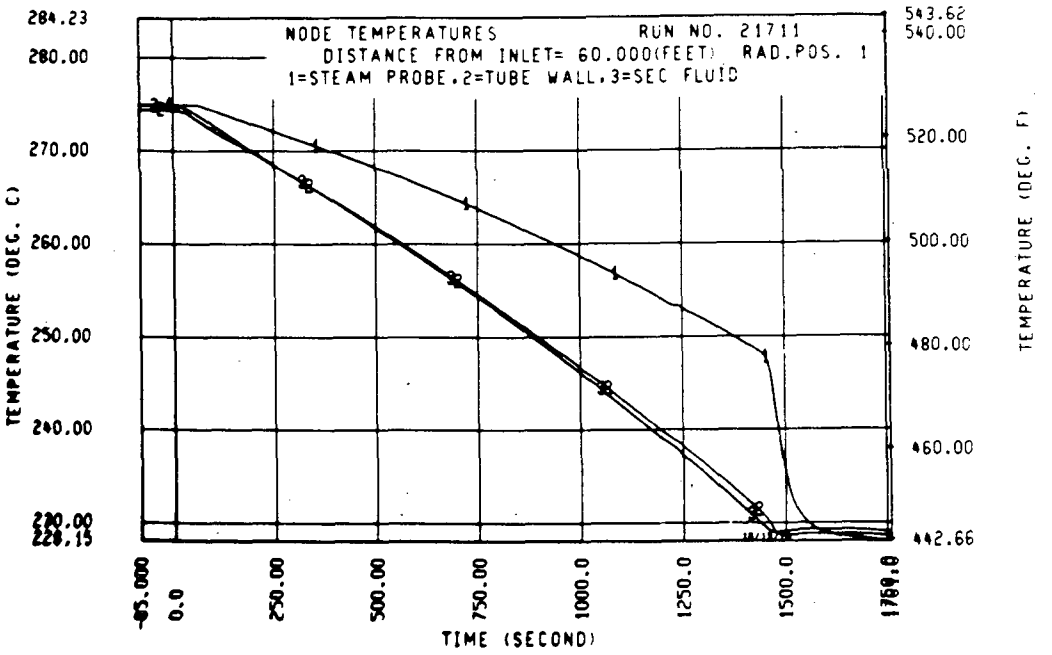


Figure 5-58. Nodal Temperatures, Replicate Run 21711, 18.3 m (60 ft) Elevation, Radial Position 1

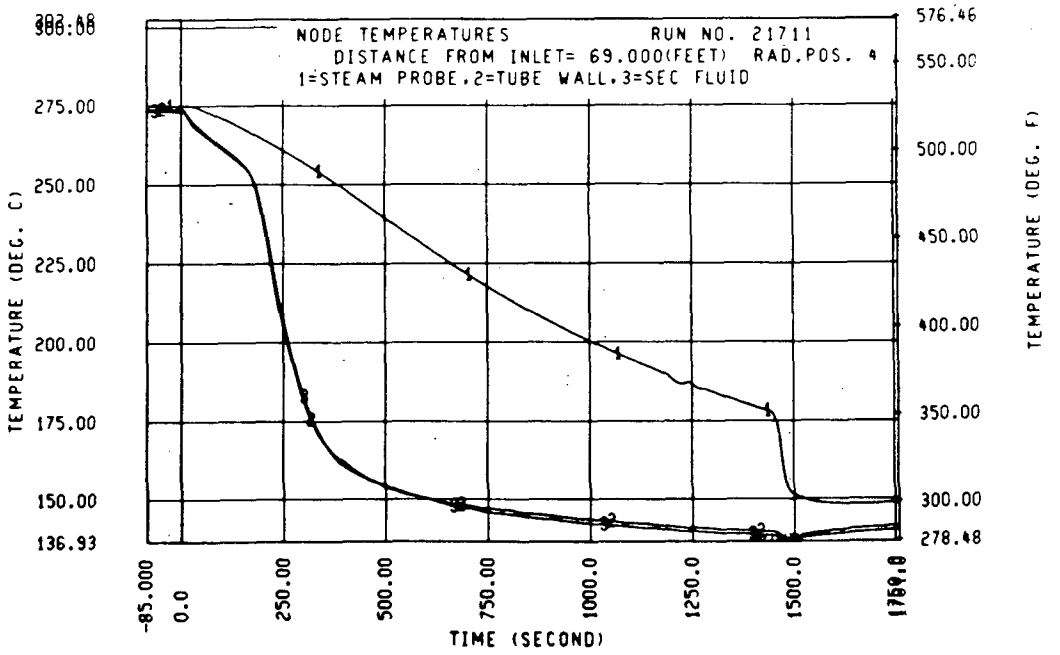


Figure 5-59. Nodal Temperatures, Replicate Run 21711, 21.0 m (69 ft) Elevation, Radial Position 4

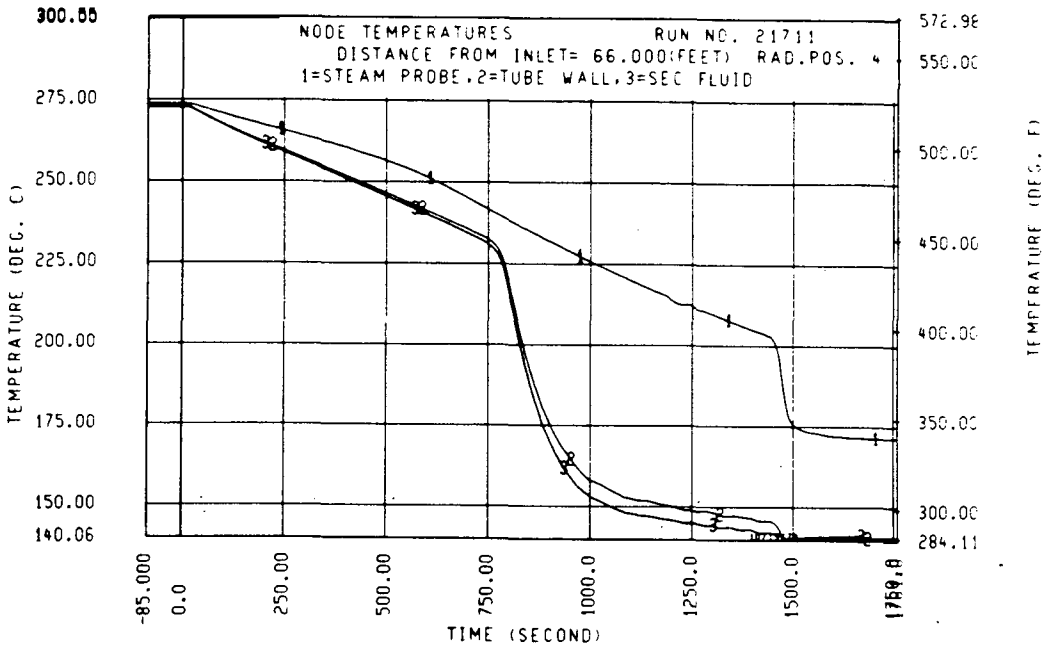


Figure 5-60. Nodal Temperatures, Replicate Run 21711, 20.1 m (66 ft) Elevation, Radial Position 4

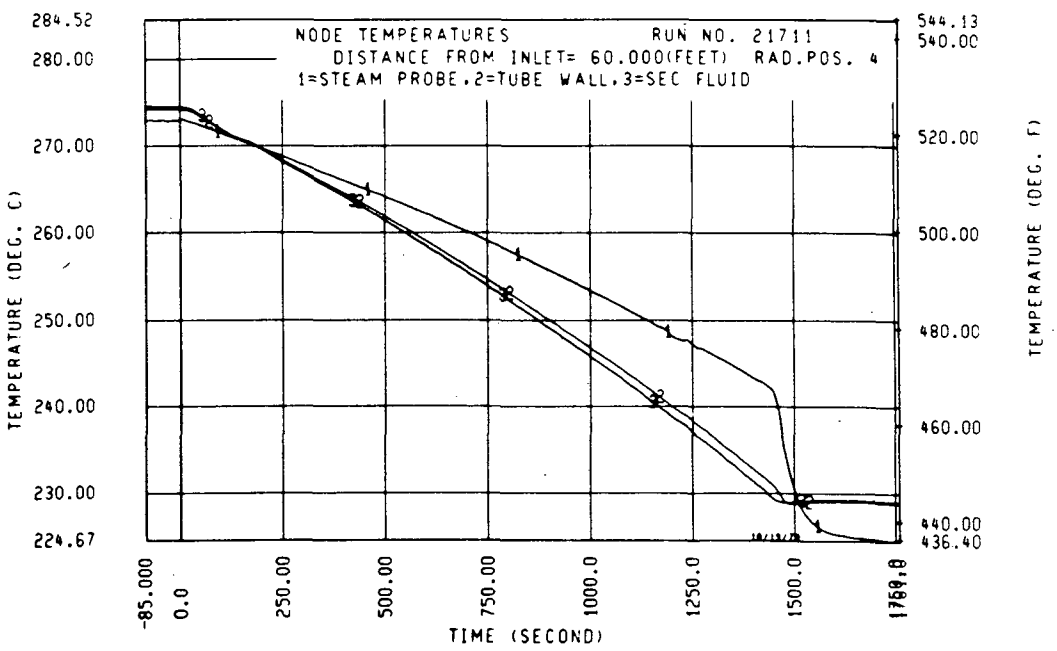


Figure 5-61. Nodal Temperatures, Replicate Run 21711, 18.3 m (60 ft) Elevation, Radial Position 4

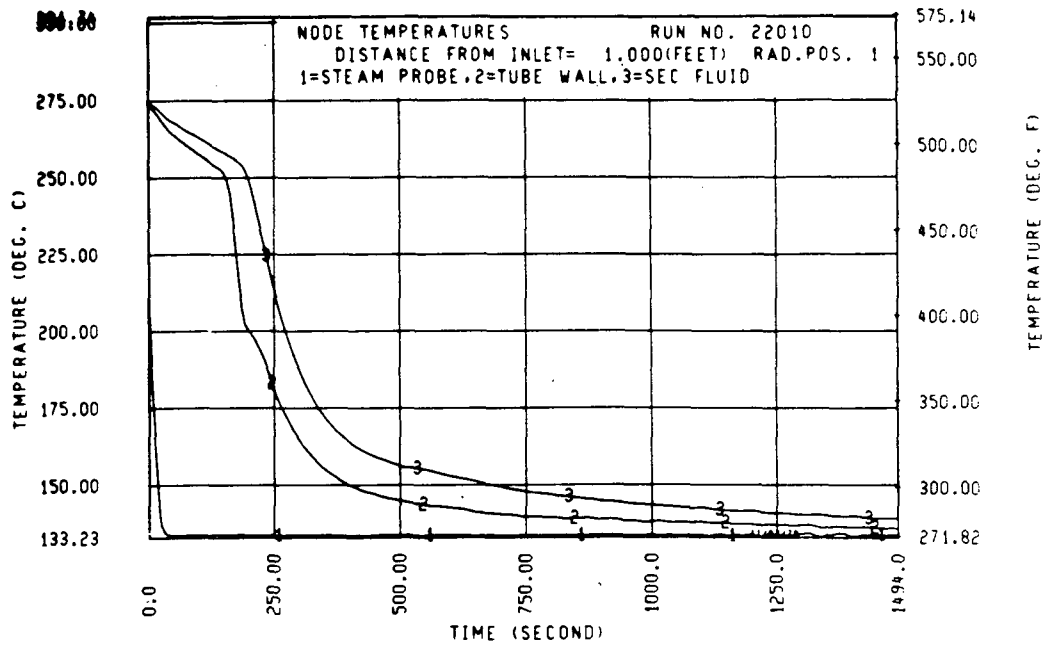


Figure 5-62. Nodal Temperatures, Replicate Run 22010, 0.30 m (1 ft) Elevation, Radial Position 1

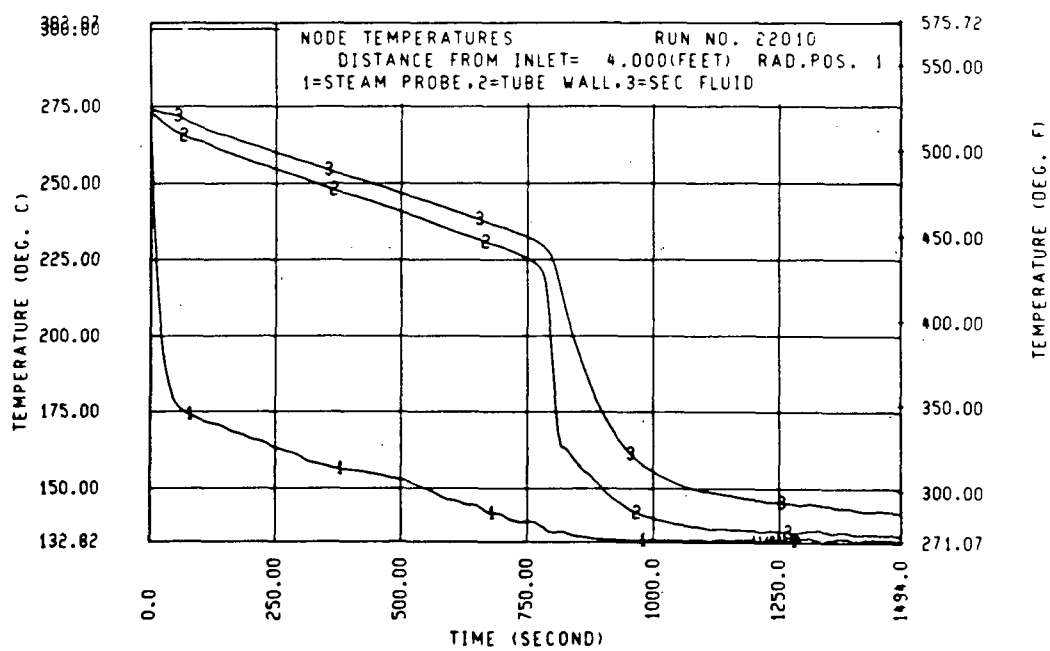


Figure 5-63. Nodal Temperatures, Replicate Run 22010, 1.22 m (4 ft) Elevation, Radial Position 1

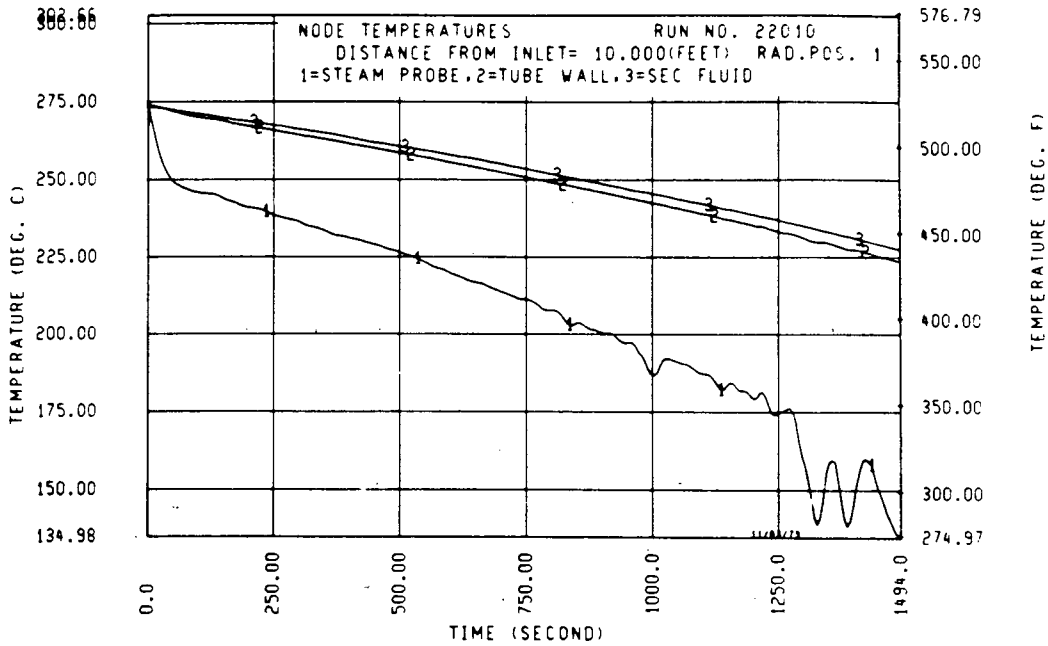


Figure 5-64. Nodal Temperatures, Replicate Run 22010, 3.05 m (10 ft) Elevation, Radial Position 1

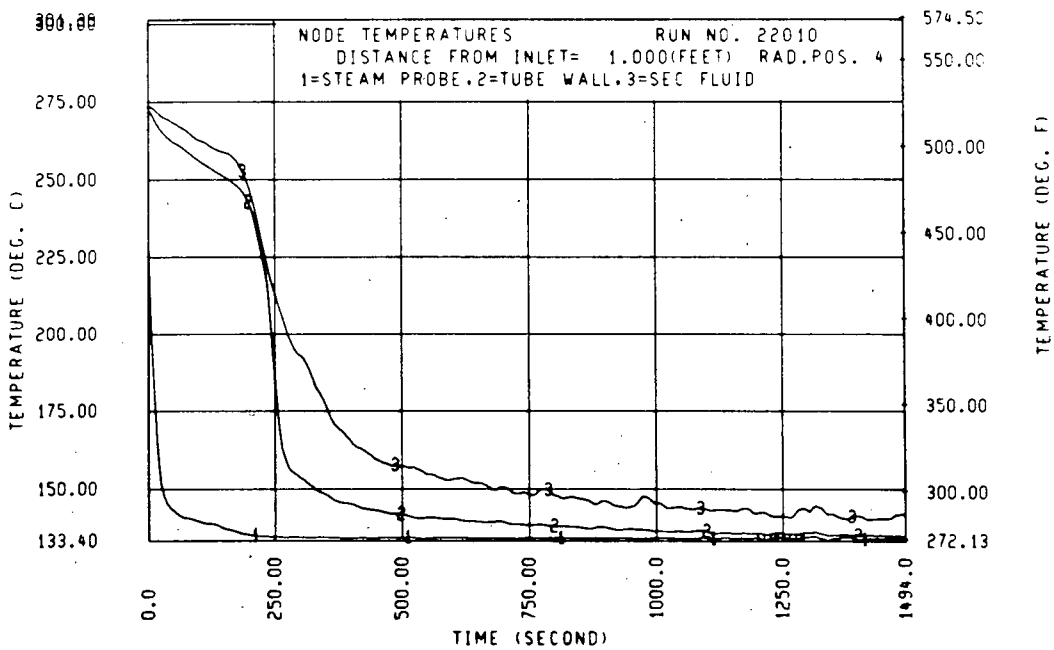


Figure 5-65. Nodal Temperatures, Replicate Run 22010, 0.30 m (1 ft) Elevation, Radial Position 4

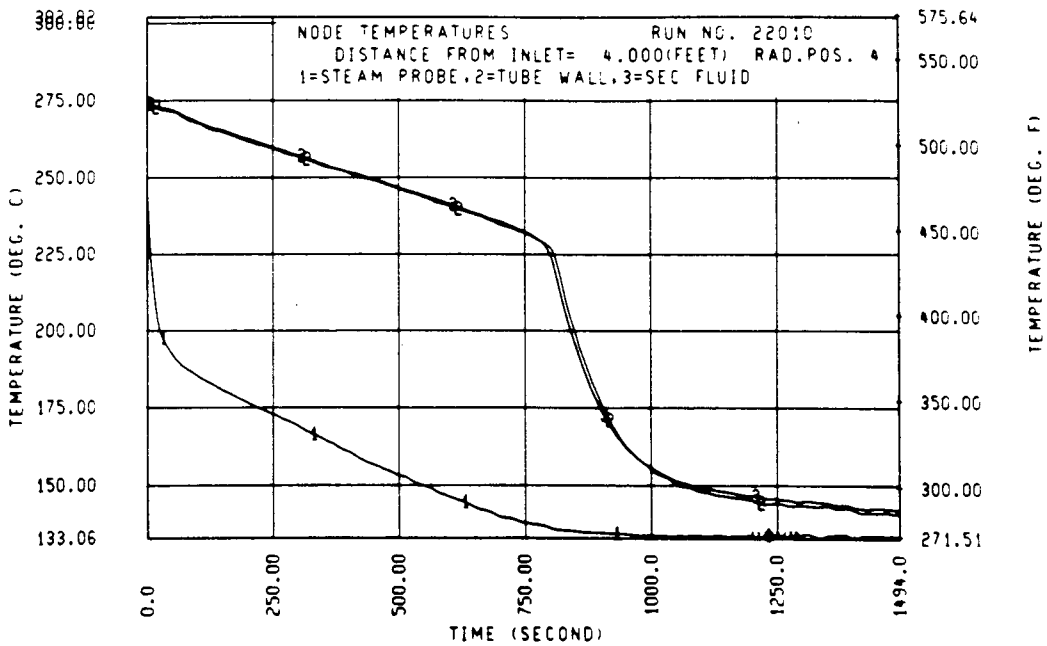


Figure 5-66. Nodal Temperatures, Replicate Run 22010, 1.22 m (4 ft) Elevation, Radial Position 4

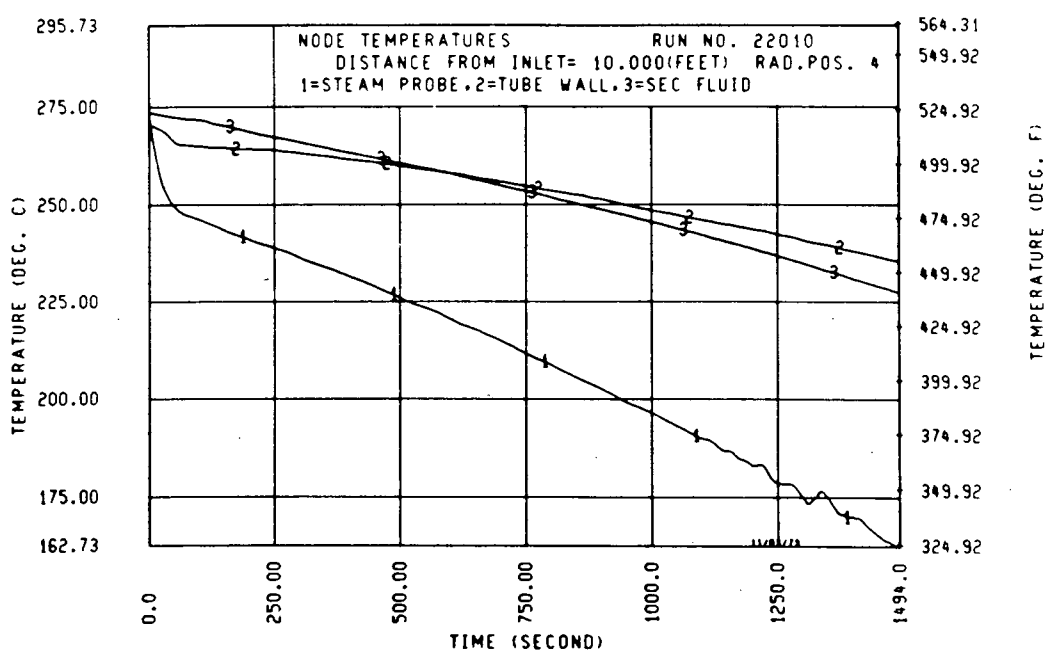


Figure 5-67. Nodal Temperatures, Replicate Run 22010, 3.05 m (10 ft) Elevation, Radial Position 4

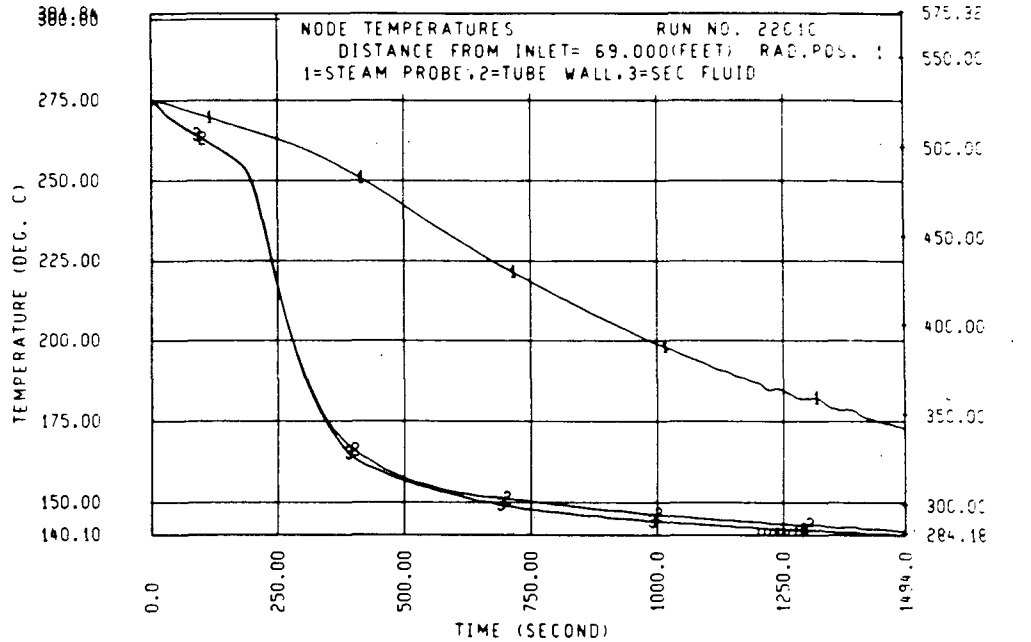


Figure 5-68. Nodal Temperatures, Replicate Run 22010, 21.0 m (69 ft) Elevation, Radiation Position 1

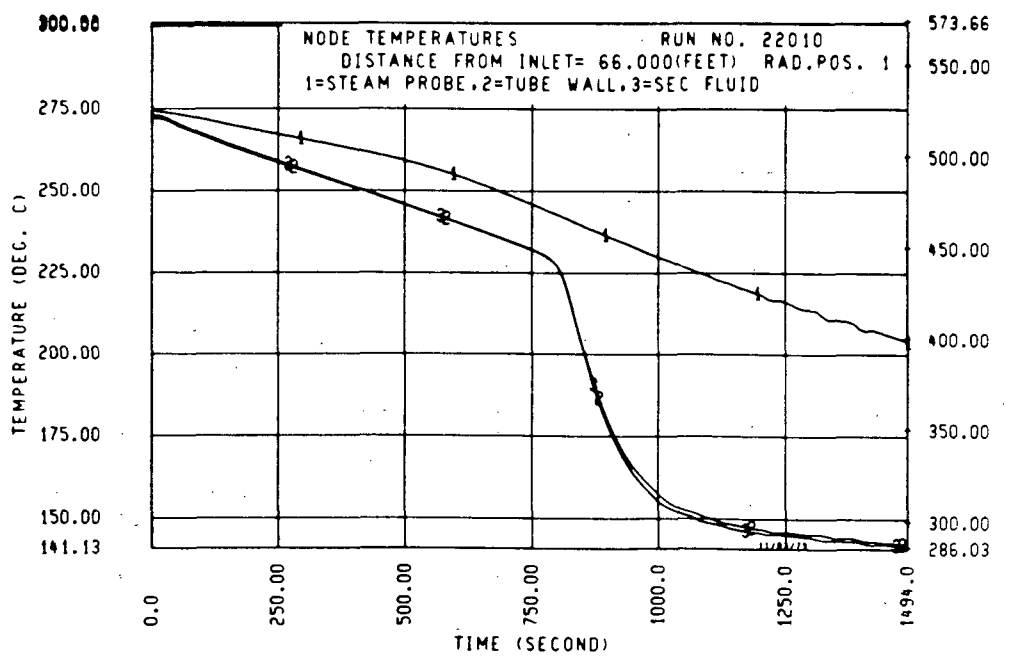


Figure 5-69. Nodal Temperatures, Replicate Run 22010, 20.1 m (66 ft) Elevation, Radial Position 1

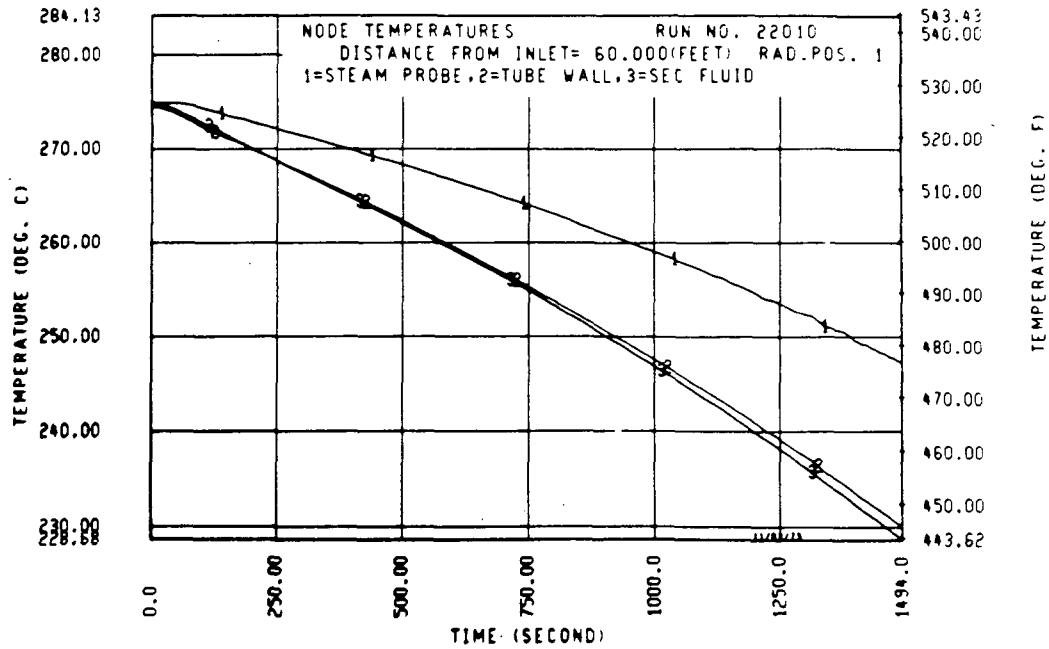


Figure 5-70. Nodal Temperatures, Replicate Run 22010, 18.3 m (60 ft) Elevation, Radial Position 1

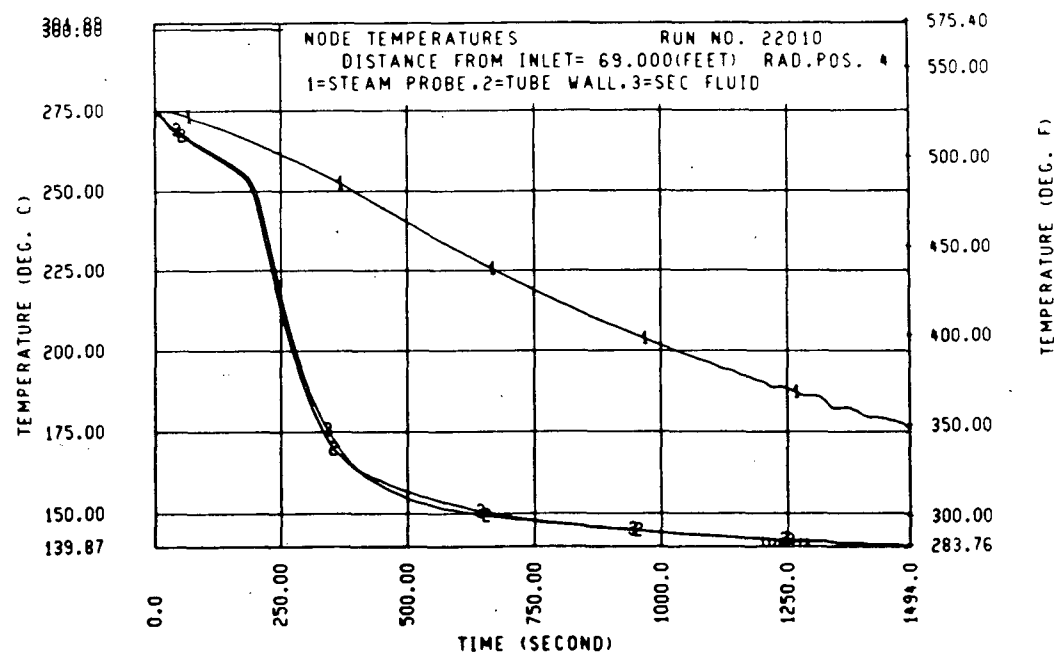


Figure 5-71. Nodal Temperatures, Replicate Run 22010, 21.0 m (69 ft) Elevation, Radial Position 4

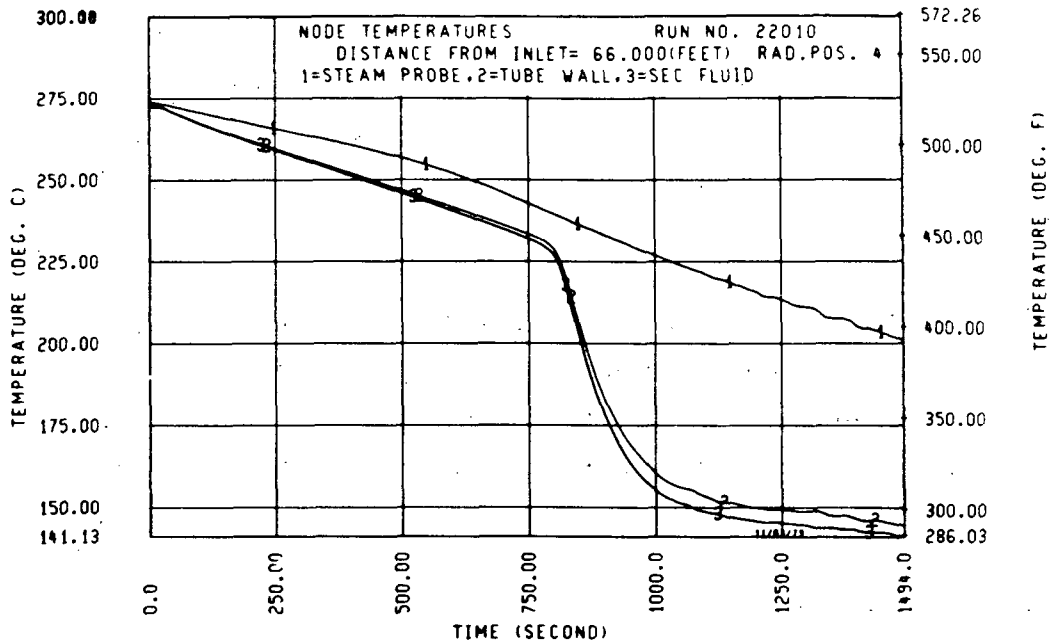


Figure 5-72. Nodal Temperatures, Replicate Run 22010, 20.1 m (66 ft) Elevation, Radial Position 4

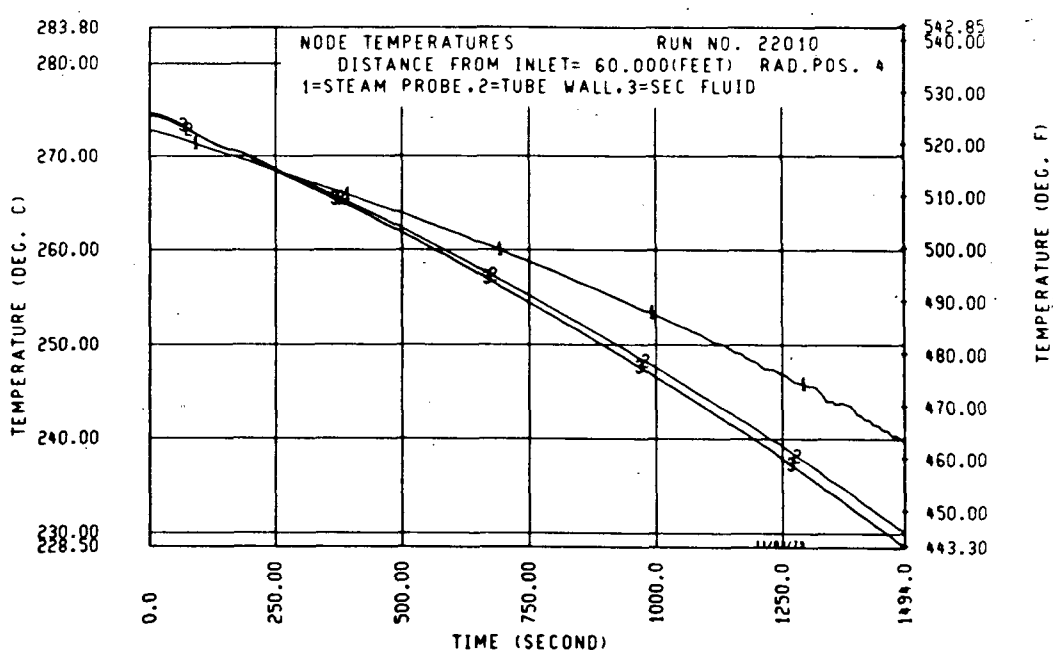


Figure 5-73. Nodal Temperatures, Replicate Run 22010, 18.3 m (60 ft) Elevation, Radial Position 4

The negative error implies that the mass flow leaving the test loop was larger than the mass flow entering the loop. Correcting the reference run overall energy exchange by the assumption that the actual exhaust steam mass flow rate was 1 percent lower than the recorded flow rate would reduce the overall energy exchange by 11.6 mw-sec (11,000 Btu), to 165 mw-sec (157,000 Btu), which is within 2 percent of the other runs. The estimated error in the overall energy exchange (appendix B of Report No. 4) is 3 percent.

A significant difference in the liquid collected in the outlet plenum is shown by comparison of the data in tables 5-2 through 5-4. Although the relative difference in the outlet plenum liquid collected was large in the three reference runs, in terms of the total mass that entered the steam generator in the test 340 kg (750 lb) the difference in outlet plenum liquid collected was quite small and did not contribute significantly to the overall bundle energy transfer. One possible explanation for the trend of increasing outlet plenum liquid collection from run 21711 to run 22701 is the plenum baffle leak. Table G-1 of Report No. 4 shows that the baffle leak was slowly increasing from run 21711 to run 22701. However, the measured leak rate only increased by about 3×10^{-7} m^3/sec (0.005 gal/min), or about 0.45 kg (1 lb) over the 25-minute duration of a test.

From visual observations of the plenum baffle plate, the baffle leak was found to be due to a crack in a seam weld between two plates in the baffle wall. The plenum leak tests verified that the leak mass flow rate was small.

The outlet plenum liquid collection data reported in the summary tables in Report No. 4 have been reviewed in an attempt to understand the data trends. The data for similar runs do not monotonically increase or decrease with time. A subset of runs with similar boundary conditions was statistically analyzed. This subset included the three reference runs, the pressure sensitivity runs, the reference run with the inlet plenum spray nozzle, the secondary temperature sensitivity run, and a replicate reference run that was invalidated because the liquid flow rate was 10 percent high. The average outlet plenum

liquid collection from this set of eight runs was 3.23 kg (7.12 lb) with a standard deviation of 0.848 kg (1.87 lb). The average of the five reference run condition tests was 3.20 kg (7.05 lb) with a standard deviation of 1.01 kg (2.22 lb). A linear regression of the data shows a negligible correlation with time. That is, later tests had no more or less liquid accumulation than earlier tests.

Late in the test program, the baffle crack was sealed with epoxy resin. In a test run after the plenum was sealed (run 23605), 10 kg (22 lb) of water was collected in the outlet plenum. In this run, the inlet quality boundary condition was 50 percent. In a similar test run before the epoxy seal, and with the spray nozzle in the inlet plenum, only 7.98 kg (17.6 lb) of water was collected in the outlet plenum.

This evidence suggests that the crack in the baffle wall was not contributing significantly to the outlet plenum liquid accumulation. Also, the outlet plenum liquid collection data have a standard deviation of about 1.0 kg (2.2 lb). Differences in liquid collection between runs of this magnitude cannot be attributed to the boundary condition change, but must be assumed to be due to random variation between runs.

5-4. SINGLE-PARAMETER VARIATIONS

The test matrix was designed to measure the effect of a change in one parameter, with all other parameters at the reference value. In this way the effect of quality variation, primary pressure, primary mass flow rate, secondary temperature, and secondary level were measured. The effects of the single-parameter variations on the time for the local tube quench front to reach the 1.22 m (4 ft) elevation are shown in figure 5-74. Figure 5-74 illustrates how strongly the parameters affect the 1.22 m (4 ft) quench time. The parameters that have a strong effect are quality, total mass flow, and secondary temperature. Changing the primary system pressure has a lesser effect on the 1.22 m (4 ft) quench time.

In the following paragraphs, the single-parameter variation runs are compared to the reference run, and significant differences are identified and explained.

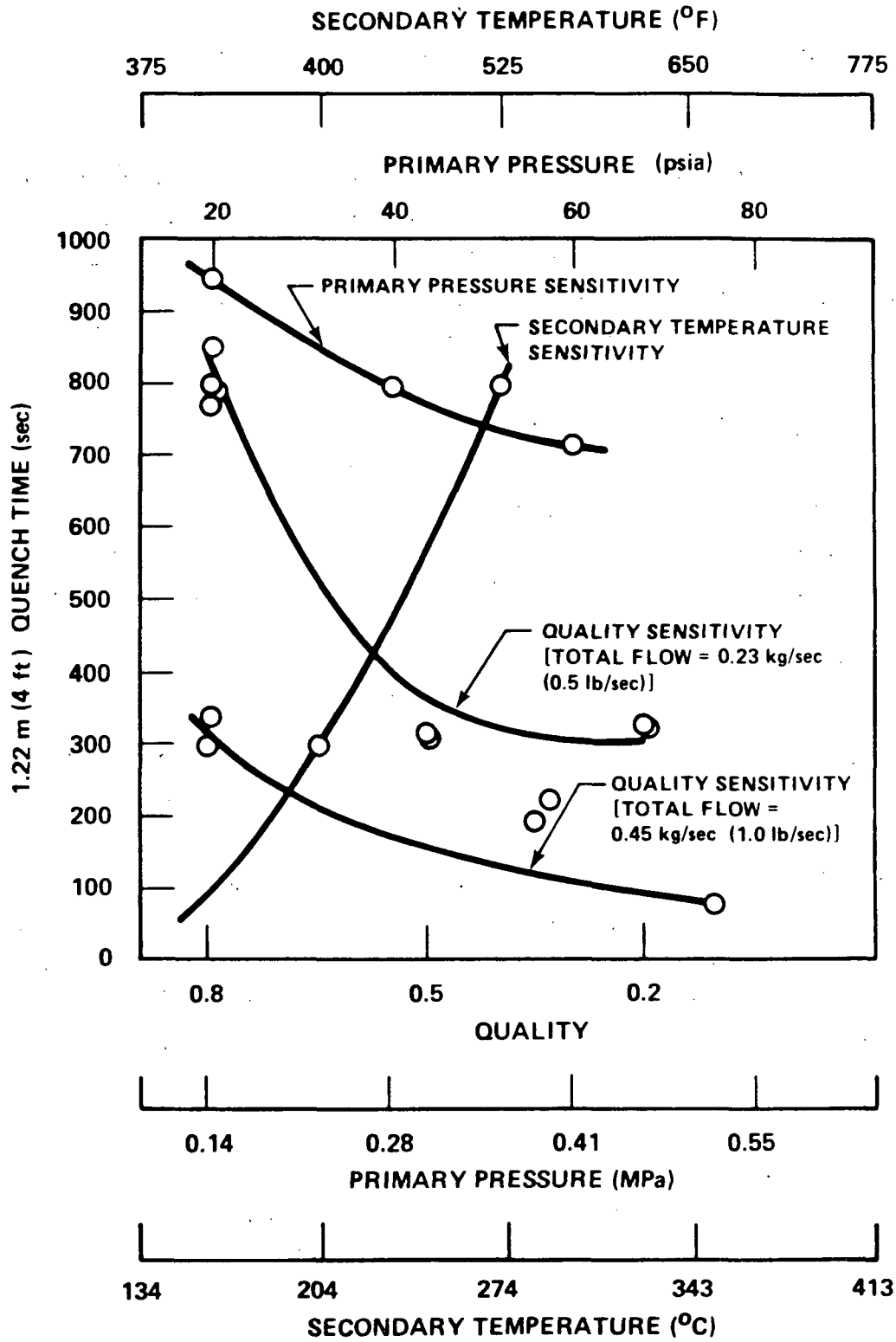


Figure 5-74. 1.22 m (4 ft) Quench Time Parameter Sensitivity

5-5. Mass Velocity Sensitivity

Figures 5-75 through 5-82 are composite plots of various parameters from the reference run and the flow sensitivity run (23402). The total flow rate in run 23402 was twice the reference run flow rate. Figures 5-75 and 5-76 illustrate local tube wall and secondary fluid temperature transients. The temperature profiles are quite similar, except that in run 23402 the rapid temperature reduction signifying the local quenching of the tube wall occurred at a much earlier time. Also, the rate of cooldown of the tube wall prior to quenching was larger in run 23402.

Local heat fluxes from two radial positions at the 0.30 m (1 ft) elevation are shown in figures 5-77 and 5-78. These plots show that the flux peak occurred earlier at the higher mass flow rate and the flux peaks were much closer in magnitude in the high flow rate run. Based on the local-condition critical heat flux assumption referred to in paragraph 5-2, the flux peaks in radial positions 1 and 4 in run 23402 suggest that the local quality at those two positions was about equal. From the air/water inlet plenum tests in appendix B of Report No. 4, the liquid distribution in the flow sensitivity run was generally more uniform than that in the reference run. The difference between the liquid flow rates in radial positions 1 and 4 was still a factor of 2 (0.70 to 1.4) in the high-flow air/water test; however, because of the air compressor capacity limitation, the fully scaled air flow could not be achieved.[1] Assuming that the trend in the air/water test data can be extrapolated, the local flux trends in the flow sensitivity run data shown in figures 5-77 and 5-78 appear reasonable.

The lower flux peak for the high flow rate run shown in figure 5-77 is consistent with the local effects CHF correlation.[2] In this correlation, the mass velocity appears in the denominator with an exponent of 0.6. This implies that in two tests where the only parameter difference was the mass velocity, the critical heat flux would be 34 percent lower in the high-flow run.

---

1. The flow sensitivity air/water test required an air flow rate of 0.238 m^3/sec (504 ft^3/min), but the air compressor could deliver only 0.156 m^3/sec (330 ft^3/min).

2. Collier, J. G., Convective Boiling and Condensation, McGraw-Hill, New York, 1972, p. 255.

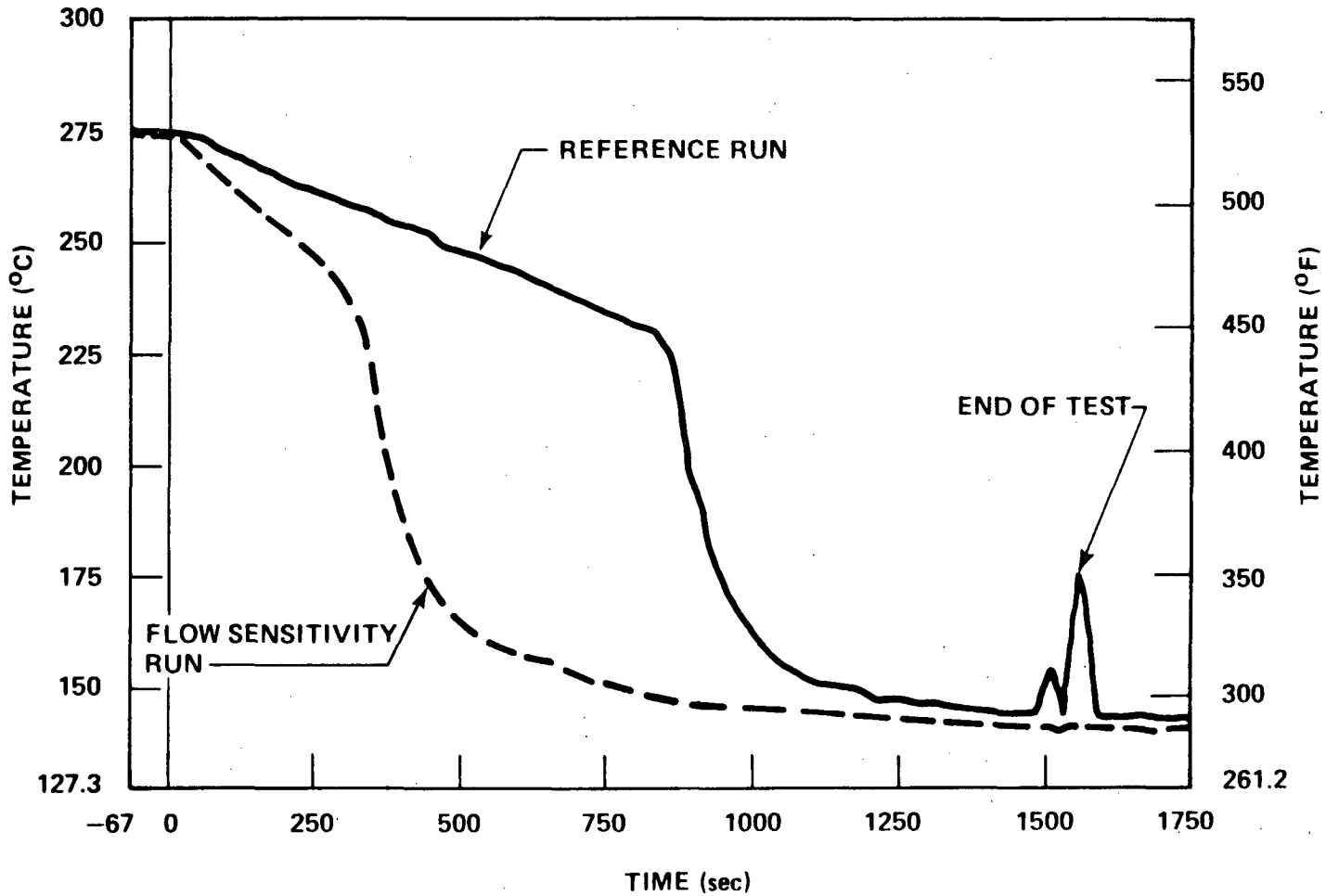


Figure 5-75. Fluid Temperatures, Reference and Flow Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

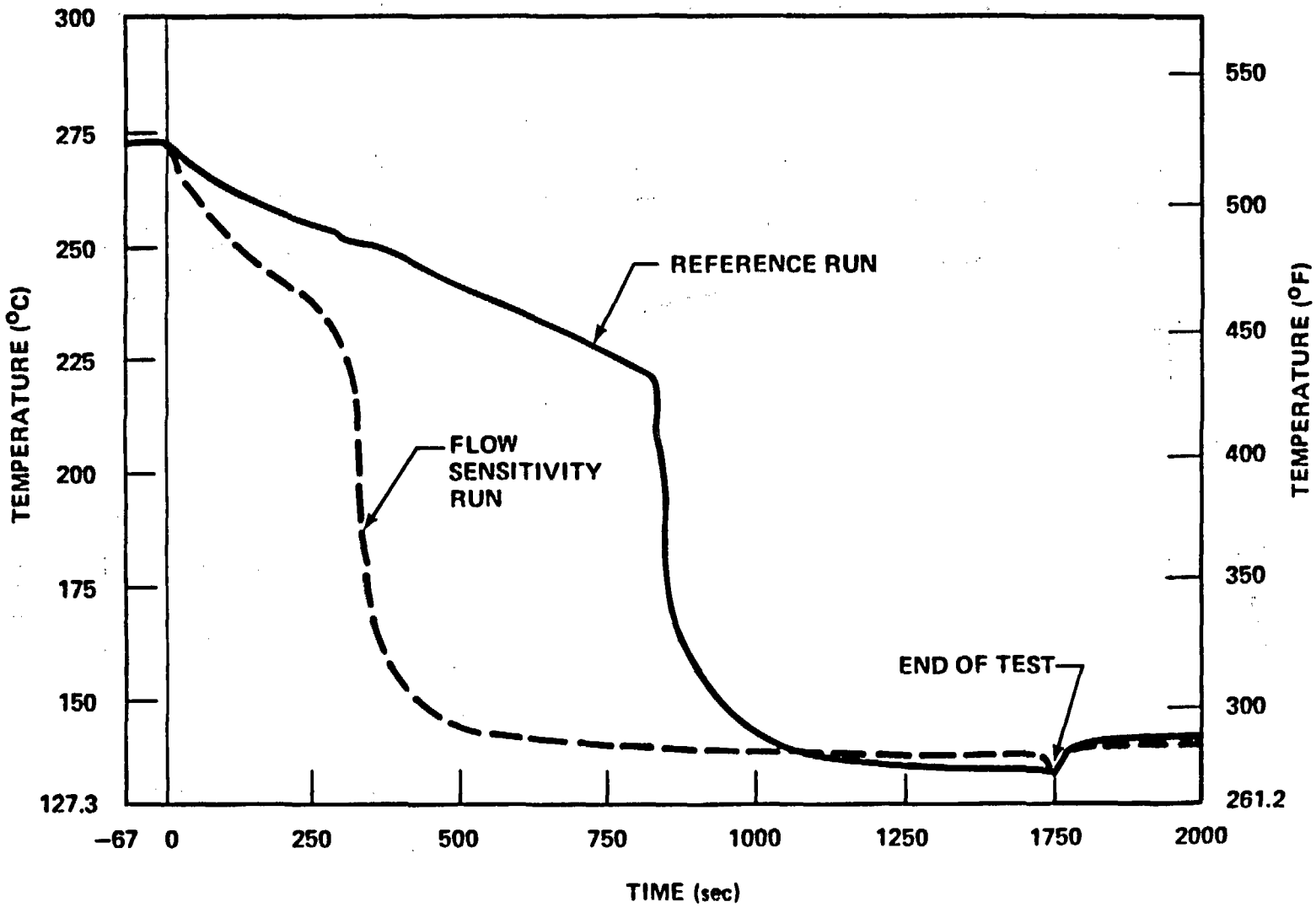


Figure 5-76. Tube Wall Temperatures, Reference and Flow Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

16817-19

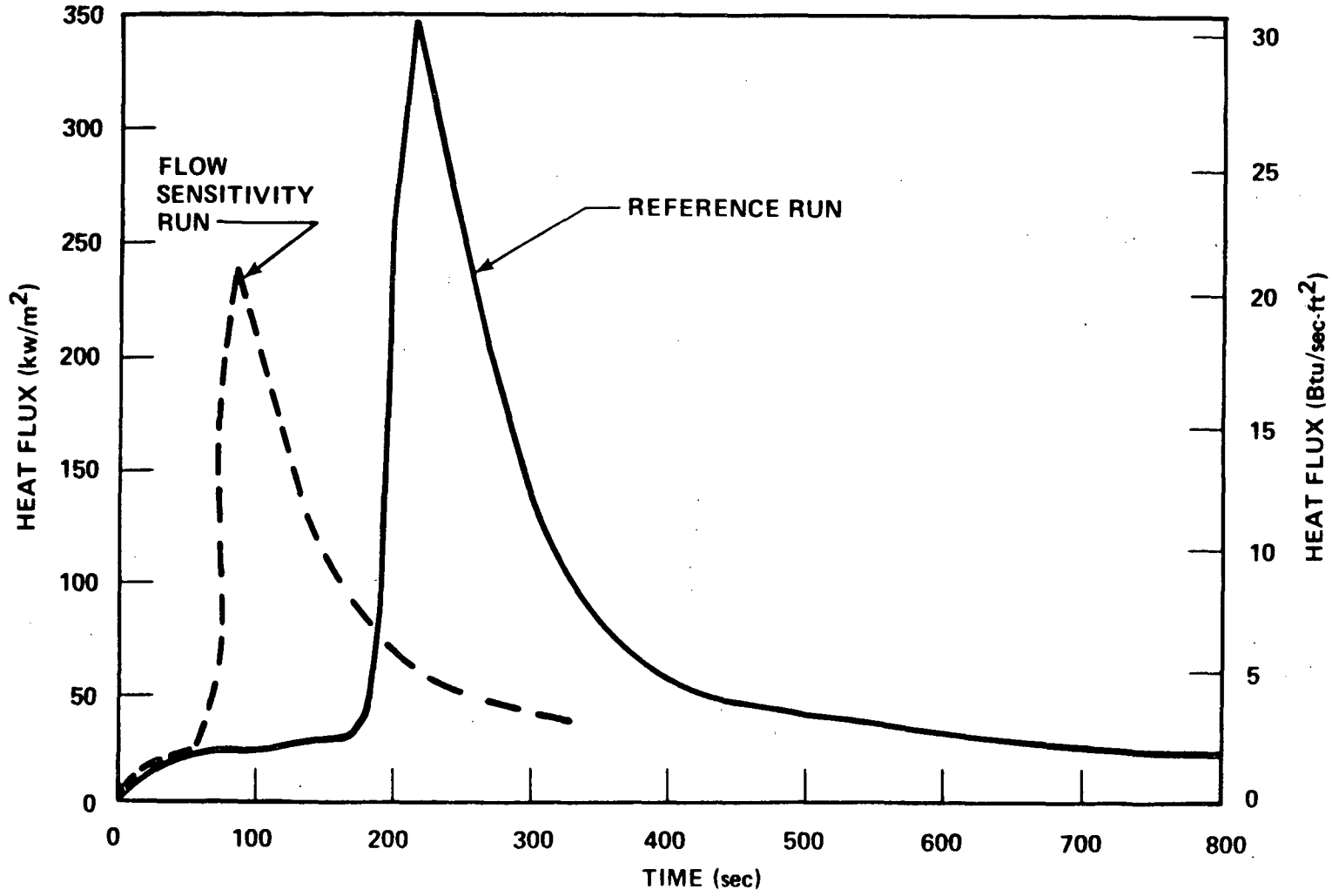


Figure 5-77. Tube Wall Heat Flux, Reference and Flow Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 1

16817-68

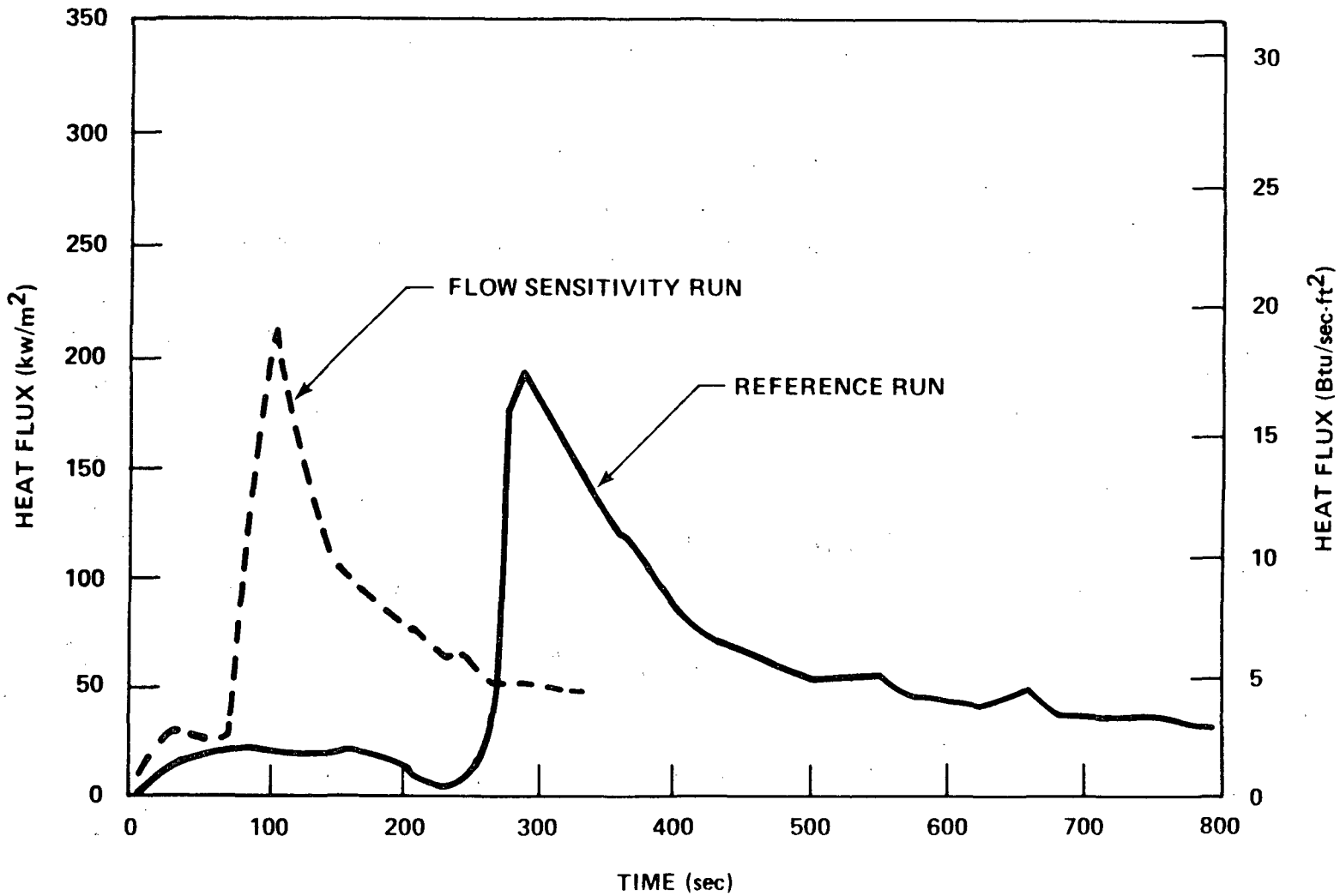


Figure 5-78. Tube Wall Heat Flux, Reference and Flow Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 4

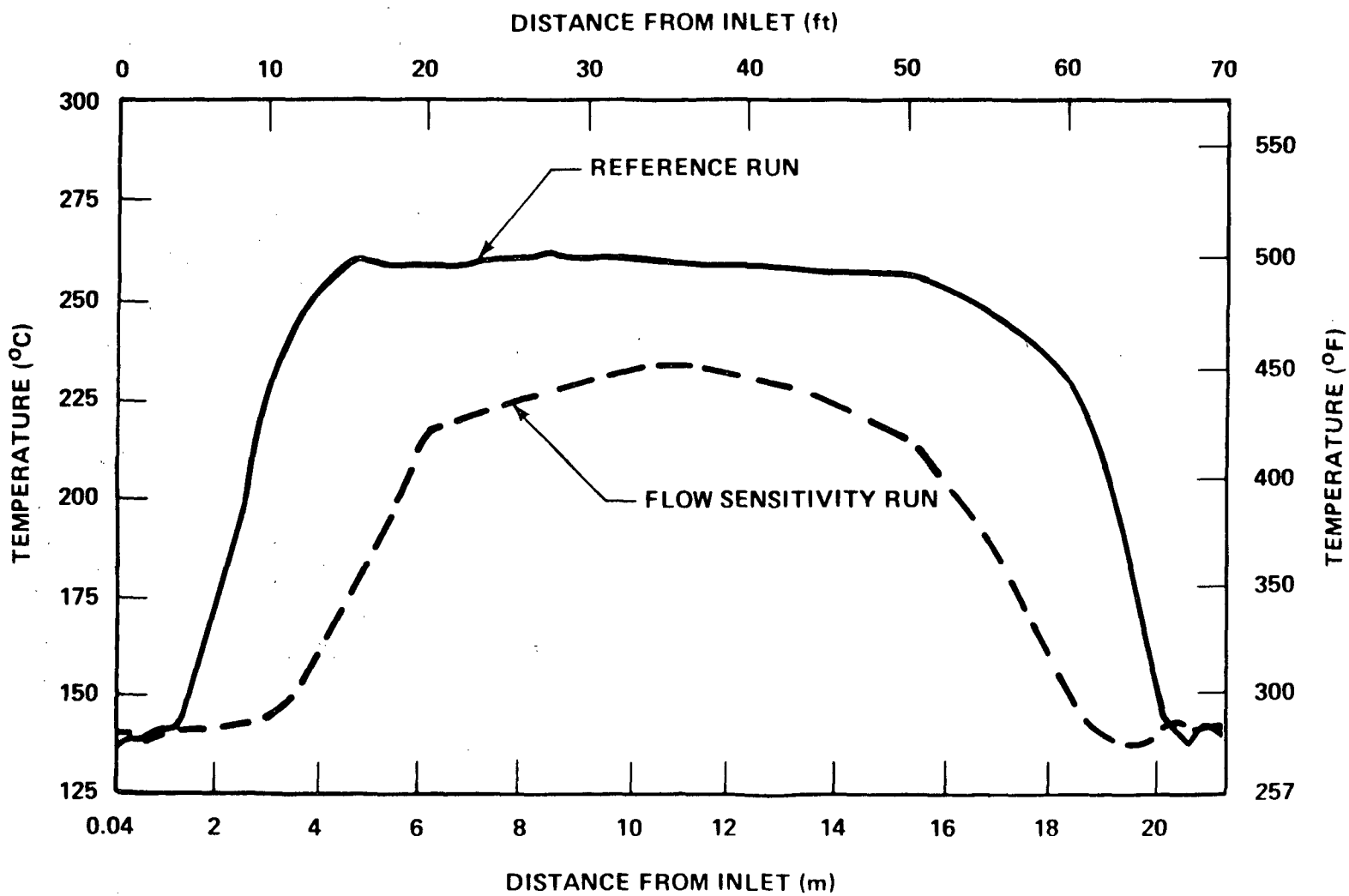


Figure 5-79. Fluid Temperatures, Reference and Flow Sensitivity Runs, End of Test, Radial Position 1

16817-37

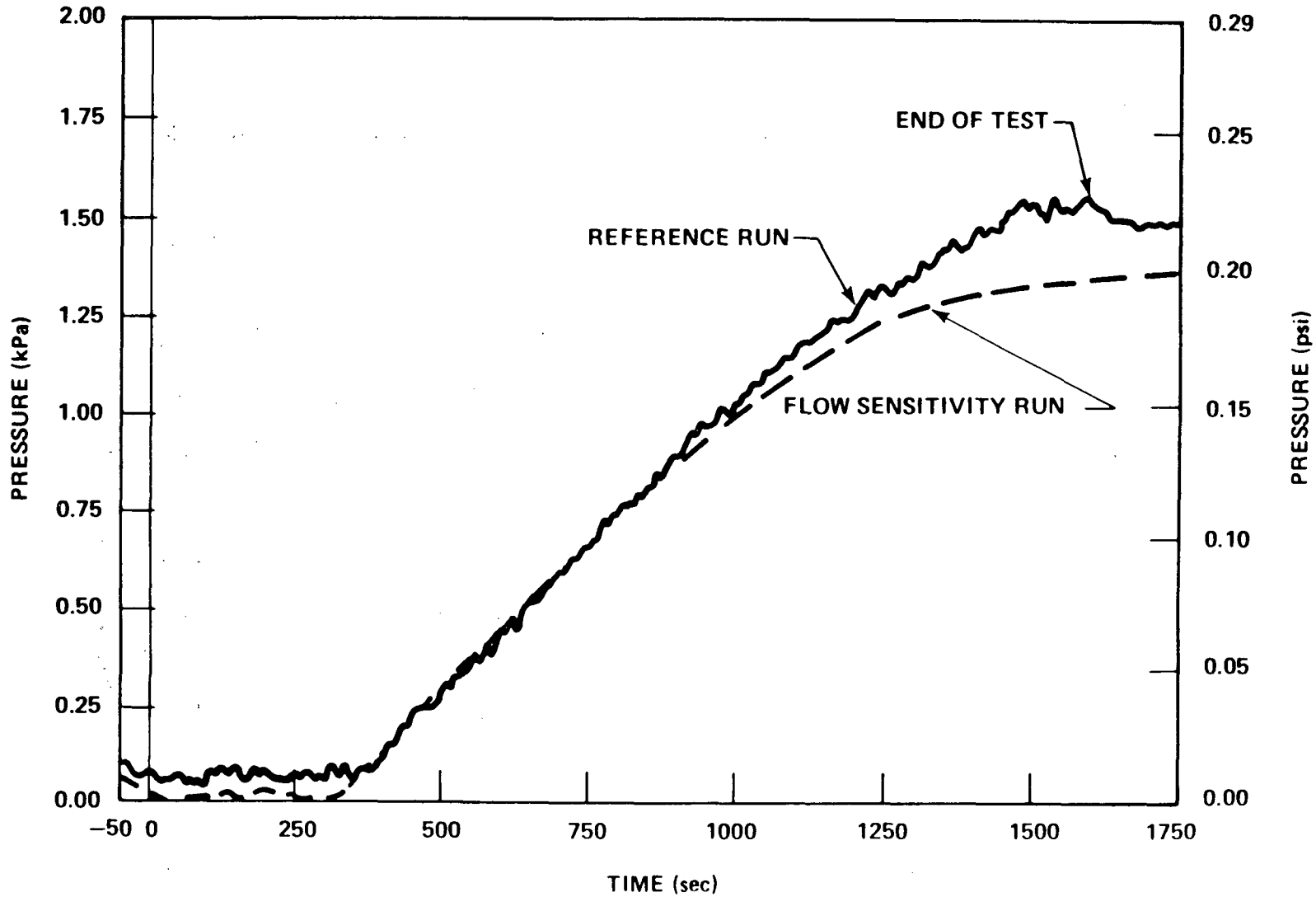


Figure 5-80. Liquid Collected, Reference and Flow Sensitivity Runs

16817-58

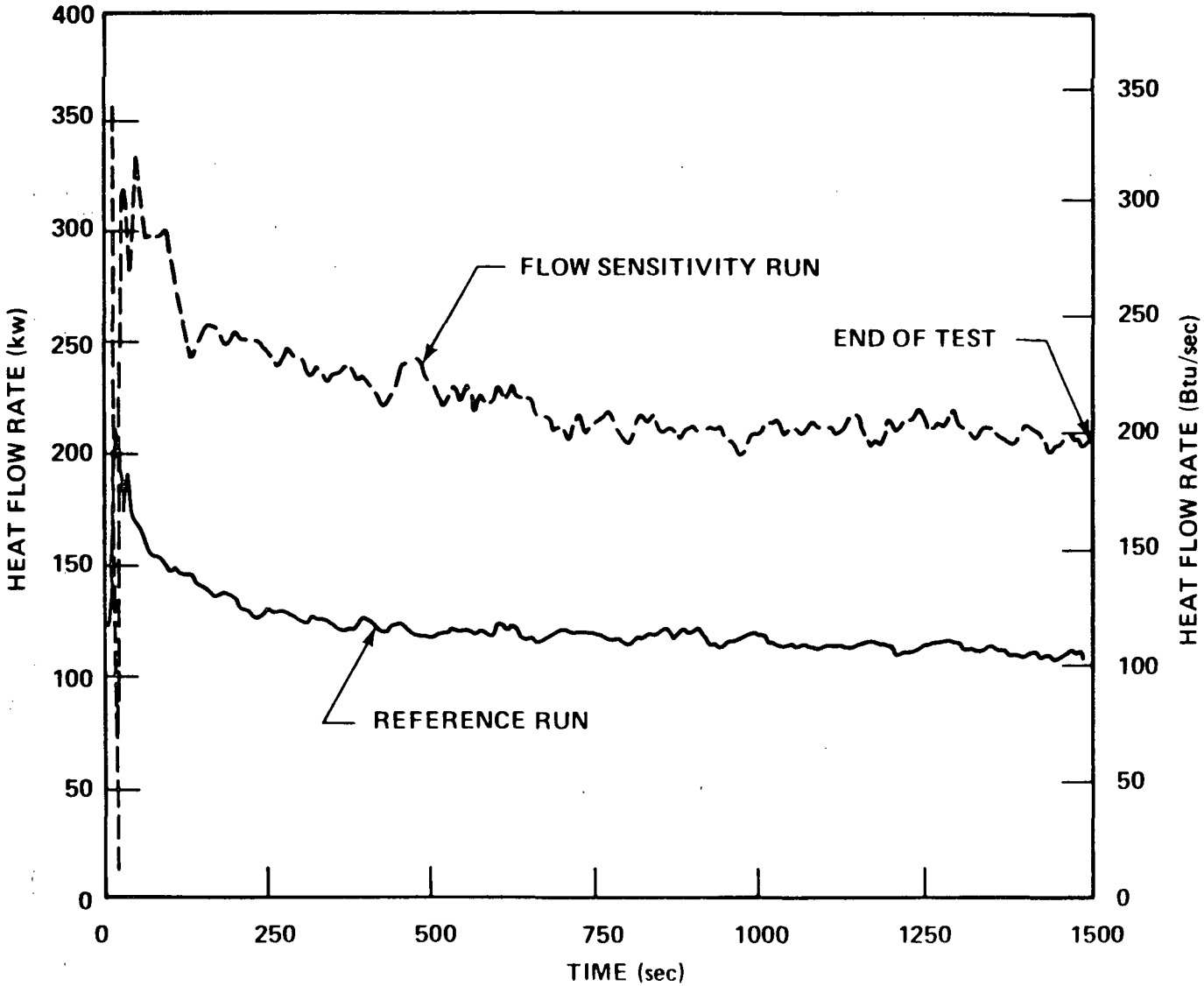


Figure 5-81. Heat Flow Rate, Reference and Flow Sensitivity Runs

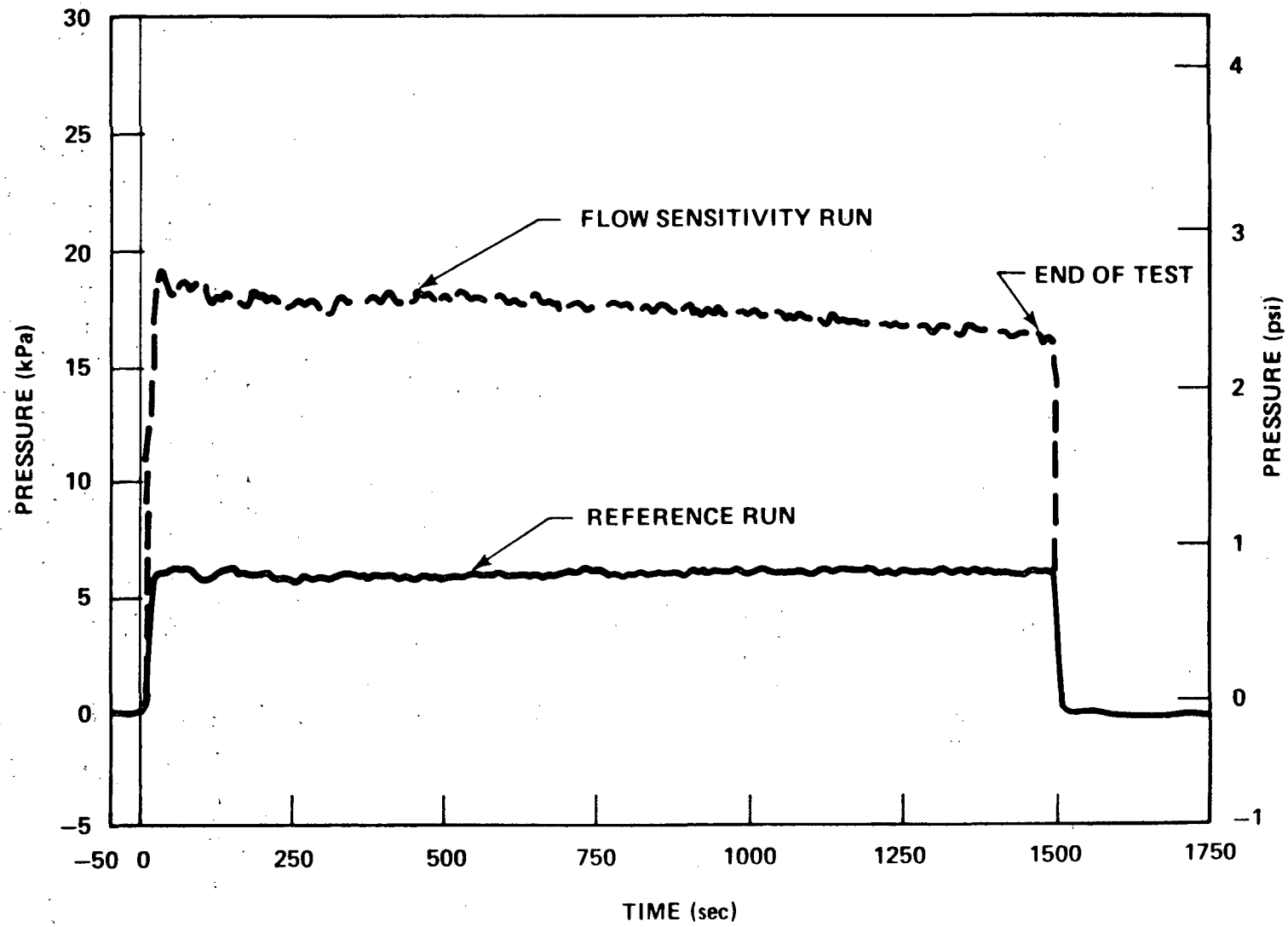


Figure 5-82. Tube Bundle Pressure Drop, Reference and Flow Sensitivity Runs

16817-63

The axial fluid temperature profile in the reference and flow sensitivity tests (figure 5-79) shows that the higher mass flow rate was more effective in cooling the bundle. In the lower bundle fluid, the zone of near-total cooling was twice as thick [3.0 m (10 ft) versus 1.5 m (5 ft)], and above the stratified cold fluid the maximum fluid temperature was lower [232°C (450°F) versus 260°C (500°F)] in the high flow rate (run 23402).

The outlet plenum liquid collection was recorded with a differential pressure transducer. The transducer recorded the hydrostatic pressure developed by the collected liquid. The outlet plenum liquid collection for the reference run and flow sensitivity run as recorded by the differential pressure transducer is shown in figure 5-80. However, as discussed in paragraph 5-3, the average reference run liquid collection was 3.2 kg (7.1 lb). Comparing run 23402 liquid collection with that of the average reference run shows that about 50 percent more liquid was collected in the outlet plenum in run 23402.

The difference in liquid collection between these two runs is only slightly larger than the standard deviation of the reference run liquid collection discussed in paragraph 5-3. The assumption of no change in the liquid collection between the two runs implies a change in the outlet plenum quality from 99 percent for the reference run to 99.5 percent for the high mass flow rate run.

In figures 5-81 and 5-82, the overall bundle heat transfer and bundle primary side pressure drops are plotted. The energy flow was twice as large in run 23402 because the same liquid fraction was evaporating and only a slight difference in the outlet plenum superheat existed between the two runs. Therefore the energy flow was directly proportional to the mass flow, as shown in figure 5-81.

The bundle pressure drop for run 23402 (figure 5-82) indicates a small but consistent drop throughout the test. A drop in ΔP at constant mass velocity occurs because of a fluid density increase, and the primary side temperature decreases from a average temperature of 274°C (525°F) at the beginning of the test to an average value estimated from the steam probe data of 191°C (375°F) at the end of the test. This change alone could cause a 20-percent drop in the bundle ΔP. The ΔP trend in figure 5-82 is believed to have been caused by the change in steam temperature. A plot of the axial distribution of the steam probe temperatures at the end of the test is shown in figure 5-83 for the reference run and run 23402.

In summary, comparison of the flow sensitivity run (23402) to the reference run shows that the local quench front velocity advances more than twice as fast when the flow rate doubles. The 1.22 m (4 ft) quench time is correlated with the mass velocity by the function $[1/G]^{1.32}$. The overall tube bundle heat transfer rate varies in direct proportion to the mass flow rate, and the outlet plenum quality (99 versus 99.5 percent) shows that in both runs virtually all of the liquid phase is evaporated in the steam generator tube bundle.

5-6. Quality Sensitivity

In the reference run (22701), the inlet plenum quality was controlled at 80 percent. The two quality sensitivity runs were run 23605, 50-percent quality, and run 21806, 20-percent quality. The influence of inlet plenum quality on the tube bundle thermal-hydraulics is evaluated in the following paragraphs.

Plots of the 1.22 m (4 ft) secondary fluid and tube wall temperature (figures 5-84 and 5-85) indicate that the 50-percent and 20-percent quality runs had the same 1.22 m (4 ft) quench time. Since a difference in the 1.22 m (4 ft) quench time was expected with the quality change, the quench times at other elevations in runs 21806 and 23605 were investigated. From the temperature plots in Report No. 4 for these runs, table 5-7 was constructed.

Table 5-7 shows that the expected trend of a shorter quench time at the lower quality did occur at the 3.05 m (10 ft) elevation, but at the 1.22 m (4 ft) elevation, the 50-percent and 20-percent quality quench times were within 10 percent of each other, and at 0.30 m (1 ft), the 50-percent quality run had a lower quench time than the 20-percent quality run.

Plots of the inlet plenum and inlet leg pressure drop in run 21806 (in Report No. 4) show that for the first 75 seconds of the test the injected liquid was accumulating in the inlet plenum. Subtracting 75 seconds from the run 21806 quench times, to account for the

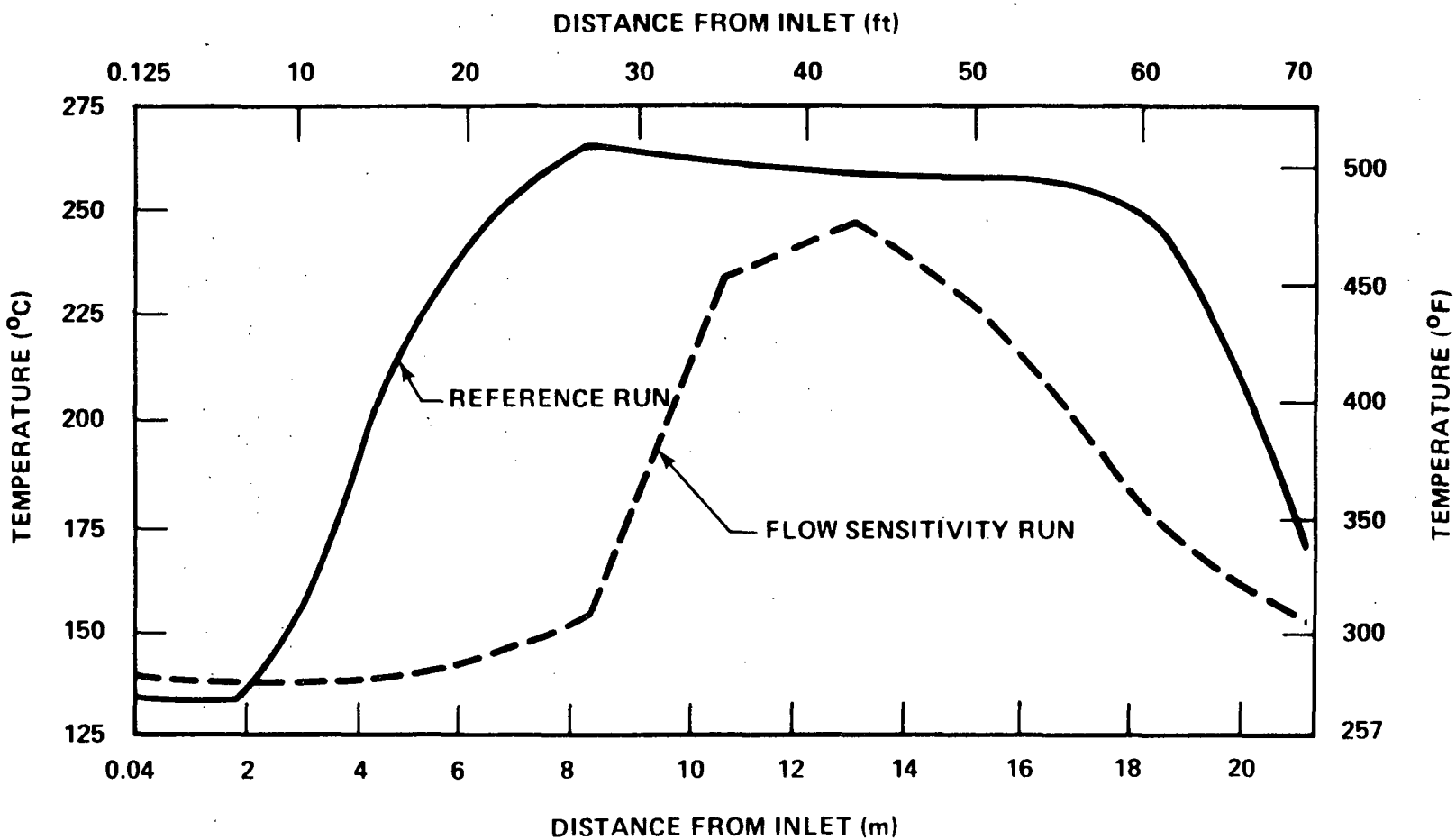


Figure 5-83. Steam Temperatures, Reference and Flow Sensitivity Runs, End of Test, Radial Position 1

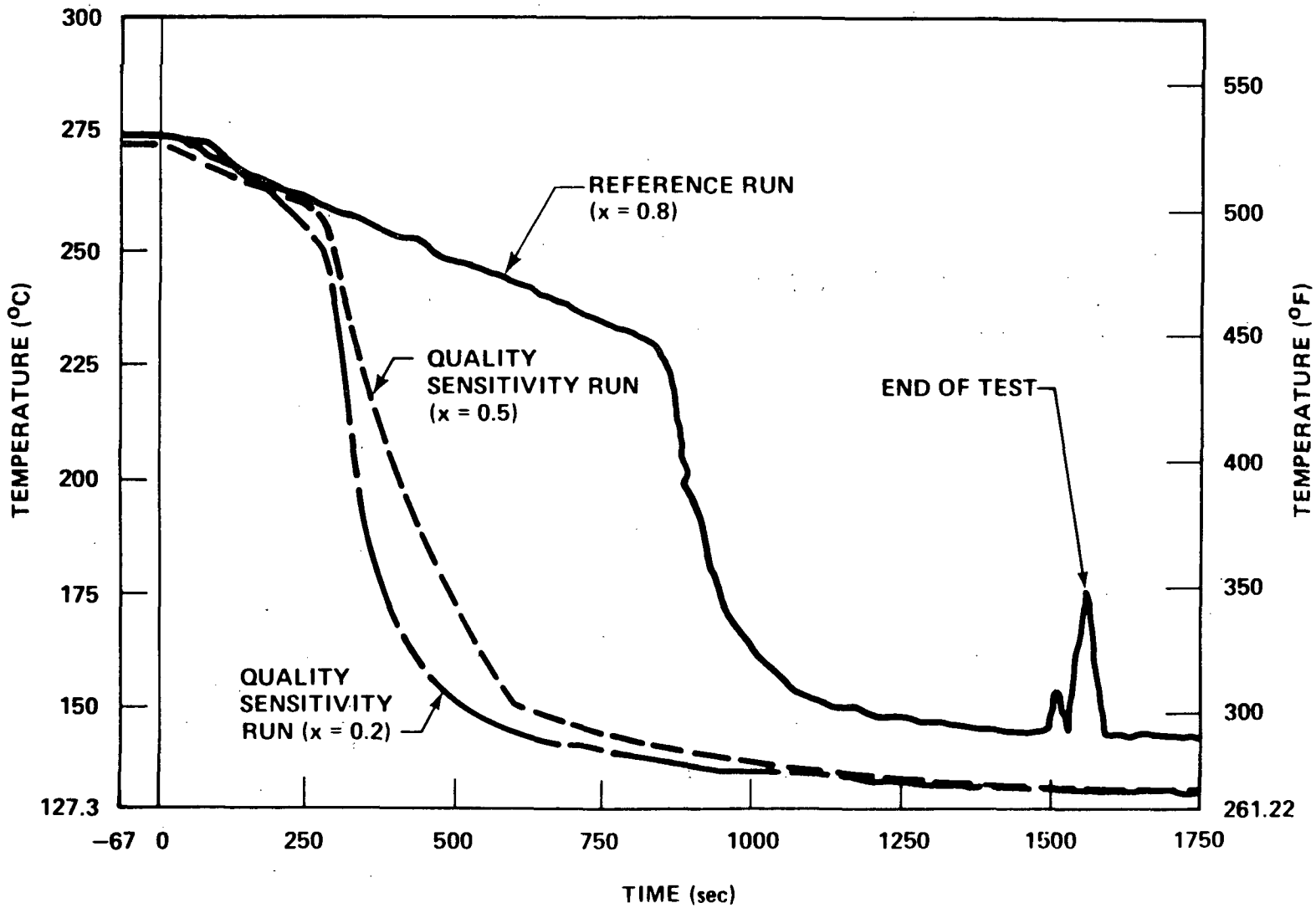


Figure 5-84. Fluid Temperatures, Reference and Quality Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

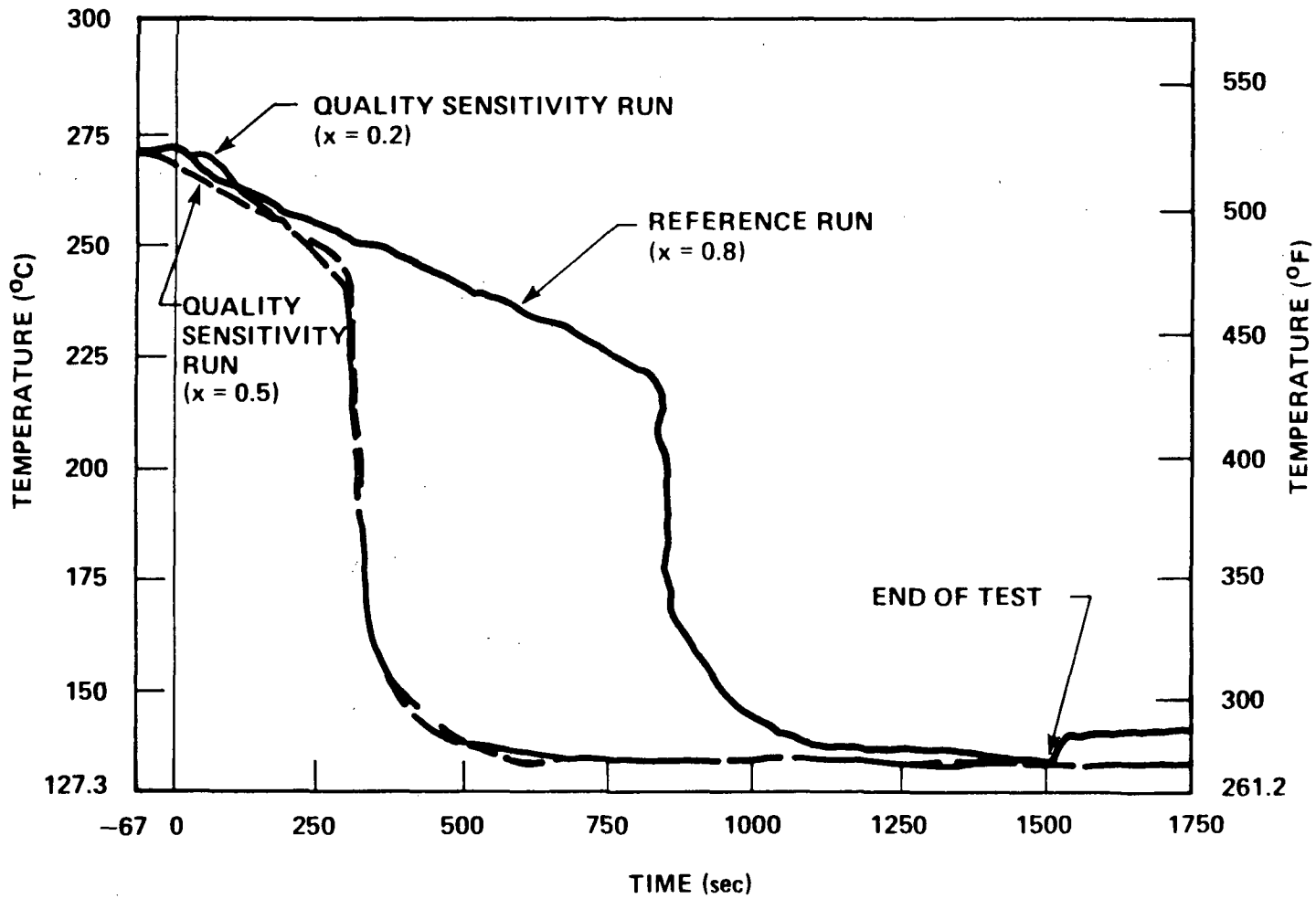


Figure 5-85. Tube Wall Temperatures, Reference and Quality Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

TABLE 5-7

QUENCH TIME VERSUS QUALITY FOR 0.30, 1.22, AND 3.05 m (1, 4, AND 10 ft) ELEVATIONS

Run No.	Quality (%)	Radial Position	Quench Time at Indicated Elevation (sec)		
			0.30 m (1 ft)	1.22 m (4 ft)	3.05 m (10 ft)
22701	80	1	200	800	--
		4	250	--	--
23605	50	1	50	300	800
		4	50	--	800
21806	20	1	125	320	580
		4	80	--	580

time delay due to the inlet plenum mass storage, would cause the 1.22 m (4 ft) and 3.05 m (10 ft) quench time data in table 5-5 to be more consistent with expected results. In fact the position 1 quench times would be 50, 245, and 505 seconds for the 0.30, 1.22, and 3.05 m (1, 4, and 10 ft) elevations, respectively.

The inlet plenum ΔP plot for run 23605 indicates that a small amount of mass accumulation occurred initially, and a spontaneous flow regime transition occurred in the inlet plenum at 600 seconds. This resulted in a significant increase in mass storage in the hot leg and inlet plenum. The initial mass storage in the inlet plenum had only a small effect on the tube bundle inlet quality, but the spontaneous flow regime transition most likely caused a delay in the 3.05 m (10 ft) quench time in the table 5-5 data for run 23605. This delay is estimated to have been about 50 seconds long, from the inlet plenum ΔP plots in Report No. 4. With these adjustments, the 0.30, 1.22, and 3.05 m (1, 4, and 10 ft) quench times for run 23605 would be 50, 300, and 750 seconds, respectively. These quench times show a general consistency with those of runs 21806 and 22701, except for the 0.30 m (1 ft) quench time of 50 seconds. The apparent anomaly in the 0.30 m (1 ft) quench times in run 23605 and in the position 4, 0.30 m (1 ft) quench time in run 21806

may be due to their close proximity to the tube bundle entrance, where quenching can occur because of the random motion of the dispersed drops in the tube before a well-defined liquid film can develop on the tube wall.

Figure 5-86 illustrates the local heat flux plots at the same bundle location for the three quality sensitivity runs. The data show that the two runs with extreme qualities (20 percent and 80 percent) had about the same heat flux profile; the intermediate quality (50-percent) run had a higher flux peak. Normally, the highest local heat flux would be expected to occur in the low quality run. However, the shape of the local heat flux from run 21806 shown in figure 5-86 indicates the effect of neighboring tubes on the local heat flux. The decreasing trend in the local flux plot in figure 5-86 for the 20 percent quality run just before the flux rose to its maximum value indicates that the surrounding secondary fluid was being cooled by neighboring tubes rather than by the tube chosen for the plot (radial position 1). The local tube wall heat flux for radial position 2, 1.22 m (4 ft) elevation, run 21806, has a flux peak above 250 kw/m^2 (22 $Btu/sec\text{-}ft^2$).

A review of the air/water inlet plenum test data in appendix B of Report No. 4 shows that the position 1 tube had about the same relative liquid mass flow rate in each of the quality sensitivity air/water tests. However, in the 50-percent quality test, the radial position 1 tube had the highest liquid flow rate in the entire bundle. In the other tests, other uninstrumented tube locations had higher liquid flow rates than the tube in radial position 1. This difference tends to distort the general influence of inlet plenum quality on tube wall heat flux; this is illustrated in figure 5-86.

Figures 5-87 and 5-88 illustrate the end-of-test secondary fluid and primary steam axial temperature distributions. Figure 5-87, run 21806 (20-percent quality), shows that almost the entire bundle had cooled to the primary side saturation temperature by the end of the test run. In the other runs, a significant fraction of the secondary fluid remained at temperatures above 232°C (450°F). The steam temperature plot in figure 5-88 shows that the steam will follow the fluid temperature profile and when a large axial temperature gradient exists, the steam exit temperature will be close to the temperature of the stratified secondary fluid near the bottom of the tube bundle.

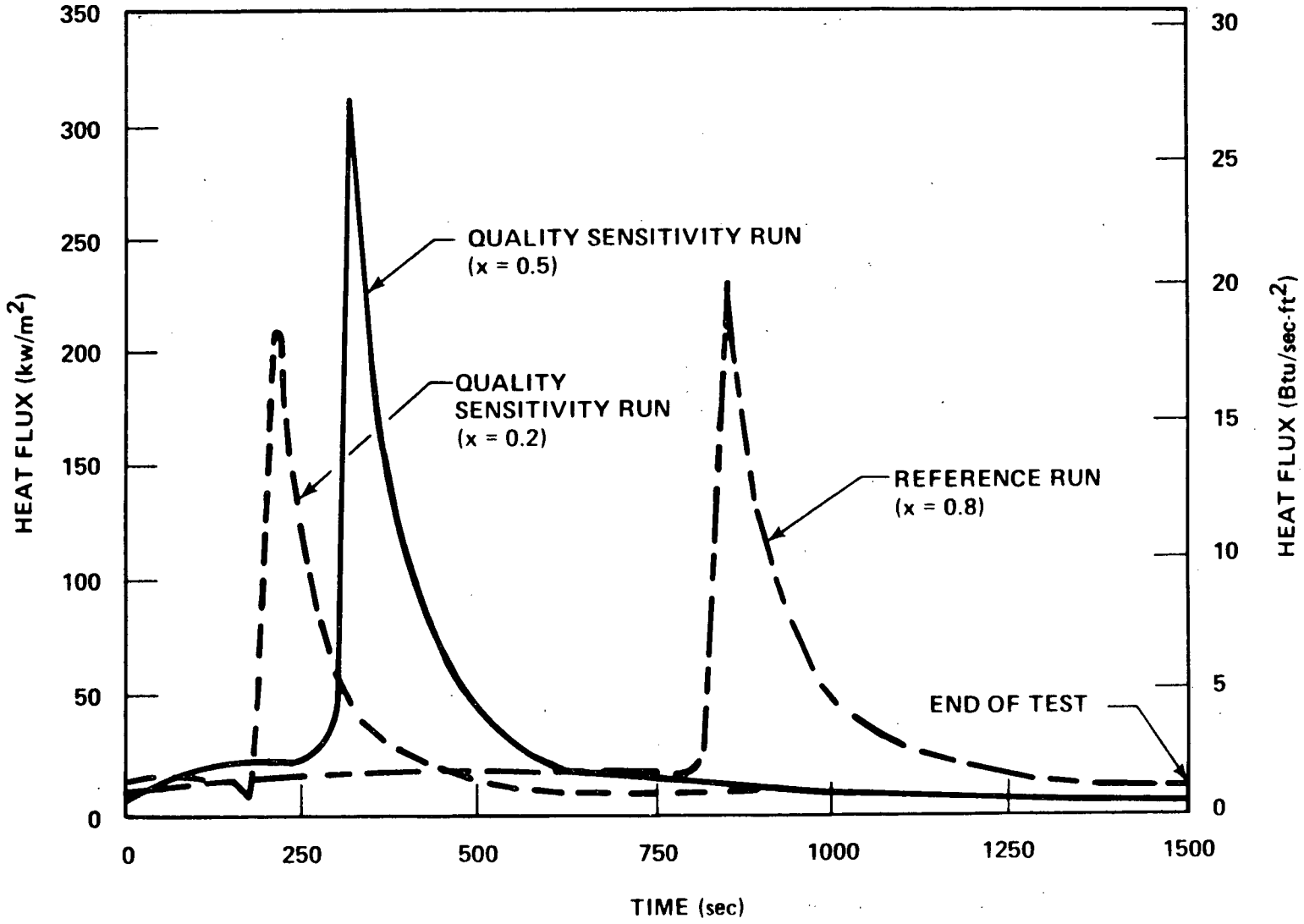


Figure 5-86. Local Heat Flux, Reference and Quality Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

16817-72

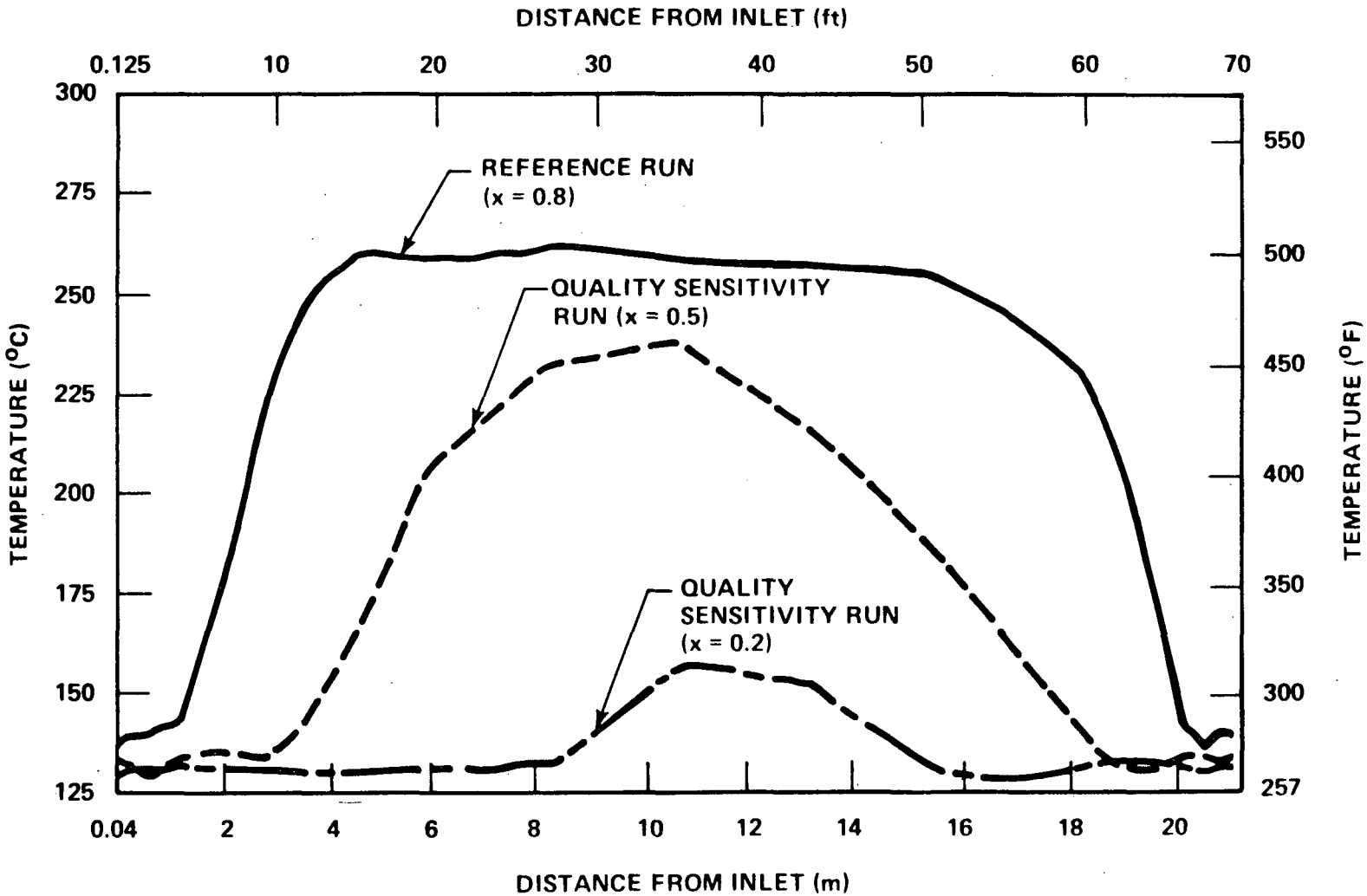


Figure 5-87. Fluid Temperatures, Reference and Quality Sensitivity Runs, End of Test, Radial Position 1

16817-35

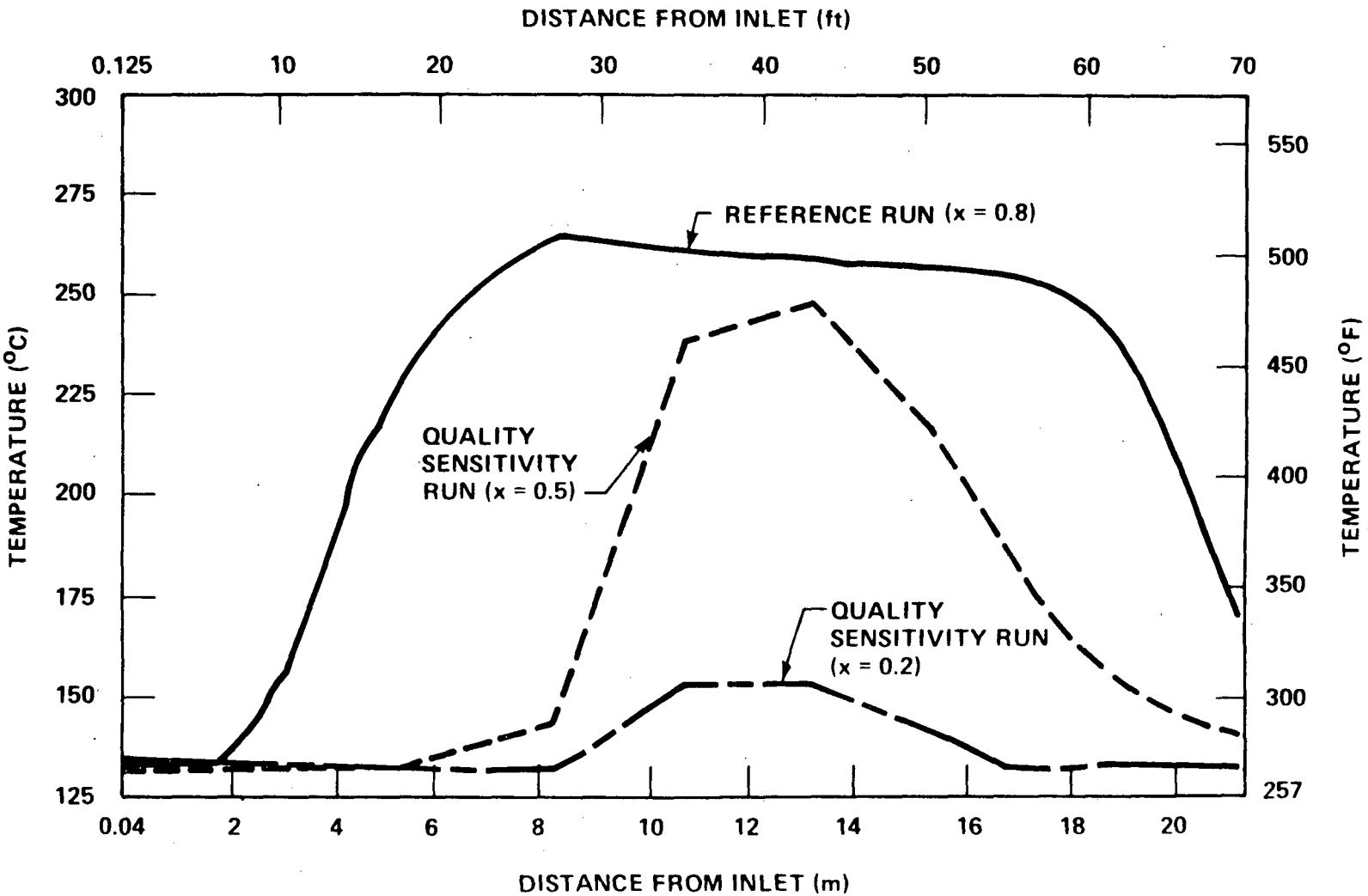


Figure 5-88. Steam Temperatures, Reference and Quality Sensitivity Runs, End of Test, Radial Position 1

16817-34

The overall bundle heat transfer rates for the three quality sensitivity plots are shown in figure 5-89. The 50-percent quality run heat transfer rate reflects the higher potential for primary side energy absorption because of the larger liquid mass flow rate at the lower quality.

Based on the 10 kg (22 lb) of liquid collected in the outlet plenum for run 23605 (table 5-4), the time-averaged outlet plenum quality was 97 percent. Thus almost all the liquid entering the tube bundle was evaporated. The negative spike in the heat transfer rate plot for run 23605 (figure 5-89) occurred at the same time as the inlet plenum flow regime transition, which temporarily accumulated additional liquid in the inlet plenum. This caused a temporary reduction in the liquid flow to the bundle and a corresponding reduction in the heat transfer rate.

The 20-percent quality run overall heat transfer rate (figure 5-89) shows the same characteristics as the 50-percent quality run for most of the transient. At 1250 seconds into the transient, the heat transfer rate rapidly decreased to near zero. The secondary fluid temperature plot (figure 5-88) shows that the bundle fluid was almost completely cooled down to the primary side temperature. The characteristic shape of the heat transfer rate data for run 21806 (figure 5-89) shows that the heat transfer rate was constant until the entire bundle had cooled down, and then dropped rapidly to near zero. From the plot of steam generator collection tank level (Report No. 4), before 1250 seconds the time-averaged liquid collection rate was 0.0059 kg/sec (0.013 lb/sec), for an average outlet plenum quality of 97 percent before the entire bundle quenched.

Figure 5-90 is a plot of the total bundle pressure drop for the three quality sensitivity runs. These plots clearly show a component of the bundle ΔP that increased with time in runs 23605 and 21806. In run 21806, for times greater than 1300 seconds, the steam flow out of the bundle was approximately equal to the steam flow in the bundle, which was 0.05 kg/sec (0.10 lb/sec). The run 22701 bundle ΔP data show that a bundle steam flow of 0.23 kg/sec (0.5 lb/sec) resulted in a ΔP of about 0.0069 MPa (1 psi). Thus the frictional ΔP in run 21806 for times beyond 1300 seconds was very small, and the total ΔP measured in figure 5-90 was due to the elevation pressure drop. Since the bundle was quenched, it can also be assumed that the quality on the primary side of the tubes was 20 percent and constant for the entire 10.7 m (35 ft) length of the upflow

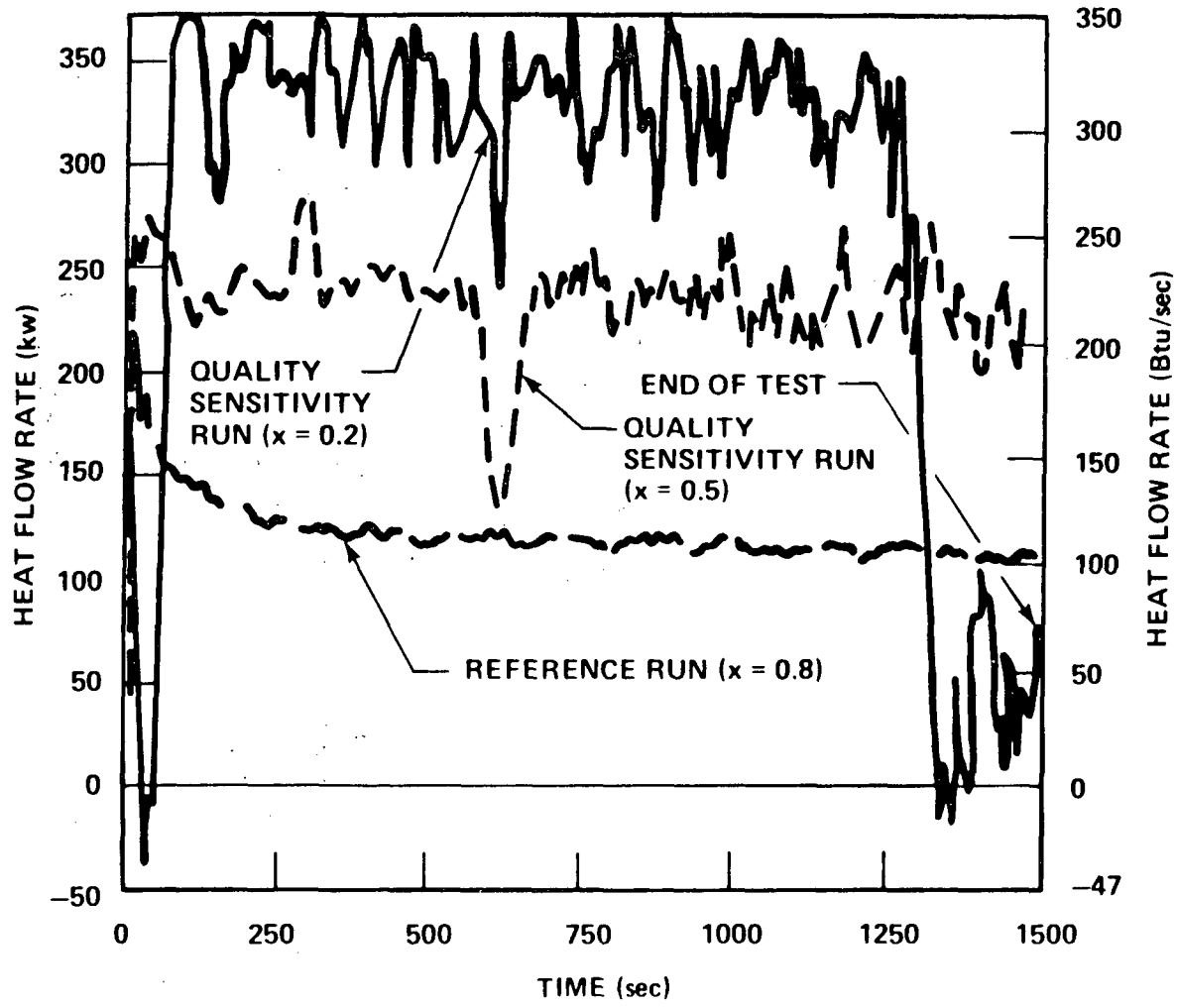


Figure 5-89. Overall Heat Transfer, Reference and Quality Sensitivity Runs

16817-53

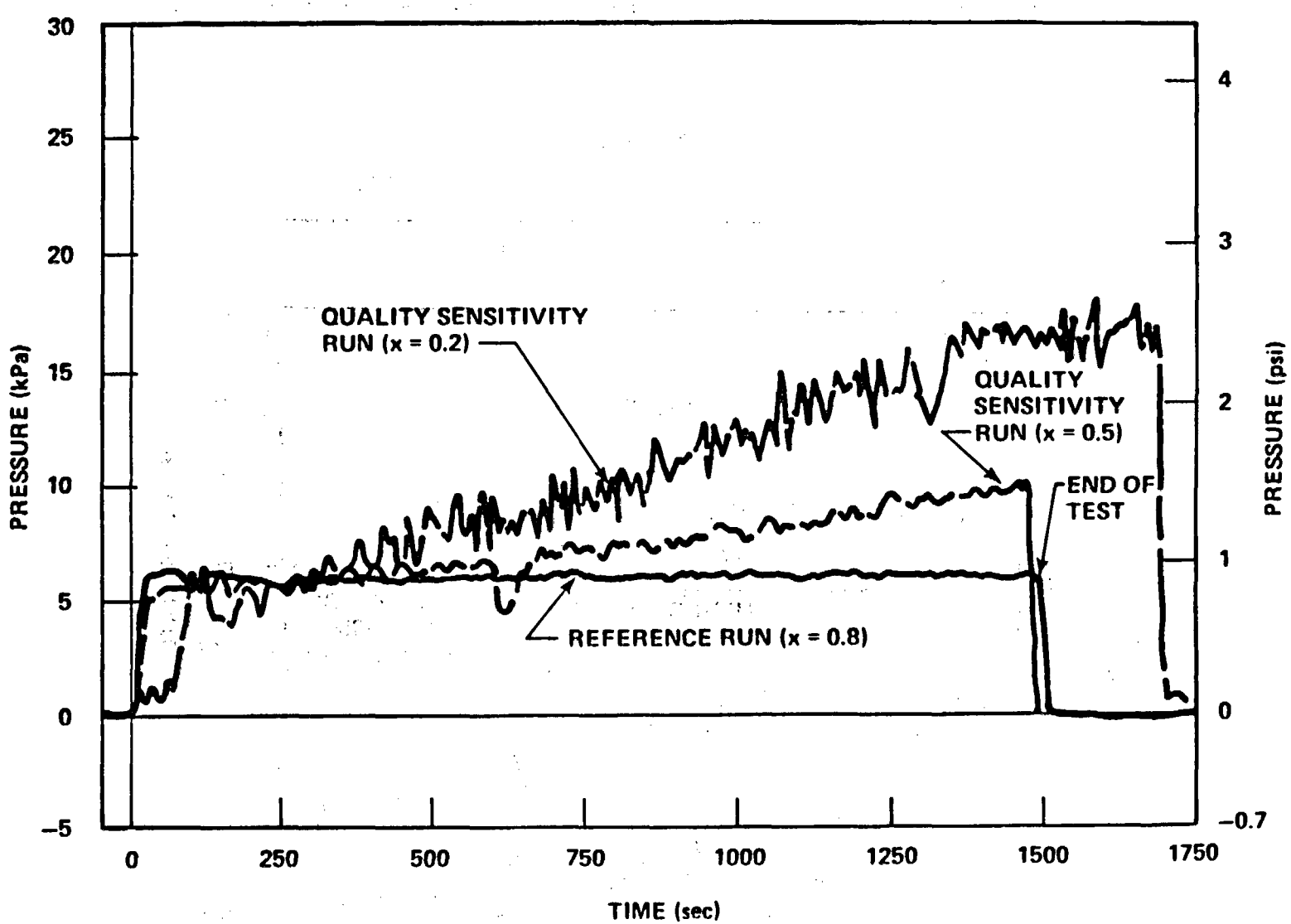


Figure 5-90. Overall Bundle Pressure Drop, Reference and Quality Sensitivity Runs

portion of the bundle. From the pressure drop, the local void fraction is calculated to be 85 percent. From Collier,[1] the predicted void fraction at 20-percent quality and 0.28 MPa (40 psia) is approximately 90 percent.

To evaluate the bundle ΔP data for run 23605 in figure 5-90, the difference between the bundle ΔP from runs 23605 and 22701 was taken to be the elevation ΔP in run 23605. According to table 5-7, the 6.1 m (20 ft) quench time in run 23605 is estimated to be 1600 seconds [twice the 3.05 m (10 ft) quench time]. From figure 5-90, the difference in ΔP between runs 23605 and 22701 at 1600 seconds is estimated to be 0.0052 MPa (0.75 psi) and the calculated void fraction is 91 percent.

In summary, evaluation of the quality sensitivity tests shows that the 1.22 m (4 ft) quench time variation with quality can be fit by a function of the form $[1/(1-x)]$ raised to the exponent 0.84. The overall tube bundle heat transfer rate varies directly with the liquid flow rate because the liquid phase is almost completely evaporated in the tube bundle. The 20-percent quality run illustrates the transition to adiabatic conditions after the entire bundle secondary cools off. The transition occurs fairly rapidly when the local quench elevation reaches the top of the U-tubes. The transition can be clearly seen in the step increase in the outlet plenum liquid collection rate after the tube bundle is quenched. The average void fraction in the tubes, as calculated from the overall bundle pressure drop, agrees with the Martinelli-Nelson void fraction model.

5-7. Primary System Pressure Sensitivity

To investigate the effects of primary system pressure on the bundle heat transfer, the reference test conditions were rerun at a pressure of 0.14 MPa (20 psia) and then repeated at 0.41 MPa (60 psia). The reference test pressure was 0.28 MPa (40 psia). The pressure sensitivity runs were 20904 [0.41 MPa (60 psia)] and 22503 [0.14 MPa (20 psia)].

Figures 5-91 and 5-92 plot local fluid and tube wall temperatures for the three pressure sensitivity runs. The data show that the high-pressure run quenched faster and the low-pressure run quenched more slowly than the reference run. Prior to the local

---

1. Collier, J. G., Convective Boiling and Condensation, McGraw-Hill, New York, 1972, p 43.

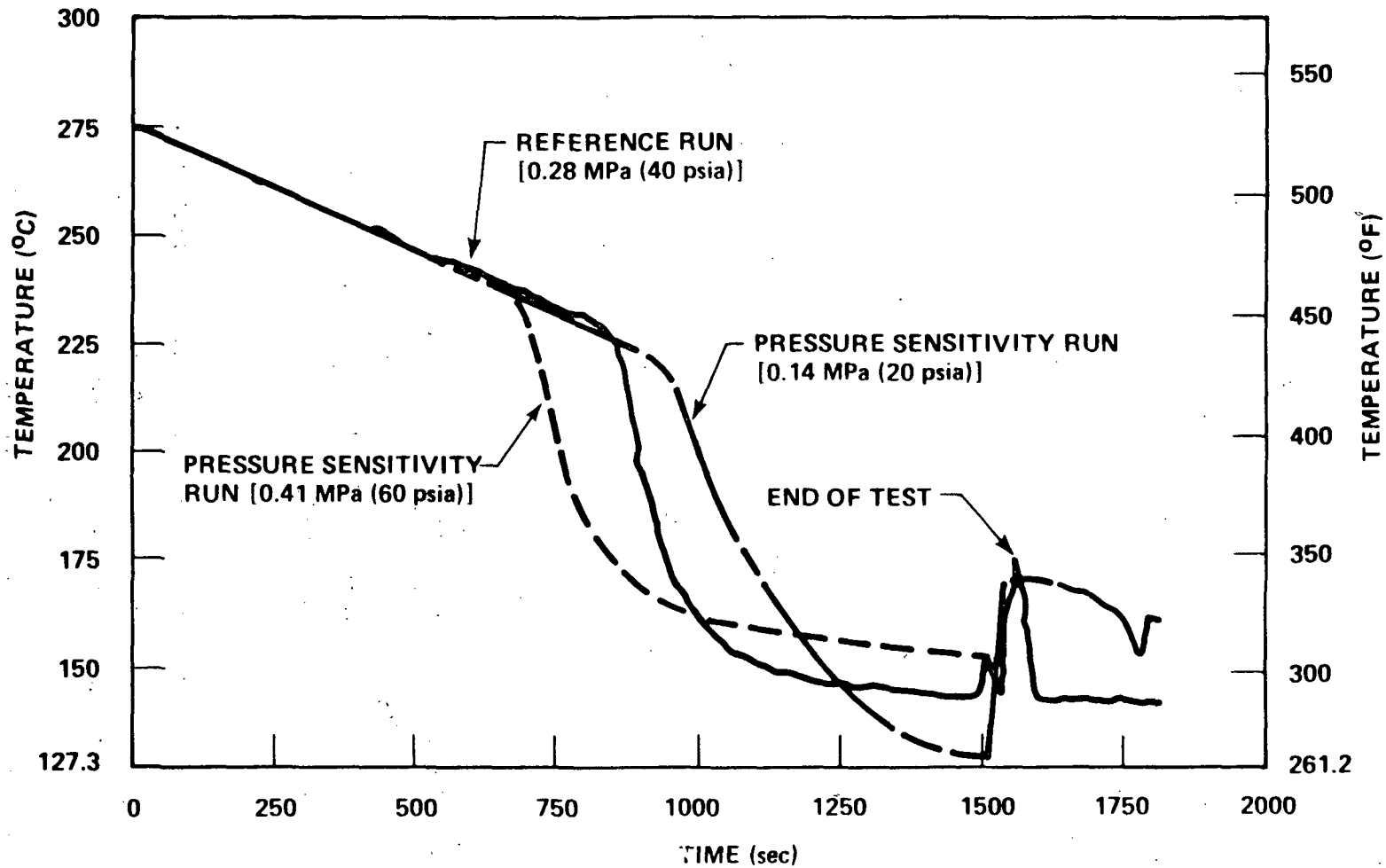


Figure 5-91. Fluid Temperatures, Reference ad Pressure Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

16817-15

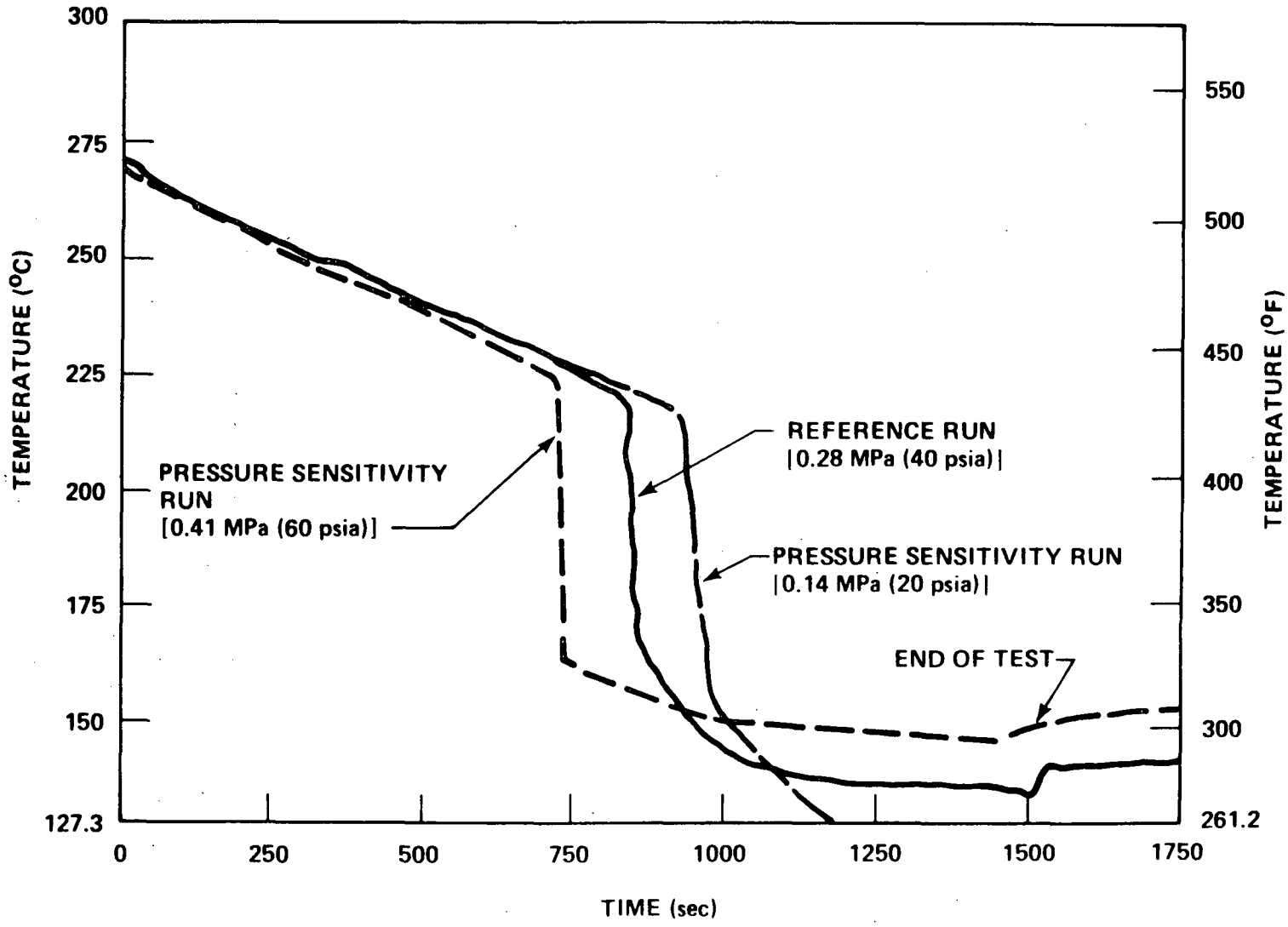


Figure 5-92. Tube Wall Temperatures, Reference and Pressure Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

16817-14

tube quench, the cooldown rates in all three test runs were equal. The 1.22 m (4 ft) quench time variation with pressure can be fit by a function of the form $(1/P)^{0.25}$.

The data in figure 5-74 show how all the parameter variations affect the local tube wall quench time at the 1.22 m (4 ft) elevation. From this plot the sensitivity of all the parameters that were varied in the test can be compared. For example, changing the primary system pressure from 0.28 to 0.41 MPa (40 to 60 psia) reduced the 1.22 m (4 ft) quench time by 80 seconds. However, from the secondary temperature sensitivity plot, a reduction in secondary temperature of 11°C (20°F) will also reduce the quench time by 80 seconds. The change in saturation temperature between the 0.28 and 0.41 MPa (40 and 60 psia) runs was 145°C-131°C (293°F-267°F), or 14°C (26°F). Thus, reducing the secondary to primary temperature difference by reducing the secondary temperature or by increasing the primary side saturation temperature has about the same effect on the 1.22 m (4 ft) quench time.

To understand the phenomena causing the quench time changes illustrated in figure 5-74, the solution for the quenching of a solid rod presented by Yeh[1] was applied to the steam generator test data. The steam generator tube quenching can be made analogous to the quenching of a solid rod by letting the stored energy in the secondary water represent the stored energy in the solid rod and the axial heat conduction in the U-tube represent the axial heat conduction in the solid rod. Yeh's analysis shows that for a quenching rod with constant properties and geometry, the quench velocity is only dependent on the Biot number and the dimensionless quenching temperature, θ_c:

$$\theta_c = \frac{T_c - T_f}{T_\infty - T_f} \tag{5-3}$$

where

T_c = local rod surface temperature at the quench elevation
T_f = saturation temperature of quenching fluid
T_∞ = local rod surface temperature above the wet/dry interface at an elevation where axial conduction effects are small

1. Yeh, H. C., "An Analysis of Rewetting of a Nuclear Fuel Rod in Water Reactor Emergency Core Cooling," Nucl. Eng. Des. 34, 317-322 (1975).

The results from the above solution for the quench velocity in a solid rod are presented in figure 5-93. This solution, if generally applicable to the quenching of the steam generator tubes, shows that the quench velocity will increase if θ_c or the Biot number increases. The Biot number is equal to the wet region heat transfer coefficient times a length divided by the tube conductivity. The only parameter in the Biot number that is subject to change between tests is the heat transfer coefficient. The wet region heat transfer coefficient is calculated from Dengler and Addoms,[1] and only varies with fluid properties, mass velocity, and the Martinelli parameter X_{tt}.

By assuming that the local-condition critical heat flux correlation of Biasi applies, the local quality can be calculated from the local peak heat flux. The local 1.22 m (4 ft) elevation heat flux from radial position 1 is plotted in figure 5-94. The plot shows that as the pressure decreased, the peak heat flux increased; this implies that the local quality at the flux peak was smaller in the 0.14 MPa (20 psia) run than in the 0.41 MPa (60 psia) run. The local conditions parameters are summarized in table 5-8.

The local quality in table 5-8 can be used to calculate the Martinelli parameter X_{tt}, so that the local heat transfer coefficient in the wet zone below the quench elevation can be calculated. The following equations are used:[1,2]

$$X_{tt} = \left(\frac{1 - X}{X}\right)^{0.9} \left(\frac{\rho_g}{\rho_f}\right)^{0.5} \left(\frac{\mu_f}{\mu_f}\right)^{0.1} \tag{5-4}$$

$$\frac{h}{h_L} = 3.5 \left(\frac{1}{X_{tt}}\right)^{0.5} \tag{5-5}$$

---

1. Dengler, C. C., and Addoms, J. N., "Heat Transfer Mechanism for Vaporization of Water in a Vertical Tube," in Heat Transfer-Louisville (Chemical Engineering Progress Symposium Series, Volume 52, Number 18, pp 95-103), AIChE, New York, 1956.

2. Collier, J. G., Convective Boiling and Condensation, McGraw-Hill, New York, 1972, p. 43.

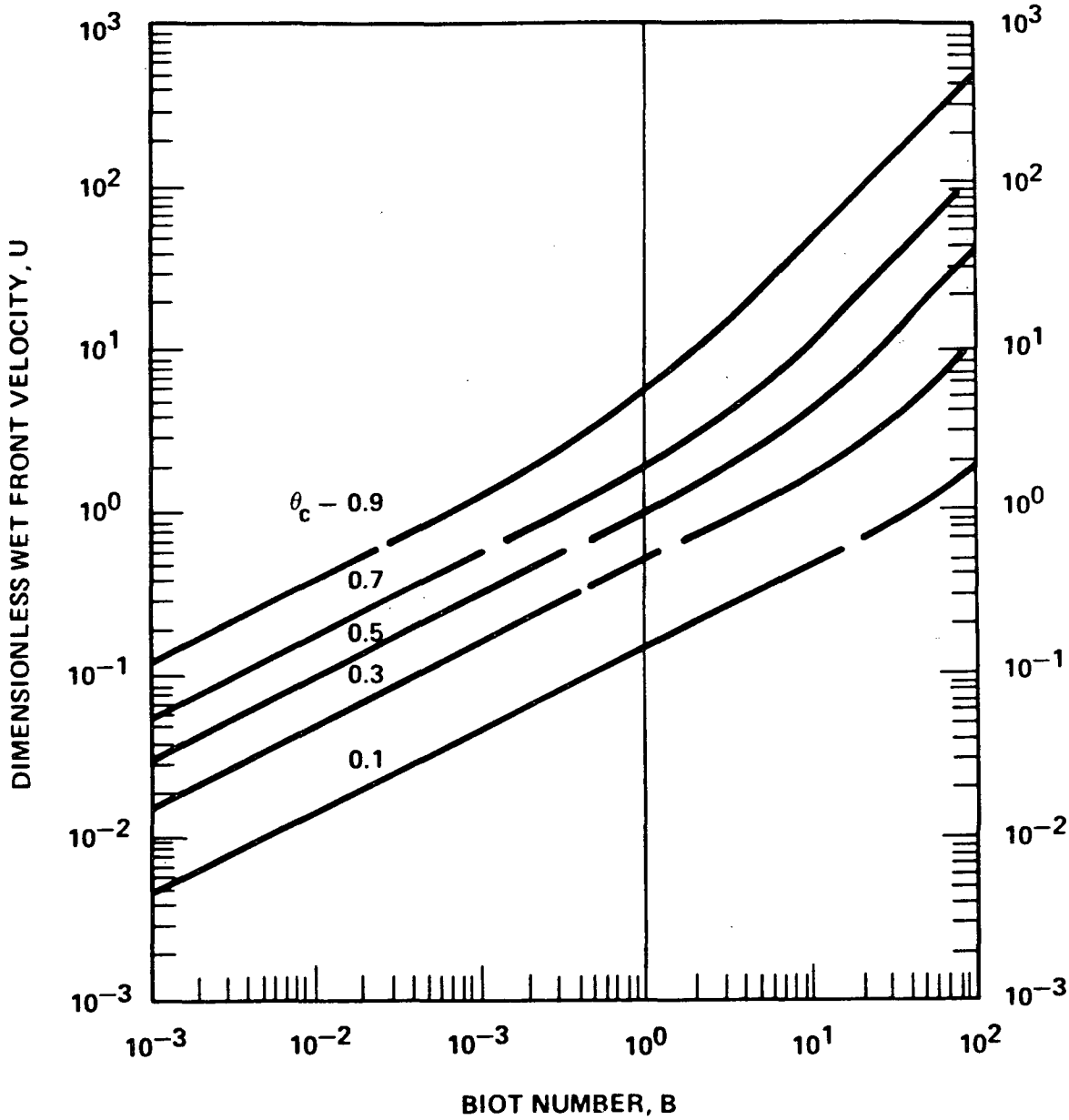


Figure 5-93. Quench Front Velocity Versus Biot Number and Interface Temperature

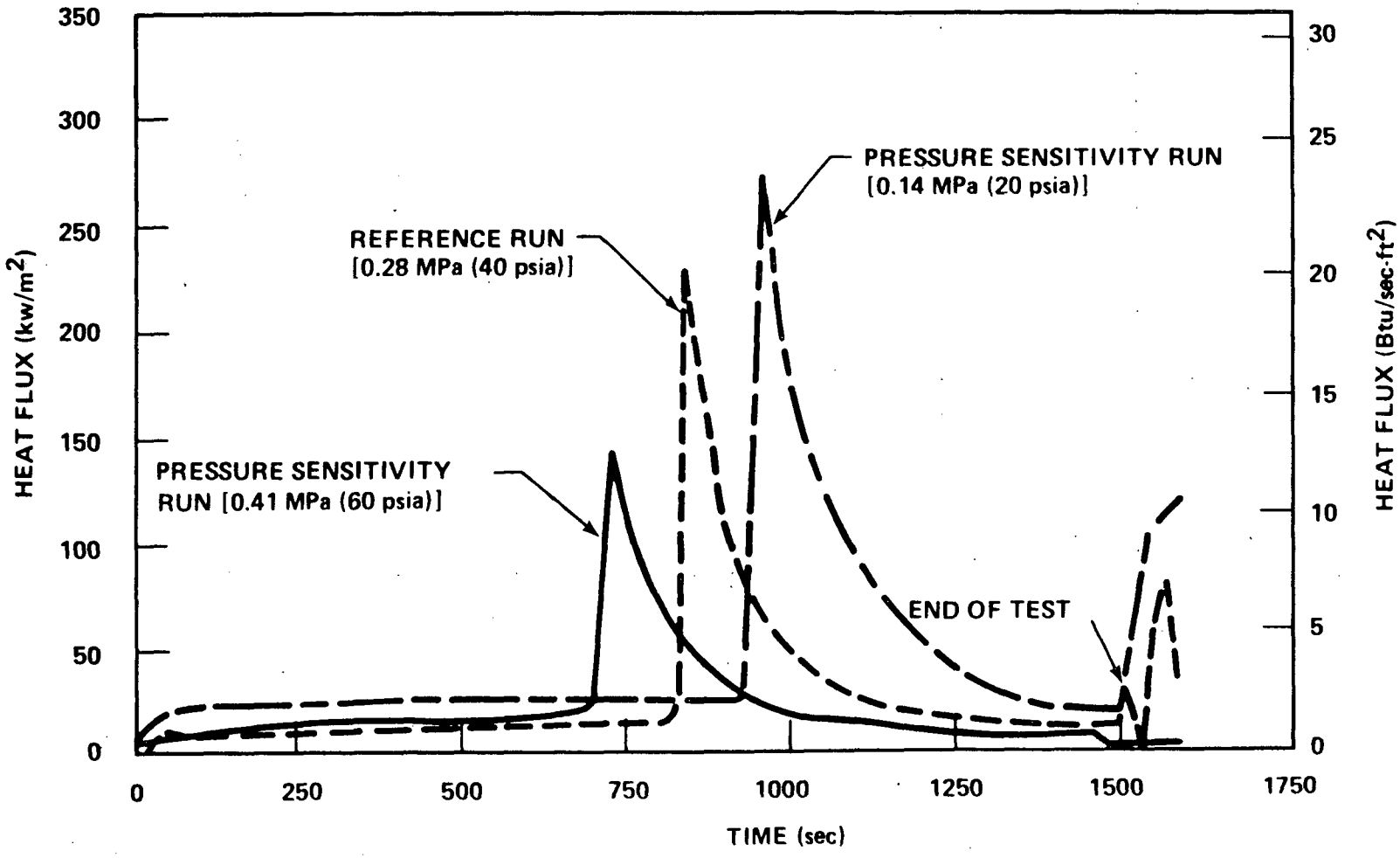


Figure 5-94. Tube Wall Heat Flux, Reference and Pressure Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

TABLE 5-8

CRITICAL HEAT FLUX LOCAL PARAMETERS

Run No.	Pressure [MPa (psia)]	Peak Heat Flux [kw/m^2 (Btu/sec-ft^2)]	CHF Correlation[a] (kw/m^2)	Local Quality (%)
22503	0.14 (20)	284 (25)	4060 (1-X)	93
22701	0.28 (40)	227 (20)	5140 (1-X)	95.5
20904	0.41 (60)	147 (13)	6220 (1-X)	97.6

a. Biasi correlation evaluated at 0.28 and 0.41 MPa, and extrapolated to 0.14 MPa

where

X_{tt} = Martinelli parameter

X = local quality

ρ = density

μ = viscosity

h = heat transfer coefficient

subscripts: L, f = liquid

g = vapor

From the above data, the local film coefficient in the 0.41 MPa (60 psia) test is calculated to be 34 percent larger than that in the 0.14 MPa (20 psia) test.

Because the Biot number in figure 5-93 is directly proportional to the heat transfer coefficient and the quench front velocity increases with Biot number, the increase in pressure will cause an increase in the quench velocity at a constant θ_c. The slope of the solution lines in figure 5-93 indicates that an increase of 34 percent in the Biot number will increase the quench front velocity by at least $\sqrt{1.34}$, or 16 percent. The measured reduction in the 1.22 m (4 ft) quench times from the 0.14 MPa (20 psia) run to the 0.41 MPa (60 psia) run is 950-720 seconds, or 230 seconds.

Assuming that the quench velocity is constant in any given test, as implied by figure 5-42, the relative increase in quench velocity from the 0.14 MPa (20 psia) run to the 0.41 MPa (60 psia) run is 32 percent. The above estimate of the quench front velocity change due to the local heat transfer coefficient change suggests that a change in the θ_c parameter may also be contributing to the increased quench velocity at 0.41 MPa (60 psia). From the definition of θ_c above, the following equations for a change in θ_c due to a change in the saturation temperature of the quenching fluid were derived:

$$\frac{\Delta\theta_c}{\theta_c} = \frac{\alpha \frac{1}{\theta_c} + 1}{\alpha + 1} \tag{5-6}$$

$$\frac{\Delta\theta_c}{\theta_c} = \frac{\alpha}{1 - \alpha} \tag{5-7}$$

where

θ_c	=	dimensionless quench velocity [see figure 5-93 and equation (5-3)]
$\Delta\theta_c$	=	change in θ_c due to an increase in T_f, assuming T_c is constant
α	=	increase in T_f divided by $T_\infty - T_f$ [see equation (5-1) for definition of T_∞]

The first equation assumes that T_c is constant, and the second equation assumes that T_c increases as T_f increases.

Equation (5-6) shows that θ_c will decrease with an increase in T_f, assuming that T_c is unchanged, but equation (5-7) shows that θ_c will increase with T_f if T_c also increases. Because the test data suggest that θ_c increases with pressure, it is reasonable to assume that T_c, the temperature at the quench interface, also increases with pressure.

The local flux profiles in figure 5-94 show that the peak heat flux decreases as the pressure increases. The principal reason for the flux decrease is the reduced overall temperature from secondary to primary (that is, the secondary fluid temperature minus

the primary saturation temperature). Assuming a secondary fluid temperature at the beginning of the 1.22 m (4 ft) tube wall quench (figure 5-91) of about 221°C (430°F), the difference in overall temperature drop due to the primary pressure change is 221°C-145°C (430°F-293°F) for 0.41 MPa (60 psia), and 221°C-109°C (430°F-228°F) for 0.14 MPa (20 psia). The increase in the temperature difference at 0.14 MPa (20 psia) is 36°C (65°F), and the relative increase is 47 percent from 0.41 MPa (60 psia) to 0.14 MPa (20 psia). The increase in the peak flux in figure 5-94 from the 0.41 MPa (60 psia) run to the 0.14 MPa (20 psia) run is about 100 percent. The 0.41 MPa (60 psia) peak heat flux selected for the plot in figure 5-94 was compared to other local fluxes in the tube bundle, and it was found that most instrumented locations had larger flux peaks than the location plotted in figure 5-94. The local flux from the 1.22 m (4 ft) radial position 2 is shown in figure 5-95. This flux peaks at 193 kw/m^2 (17 Btu/sec-ft^2) and is in closer agreement with the expected flux change with pressure.

Figures 5-96 and 5-97 show the end-of-test secondary fluid and primary steam temperatures for the three pressure sensitivity runs. The plots show that the only difference in the secondary fluid temperature was that the cold stratified water below the 1.22 m (4 ft) elevation in the bundle approached the primary side saturation temperature. The end-of-test steam temperatures were virtually identical over most of the tube bundle length. At the tube bundle exit, only the difference in the temperature of the cold stratified secondary temperature caused a small difference in the outlet plenum steam temperature. The difference in steam temperature shown in figure 5-97 at the 8.23 m (27 ft) elevation is not the result of measured data. The highest steam probe elevation was 4.57 m (15 ft), and the steam temperature profile above this elevation is plotted from interpolated data generated from the 0 to 4.57 m (15 ft) steam probe test data.

Figure 5-98 illustrates the outlet plenum liquid collection in the three pressure sensitivity runs. The plot shows that the 0.28 MPa (40 psia) reference run had more outlet plenum liquid than either the 0.14 or 0.41 MPa (20 psia or 60 psia) run. However, as discussed in paragraph 5-3, the average outlet plenum liquid collection of the reference runs is believed to be a more accurate measure of the true outlet plenum liquid. The average reference run liquid collection (paragraph 5-4) was 3.20 kg (7.05 lb). In the pressure sensitivity runs, the liquid collection was 3.30 kg (7.27 lb) at 0.41 MPa (60 psia)

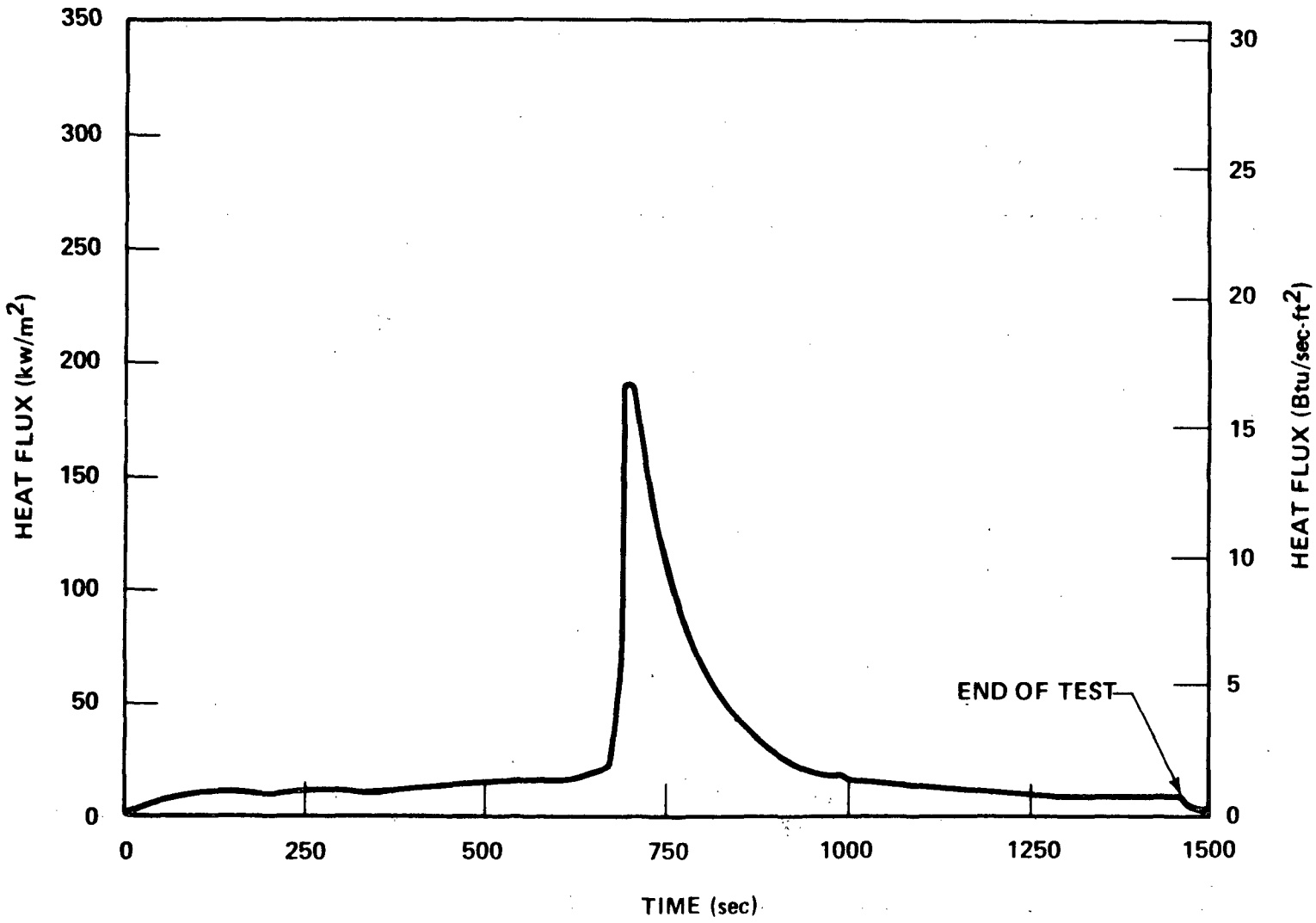


Figure 5-95. Tube Wall Heat Flux, Run 20904, 0.41 MPa (60 psia), 1.22 m (4 ft) Elevation, Radial Position 2

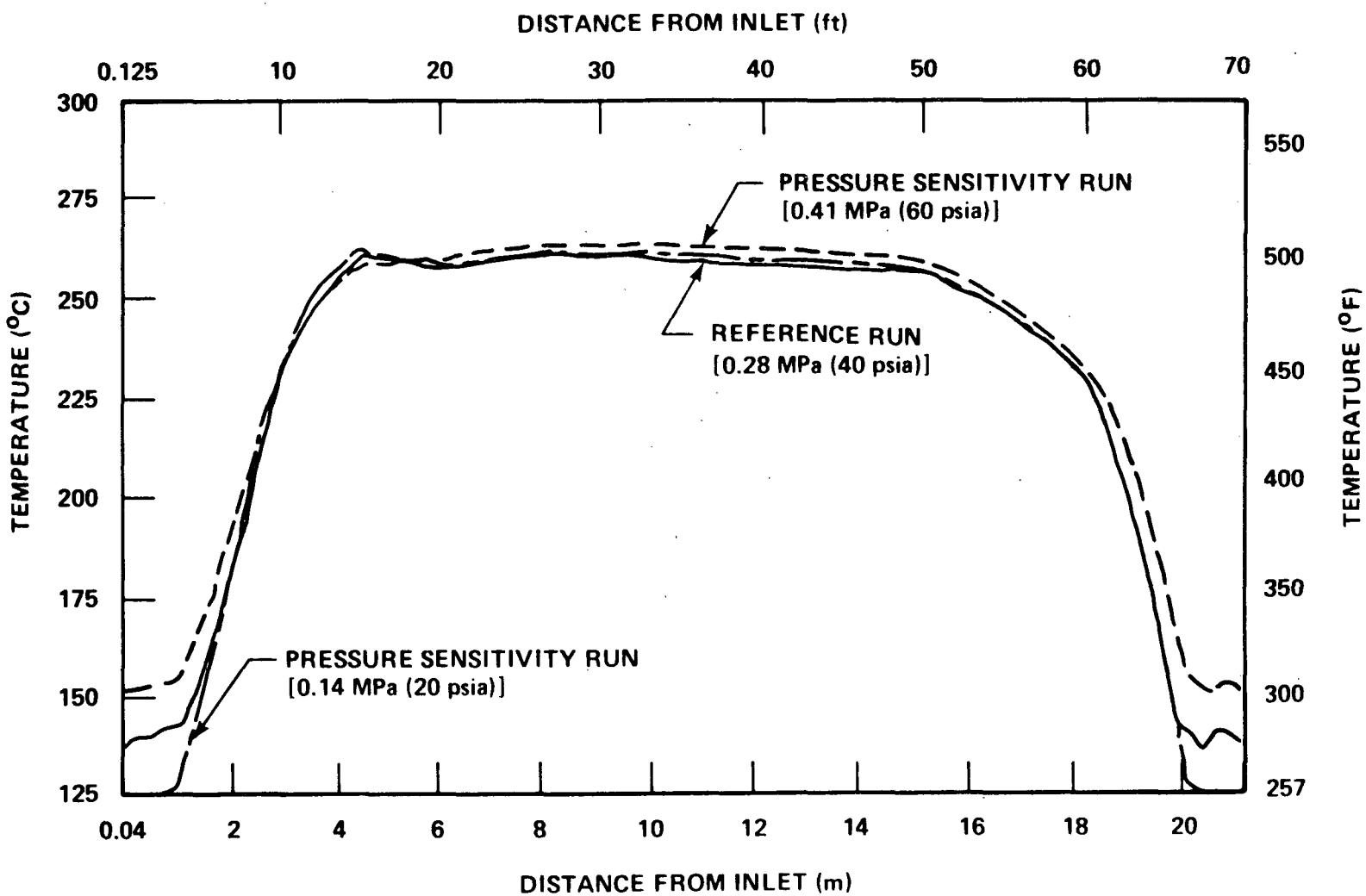


Figure 5-96. Fluid Temperatures, Reference and Pressure Sensitivity Runs, End of Test, Radial Position 1

16817-33

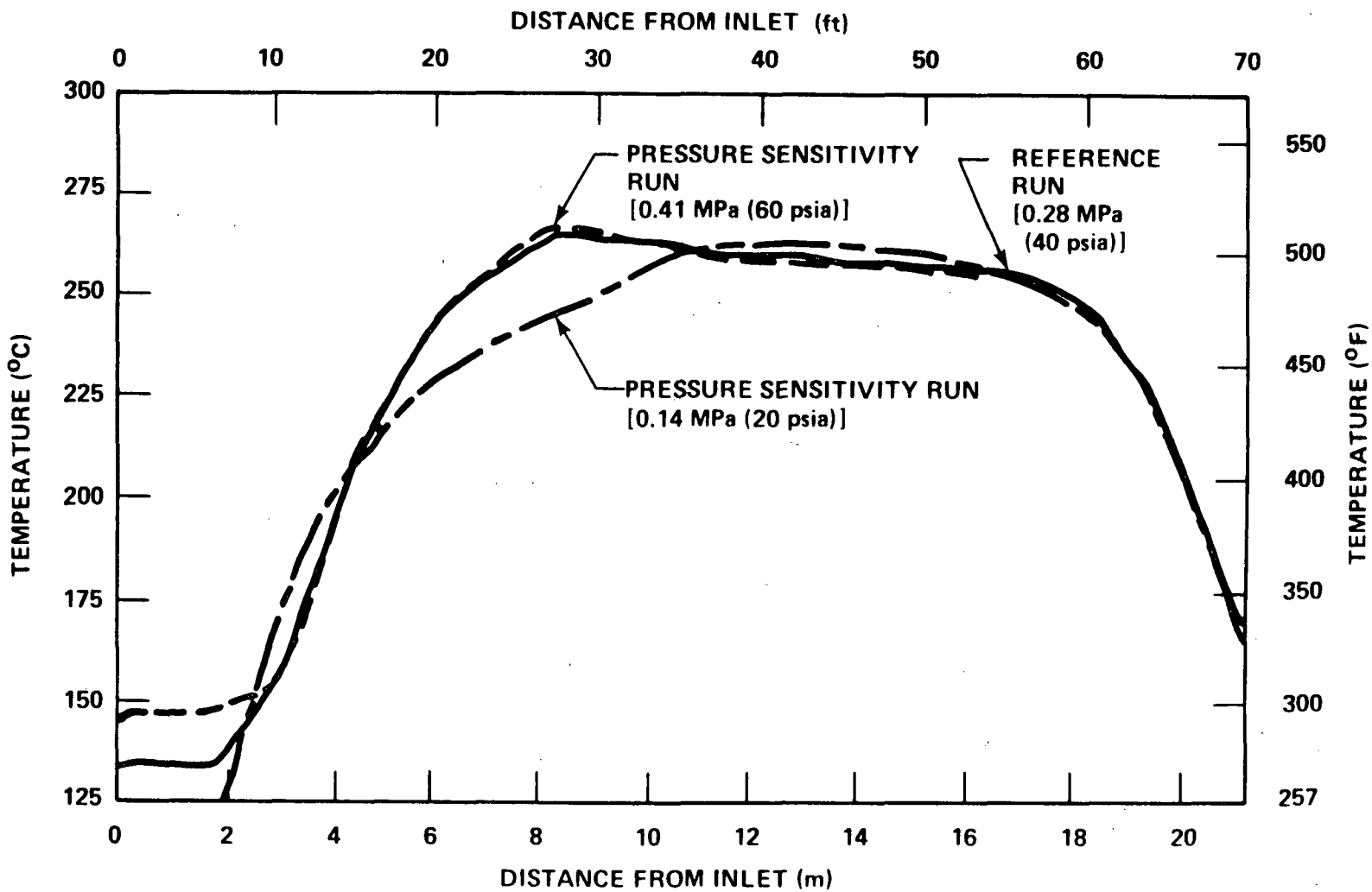


Figure 5-97. Steam Temperatures, Reference and Pressure Sensitivity Runs, End of Test, Radial Position 1

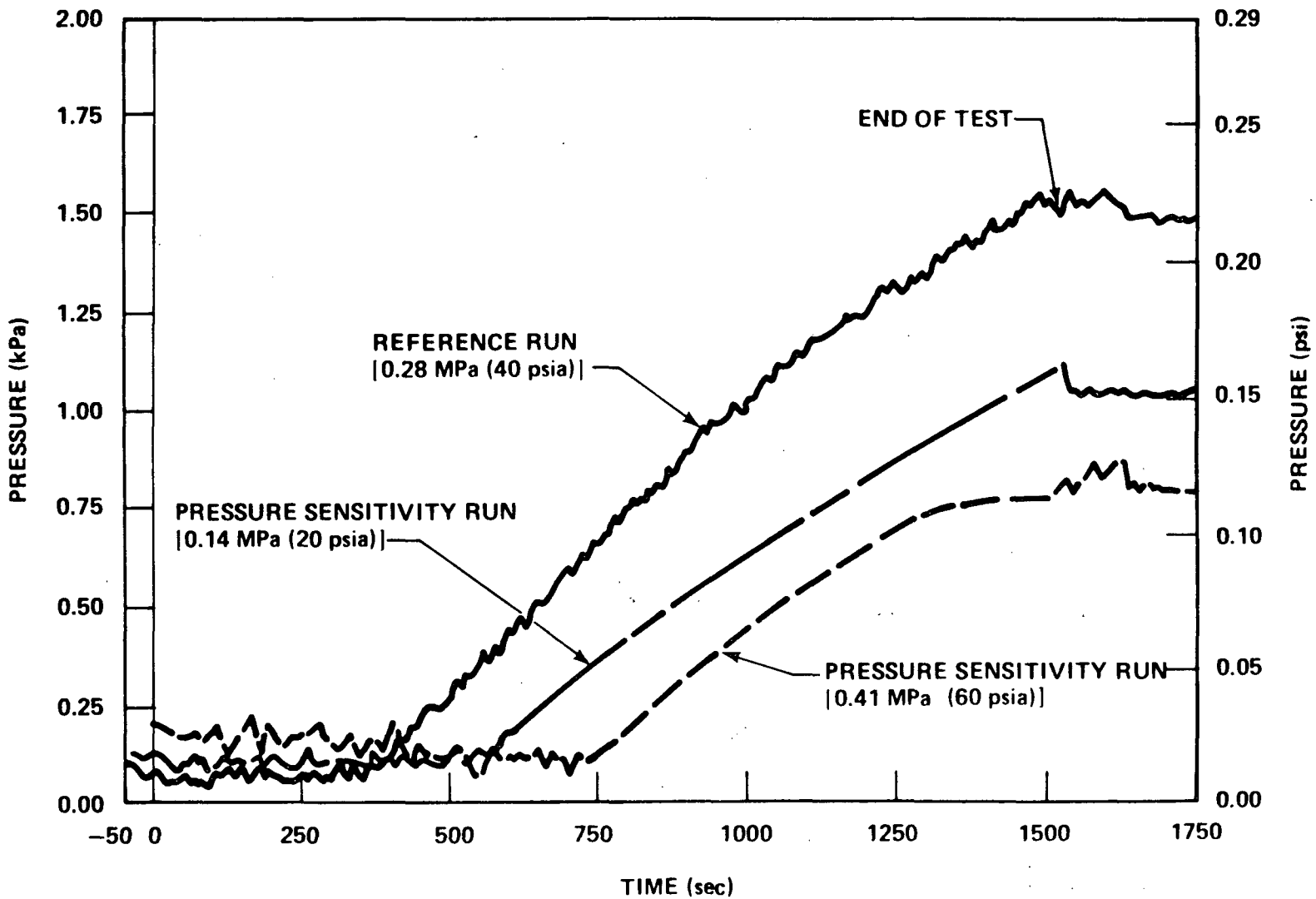


Figure 5-98. Outlet Plenum Liquid Collection, Reference and Pressure Sensitivity Runs

and 3.98 kg (8.78 lb) at 0.14 MPa (20 psia). The standard deviation in the liquid collection data from the five reference runs was 1.0 kg (2.2 lb). Because the outlet plenum liquid mass changes in the pressure sensitivity runs are smaller than the standard deviation in the reference run data, a clear trend in the outlet plenum liquid mass change with pressure cannot be determined.

The total bundle pressure drops from the three pressure sensitivity runs are compared in figure 5-99. A hand calculation for the 0.14 MPa (20 psia) run, based on the assumption that the total flow is single-phase steam at 260°C (500°F), produced a pressure drop of 11 kPa (1.6 psi), which is identical with the measured pressure drop. The 0.28 and 0.41 MPa (40 and 60 psia) pressure drops also agreed with the calculated pressure drop.

Figure 5-100 illustrates the overall bundle heat flow rate for the three pressure sensitivity runs. The reference run 22701 overall heat flow rate is higher than the pressure sensitivity heat flow rates. However, as discussed in paragraph 5-4, the run 22701 overall heat flow rate was overestimated because of the mass balance error in the same run. The overall heat flow rate in both replicate reference runs (21711 and 22010) is almost 10 percent lower than that in run 22701. Comparing the heat flow rates from the pressure sensitivity runs (20904 and 22503) to those from the replicate reference runs (21711 and 22010) would show no significant differences. That is, the overall bundle heat flow rate is insensitive to the system pressure.

In summary, the pressure sensitivity runs combined with the reference run covers the steam generator thermal-hydraulic response over a range from 0.14 to 0.41 MPa (20 to 60 psia). The test data show that 1.22 m (4 ft) quench time can be correlated with pressure using a function of the form $[1/P]^{0.25}$.

The quench velocity data trends are consistent with the solution for the quenching of a solid rod given by Yeh.[1] The local quality at the quench elevation was calculated from the local-condition CHF correlation of Biasi. From the local quality at the quench elevation and the closed form solution for quench velocity in Yeh, it is concluded

---

1. Yeh, H. C., "An Analysis of Rewetting of a Nuclear Fuel Rod in Water Reactor Emergency Core Cooling," Nucl. Eng. Des. 34, 317-322 (1975).

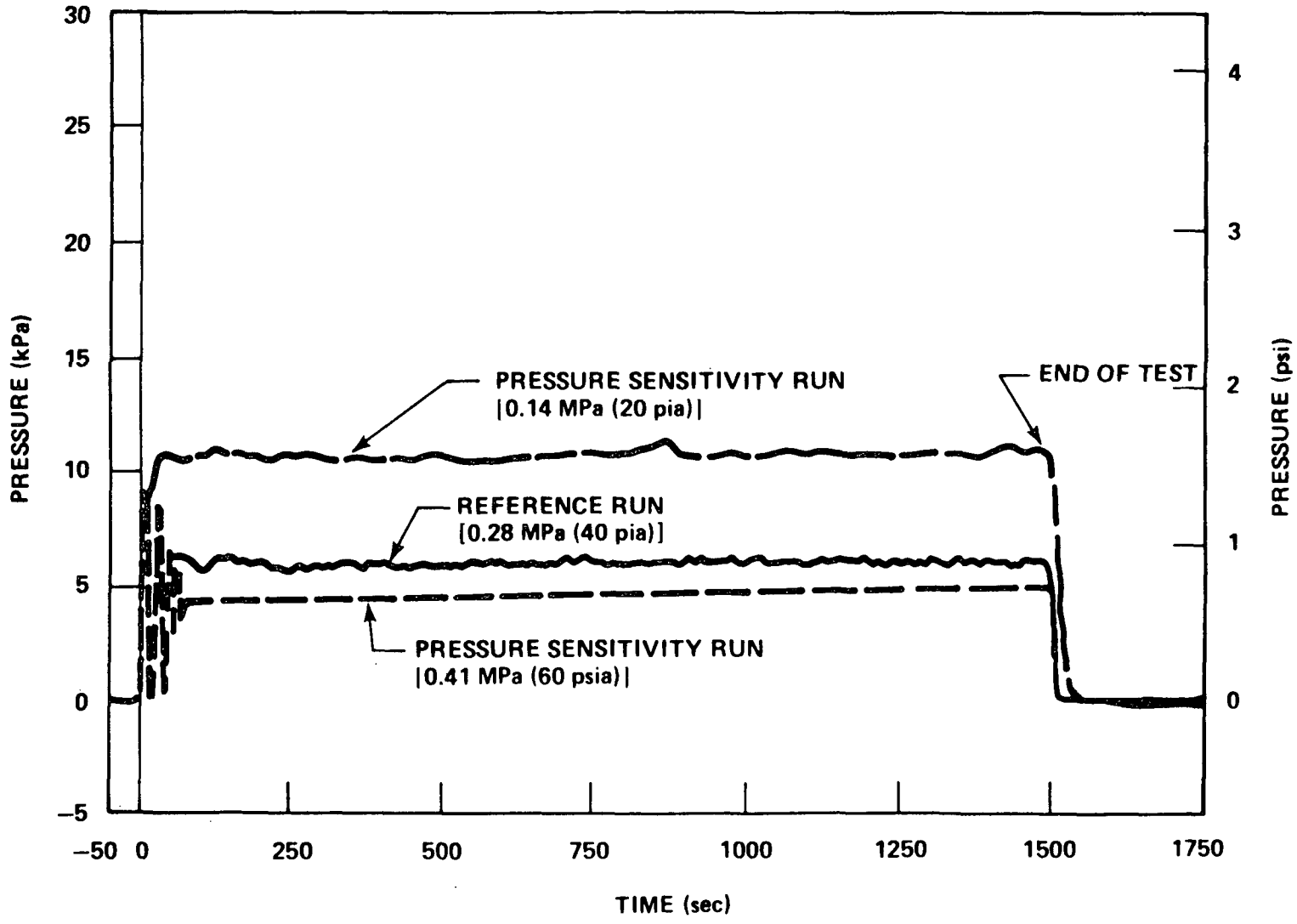


Figure 5-99. Overall Bundle Pressure Drop, Reference and Pressure Sensitivity Runs

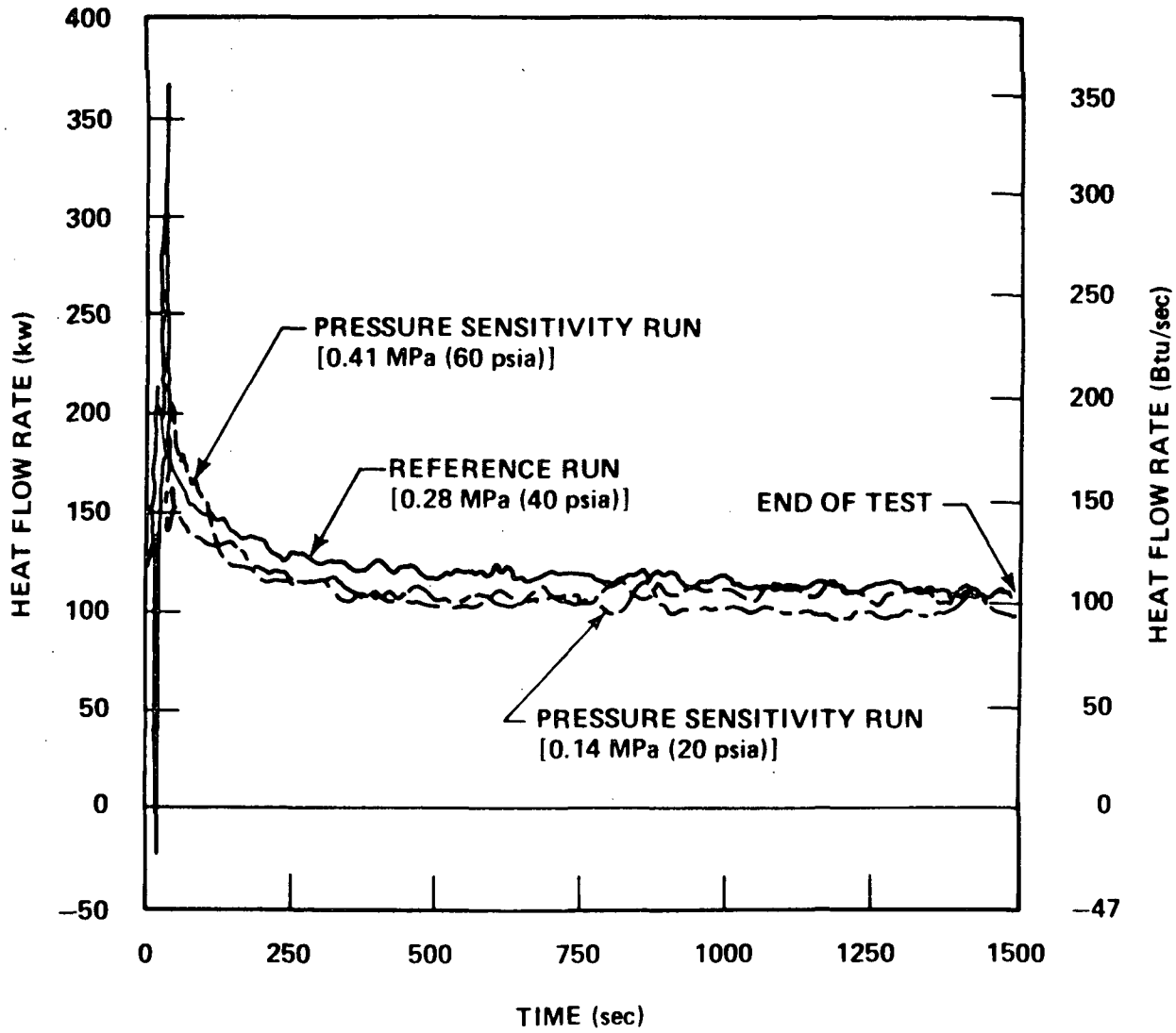


Figure 5-100. Overall Bundle Heat Transfer, Reference and Pressure Sensitivity Runs

that the tube wall temperature at the quenching interface increases with pressure. The outlet plenum liquid collection shows no clear trend with pressure. The overall bundle pressure drop and heat transfer rate data reflect expected data trends.

5-8. Secondary System Temperature Sensitivity

The effect of the secondary fluid initial temperature on the steam generator heat transfer response was determined from run 23207, where the initial secondary temperature was 204°C (400°F). The reference run with a 274°C (525°F) initial secondary temperature was compared to run 23207.

In figures 5-101 and 5-102, the 1.22 m (4 ft) elevation, radial position 1 fluid and tube wall thermocouple readings are plotted. The plots show a much earlier 1.22 m (4 ft) quench time and generally smaller fluid to wall temperature differences. The earlier quench times of the lower secondary temperature are consistent with the analysis illustrated in figure 5-93. The lower secondary temperature results in a lower T_∞ in equation 5-3. The lower T_∞ in the denominator of equation (5-3) results in a larger θ_c, which results in a higher quench velocity at a constant Biot number. Because the quench velocity theoretically approaches infinity as θ_c approaches 1.0, even small increases in θ_c will cause a large quench velocity increase if the original θ_c is relatively large. From the two data points on quench velocity versus secondary fluid temperature from these two runs, an estimate of the fluid temperature T_∞ corresponding to an infinite quench velocity can be generated. From figure 5-101, the secondary fluid temperature at the beginning of rod quench is estimated at 232°C (450°)F for run 22701 and 190°C (375°F) for run 23207. The reciprocal quench velocities were 656 sec/m (200 sec/ft) for run 22701 and 246 sec/m (75 sec/ft) for run 23207. From these data the extrapolated temperature to yield zero reciprocal quench velocity (infinite quench velocity) is 163°C (325°F). Because at this condition $\theta_c = 1.0$, the above value of 163°C (325°F) for T_∞ is also the value of T_c. This temperature, T_c, is the temperature at the quenching interface in the reference run. This temperature must be known before the quench velocity can be calculated using the solution illustrated in figure 5-93. This extrapolation implies that at an initial secondary bundle temperature of 163°C (325°F), the bundle would quench immediately.

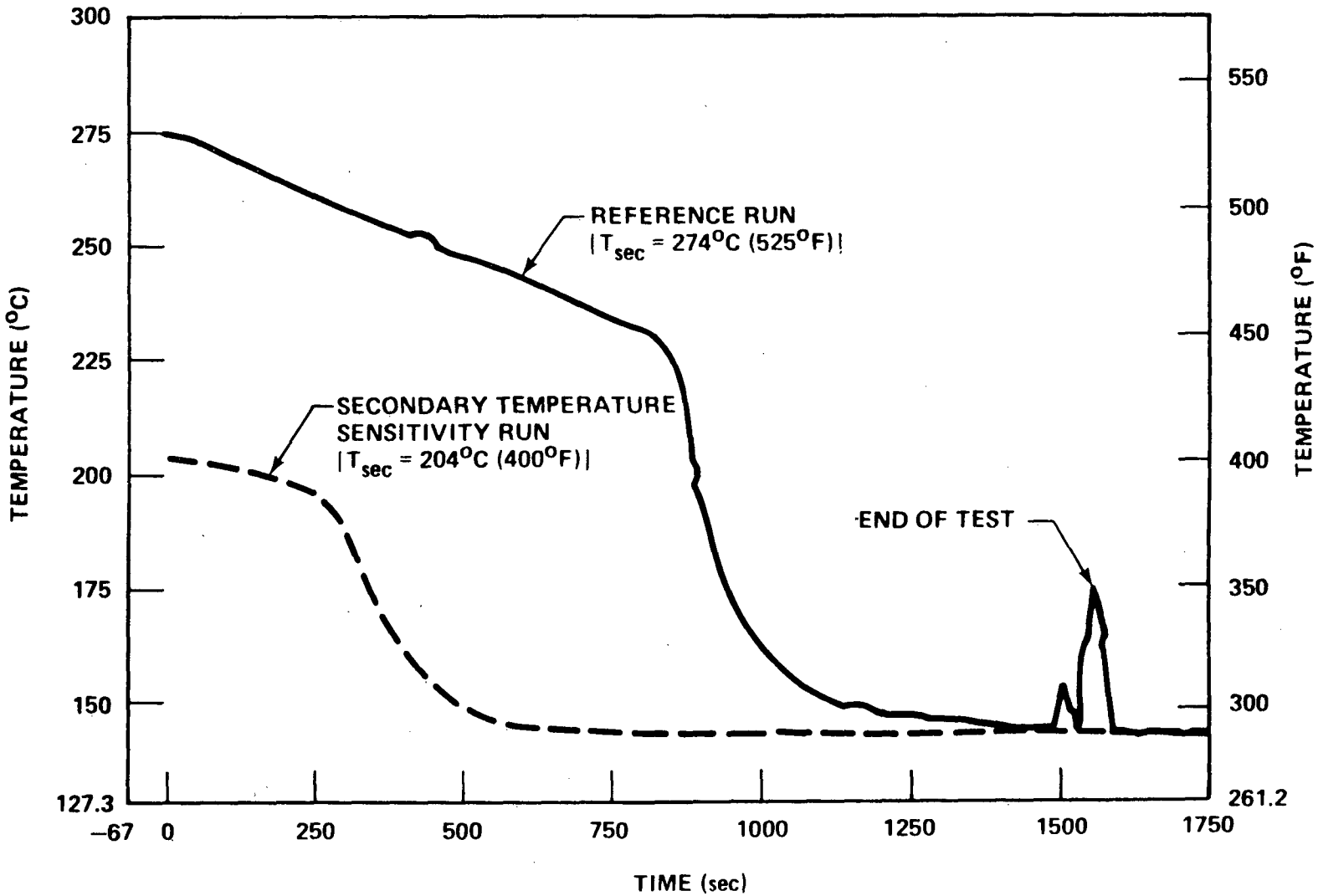


Figure 5-101. Fluid Temperatures, Reference and Secondary Temperature Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

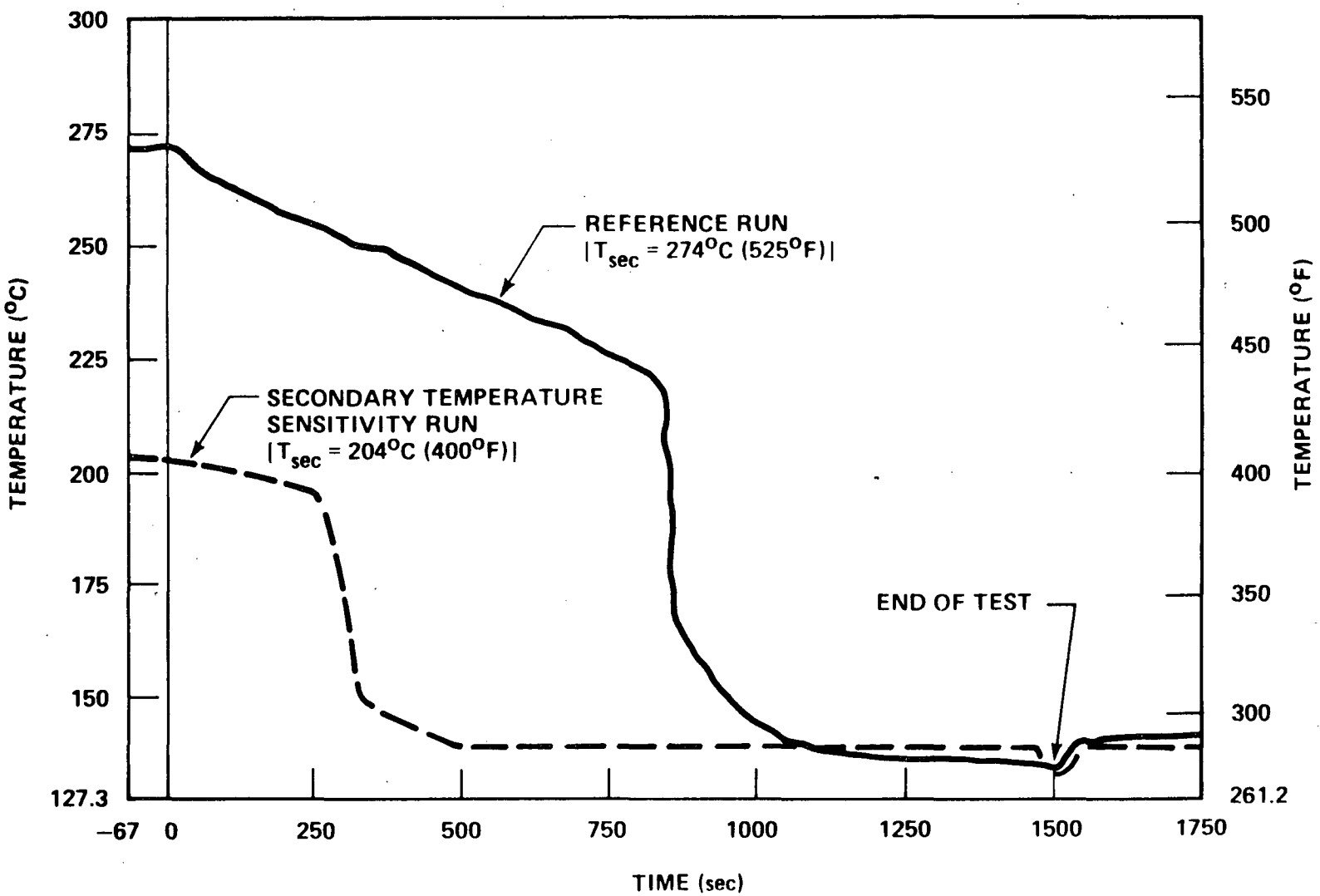


Figure 5-102. Tube Wall Temperatures, Reference and Secondary Temperature Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

16817-13

Figures 5-103 through 5-105 plot local heat flux at three locations in the tube bundle. The plots show that the peak heat flux was very nearly the same at all three locations in run 23207 [204°C (400°F) secondary temperature], but varied widely in the reference run. Since the only significant difference between runs 22701 and run 23207 was the secondary temperature, this effect was responsible for the change in the local heat flux. The above discussion of local heat flux suggests two phenomena that can limit the flux peak: the overall secondary to primary temperature difference and the local critical heat flux. The secondary temperature change will change the flux peak, because of the overall temperature difference, but not the local critical heat flux. The same flux peak in figures 5-103 through 5-105 suggests that the controlling mechanism is the overall temperature difference.

Figure 5-106 and 5-107 are plots of the end-of-test secondary fluid and primary side steam temperature distributions. These figures show that the secondary fluid cooldown was similar, in that a cold stratified layer accumulated in the lower bundle elevations, and above this region the bundle temperatures dropped only slightly. The steam temperature also followed the same trend in both runs. After the secondary fluid temperature stratified, steam in the downflow section of the bundle decreased until, by the end of the tests, the steam temperature reduction in the downflow section of the bundle could exceed 56°C (100°F).

The outlet plenum liquid collection, as measured by the outlet plenum water level D/P cell, is shown in figure 5-108. As noted in the evaluation of the reference run, the outlet plenum liquid collection in run 22701 was atypical; a better estimate of the liquid collection for the reference run is the average liquid collected in five reference runs. The liquid collection in run 21711 is close to this average and the liquid collection as indicated by the outlet plenum ΔP for run 21711 is also plotted in figure 5-108. The plot shows no significant difference between the amounts of liquid collected in these two runs. From the outlet plenum liquid collection, the average outlet plenum quality in the reduced secondary temperature run (23207) was 99.2 percent.

Figures 5-109 and 5-110 are plots of the overall bundle pressure drop and heat transfer. The slightly lower bundle pressure drop and heat transfer in run 23207 was due

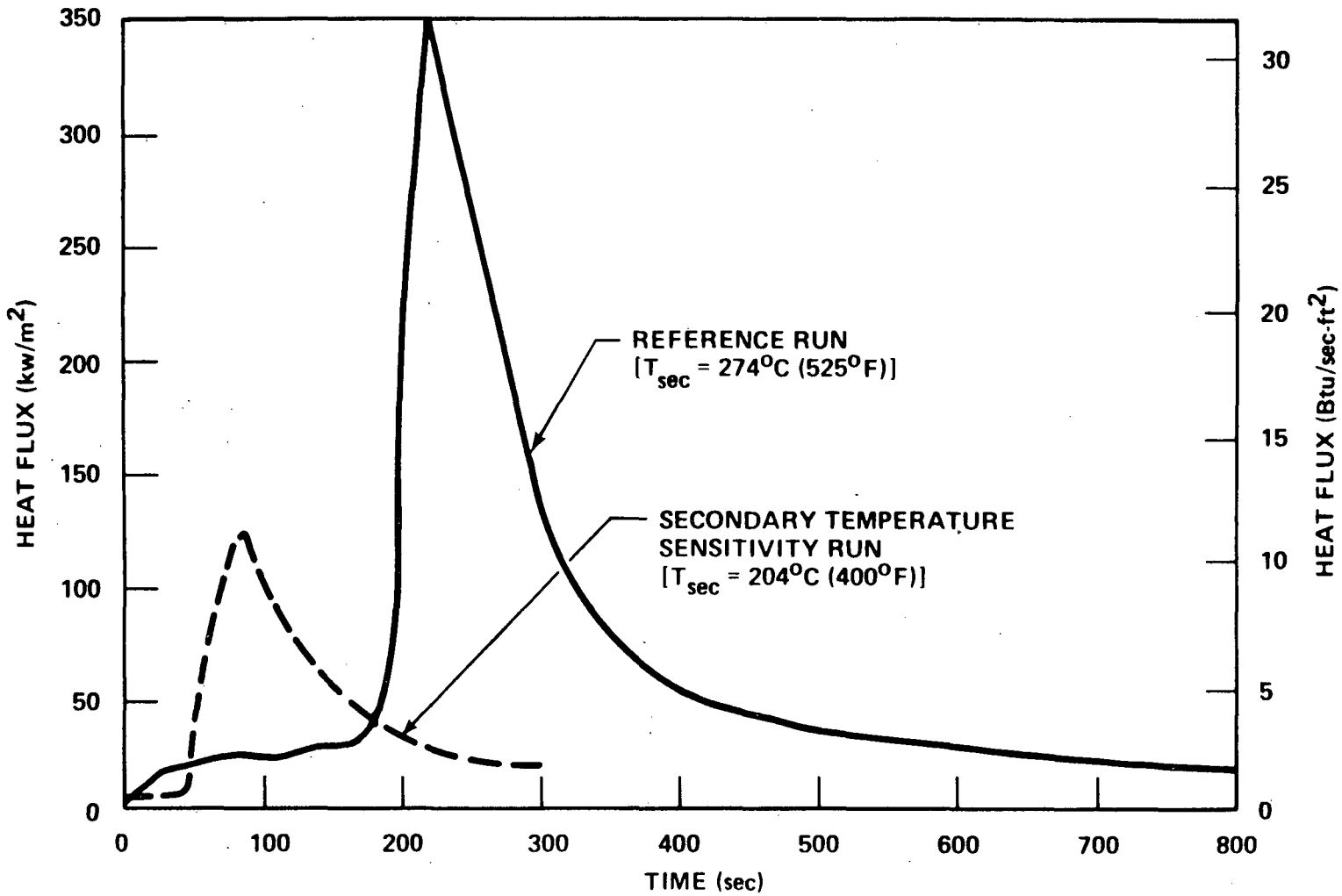


Figure 5-103. Tube Wall Heat Flux, Reference and Secondary Temperature Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 1

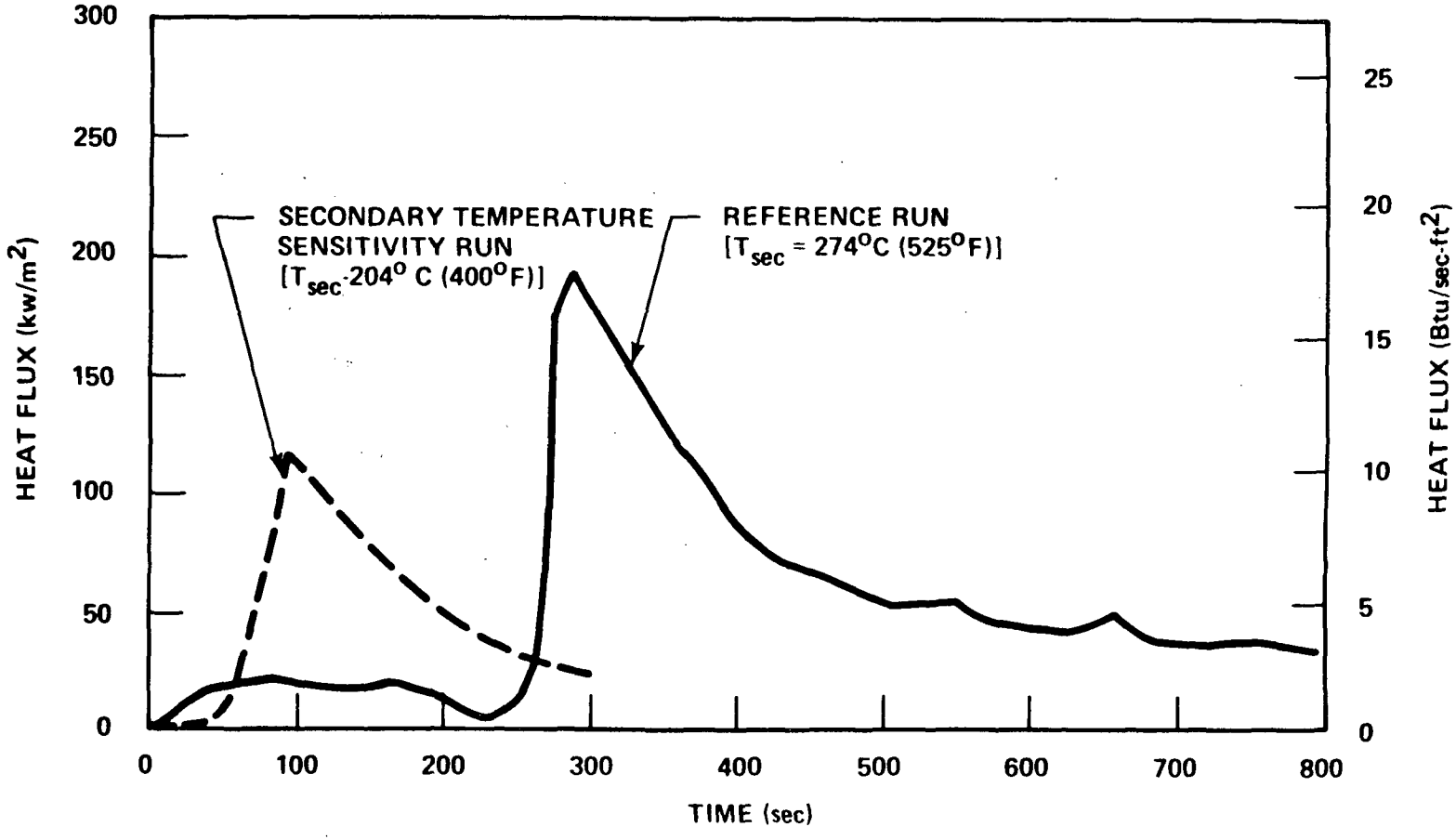


Figure 5-104. Tube Wall Heat Flux, Reference and Secondary Temperature Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 4

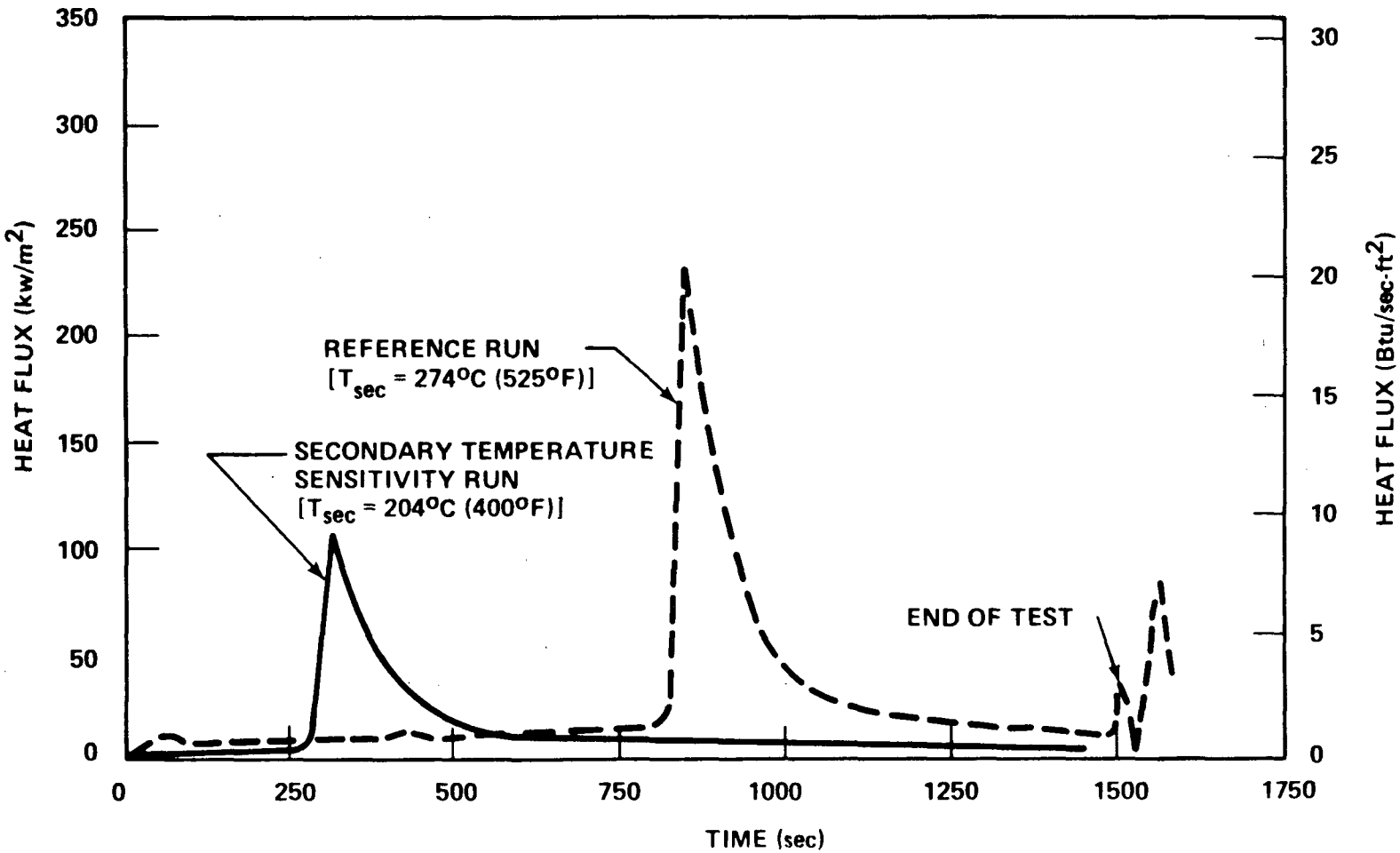


Figure 5-105. Tube Wall Heat Flux, Reference and Secondary Temperature Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

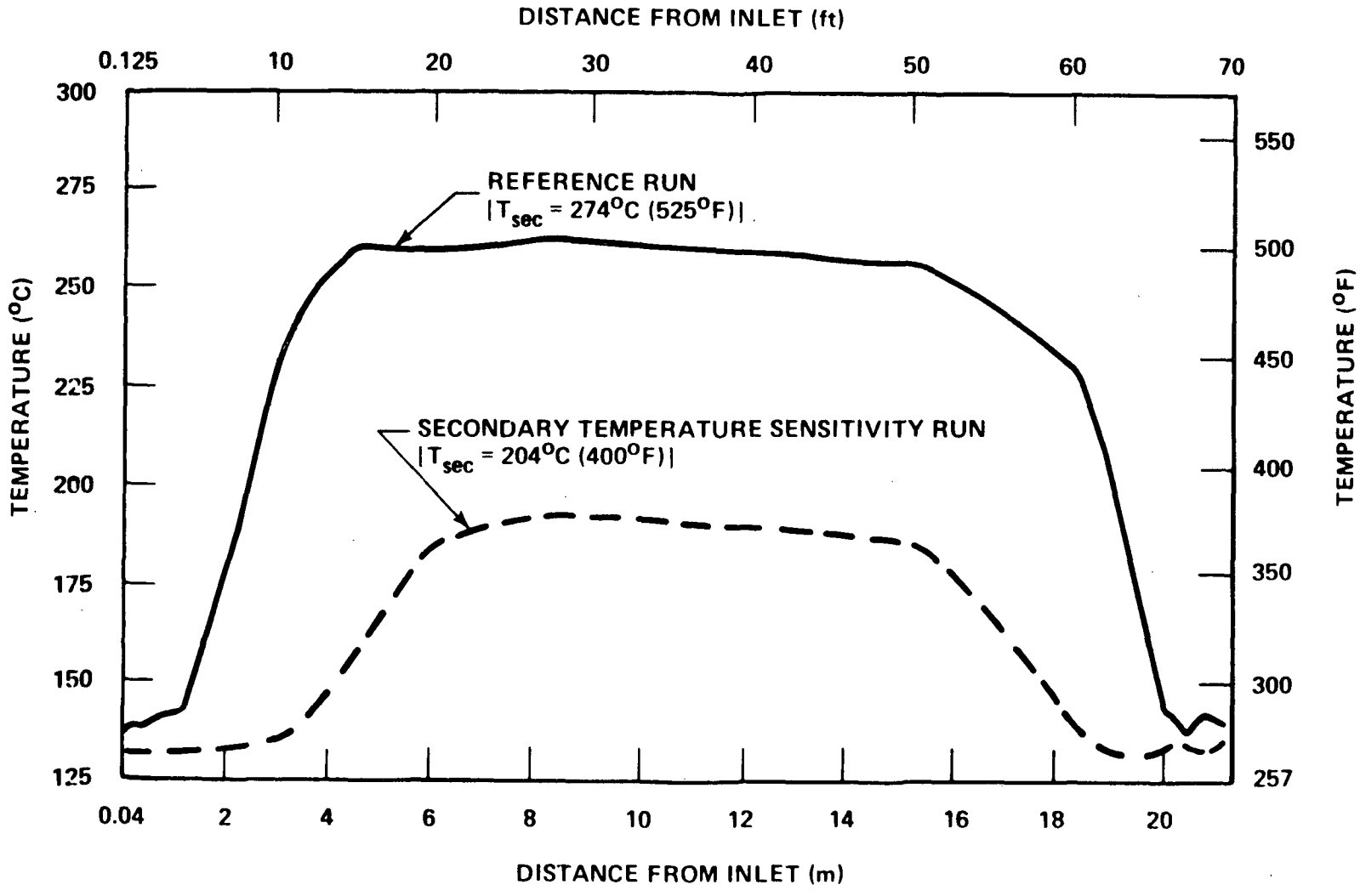


Figure 5-106. Fluid Temperatures, Reference and Secondary Temperature Sensitivity Runs, End of Test, Radial Position 1

16817-31

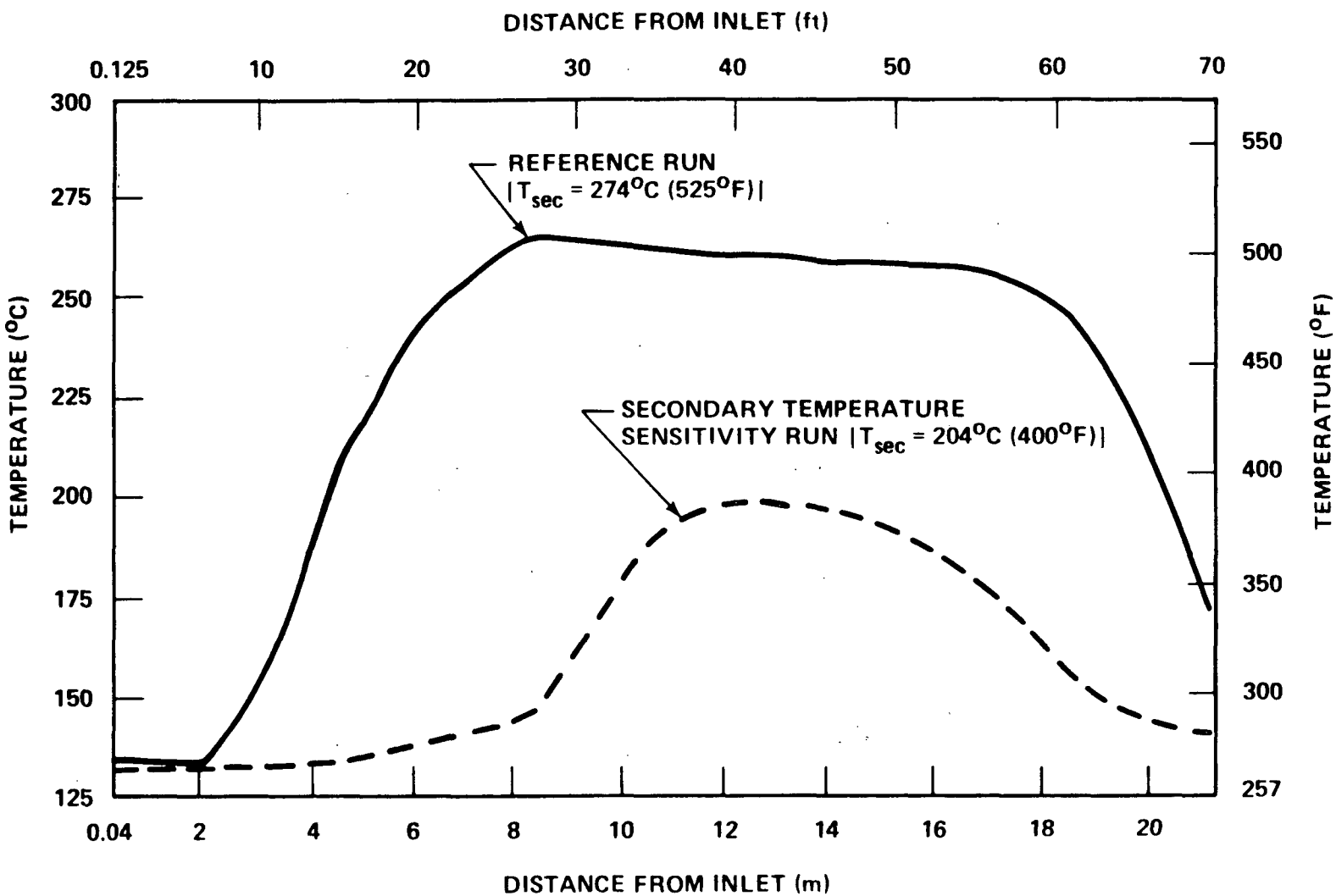


Figure 5-107. Steam Temperatures, Reference and Secondary Temperature Sensitivity Runs, End of Test, Radial Position 1

16817-30

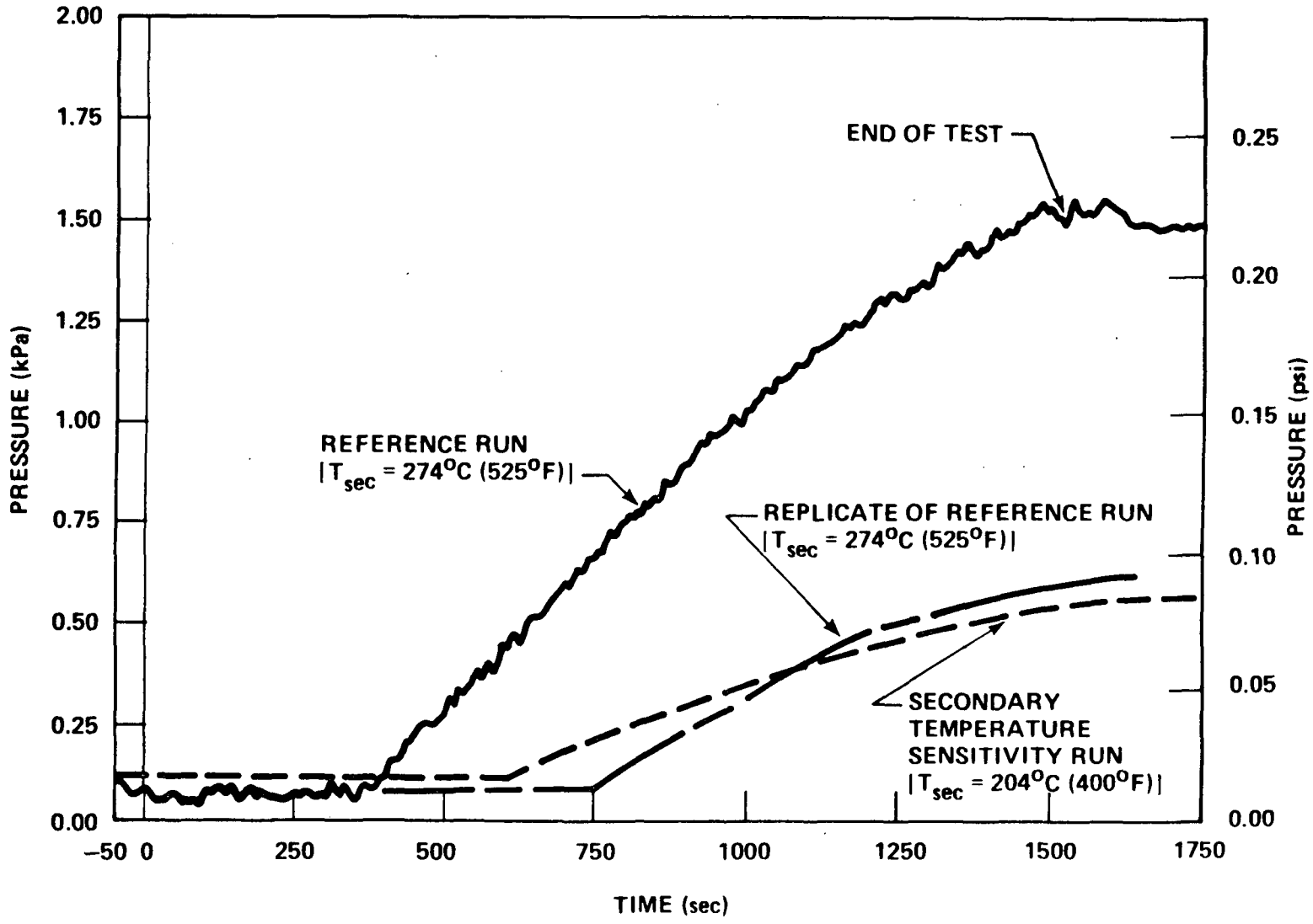


Figure 5-108. Outlet Plenum Liquid Collection, Reference, Replicate, and Secondary Temperature Sensitivity Runs

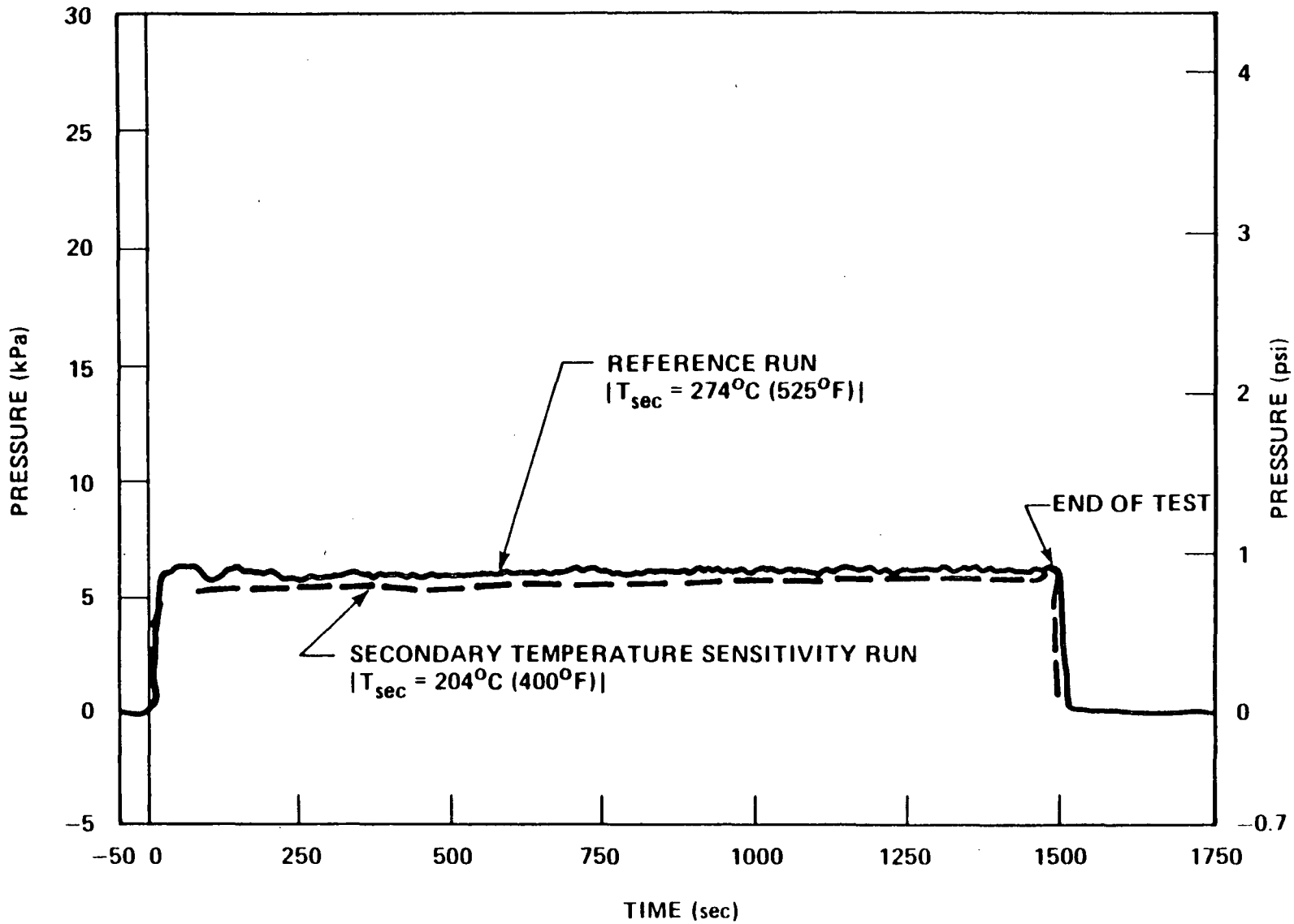


Figure 5-109. Overall Bundle Pressure Drop, Reference and Secondary Temperature Sensitivity Runs

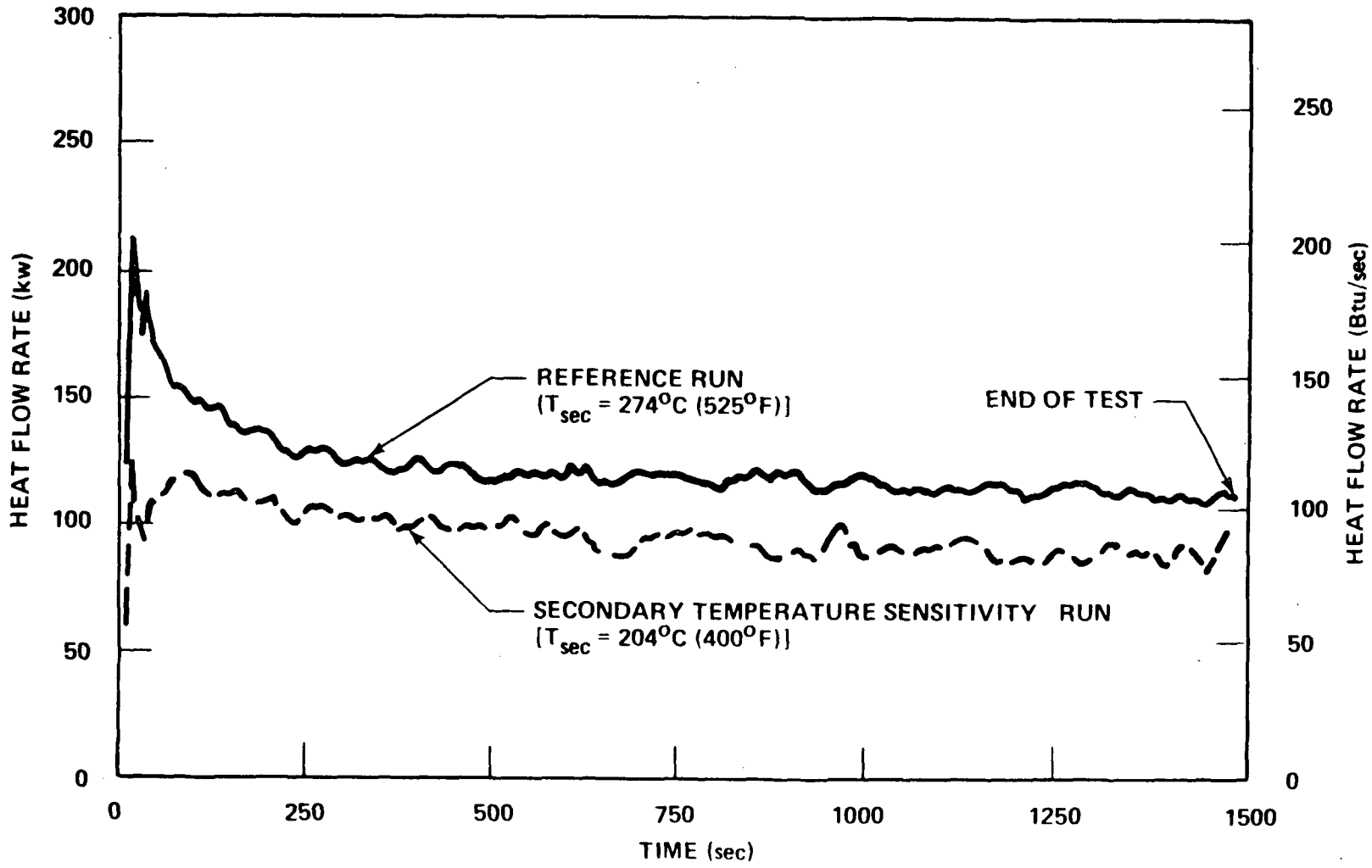


Figure 5-110. Overall Bundle Heat Transfer, Reference and Secondary Temperature Sensitivity Runs

to the lower secondary temperature. Because of the lower temperature, the primary steam specific volume was 13 percent lower. The bundle frictional pressure drop change should be directly proportional to the specific volume change. The run 23207 bundle pressure drop initially was about 10 percent below that of the reference run, but the difference decreased with time. In run 23207, two changes that affect the bundle pressure drop occurred simultaneously. The overall steam temperature reduction reduced the pressure drop, but the climbing liquid film in the inlet region increased the bundle pressure drop. Figure 5-109 shows that the net result of these two effects was to cause a slight increase in the bundle pressure drop as time increased. The difference in the overall heat transfer rate (figure 5-110) was due to the lower outlet plenum steam temperature in run 23207. The outlet plenum steam temperature in run 23207 was 28°C to 56°C (50°F to 100°F) lower than in the reference run. In terms of energy flow at a mass flow rate of 0.23 kg/sec (0.5 lb/sec), the lower steam temperature reduced the outlet plenum energy flow by 26 to 53 kw (25 to 50 Btu/sec). This is the same magnitude as the difference shown in figure 5-110.

In summary, this evaluation of the secondary temperature sensitivity run shows the expected increase in the quench velocity with the secondary temperature reduction. The 1.22 m (4 ft) quench time variation with temperature is correlated by a function of the form $(1.8T-235)^{1.48}$, where T equals the secondary fluid initial temperature in °C. From the quench velocity data at the two secondary temperatures, the local tube wall temperature at the quenching interface in the reference run is estimated to be 163°C (325°F). The local heat flux peaks in the lower secondary temperature run are lower and more uniform than those in the reference run, because of the lower secondary to primary temperature difference. The overall bundle pressure drop, heat transfer, and outlet plenum liquid collection were only slightly affected by the secondary fluid temperature change.

5-9. Secondary Water Level Sensitivity

The final parameter sensitivity run (22608) involved reducing the steam generator secondary water level to 25 percent. In all other test runs, the water level was 100 percent, which corresponds to a water level of 10.1 m (33 ft), and the length of the steam generator U-tubes was 10.7 m (35 ft).

Figure 5-111 and 5-112 compare the 1.22 m (4 ft) radial position 1 secondary fluid and tube wall temperature transients between the secondary level sensitivity run and the reference run. These plots show very similar temperature transients at the 1.22 m (4 ft) elevation.

The quench time was slightly shorter in run 22608. In this run, the lower secondary fluid level resulted in lower steam temperatures in the tubes. The lower steam temperature caused less primary to secondary heat flow in the outlet region of the tube bundle after the stratified cold layer developed in the lower region of the tube bundle. The net result is that the stratified cold layer developed faster in run 22608, resulting in shorter quench times.

Three plots of local tube wall heat flux showing sensitivity to secondary level are shown in figures 5-113 through 5-115. Figures 5-113 and 5-115 show very similiar flux characteristics, with the low secondary level heat fluxes showing a slightly earlier quench time. In figure 5-114, the local heat flux appears to have two flux peaks in the 200- to 300-second interval, with an interval at 250 seconds where the flux is zero. This anomaly is caused by the data reduction program SGFLUX. In SGFLUX the tube wall correction factor is tested against the measured secondary fluid minus tube wall temperature difference. If the correction factor is excessively large, an alternate calculation of the tube wall heat flux is made using an assumed primary side heat transfer regime and film coefficient. In the case illustrated in figure 5-114, SGFLUX calculated a primary side film coefficient based on an assumed dry wall heat transfer correlation, but the tube wall temperature data for this location shown on page 22608-12 of Report No. 4 clearly show that the tube wall has already been quenched. Thus the dry wall assumption is incorrect. Without this anomaly, the local flux transient in figure 5-114 would be very similar to the flux plots in figures 5-113 and 5-115.

Figures 5-116 and 5-117 show the end-of-test secondary fluid and primary steam temperatures. Since the liquid level in run 22608 was only 2.35 m (7.7 ft), the fluid thermocouples above this elevation were detecting the ambient steam temperature on the secondary side of the tube bundle. Figure 5-116 shows that the secondary fluid temperatures in the liquid zone [that is, 0-2.35 m (0-7.7 ft) and 19.0-21.3 m (62.3-70 ft)] were lower in run 22608 than in the reference run. The primary side steam temper-

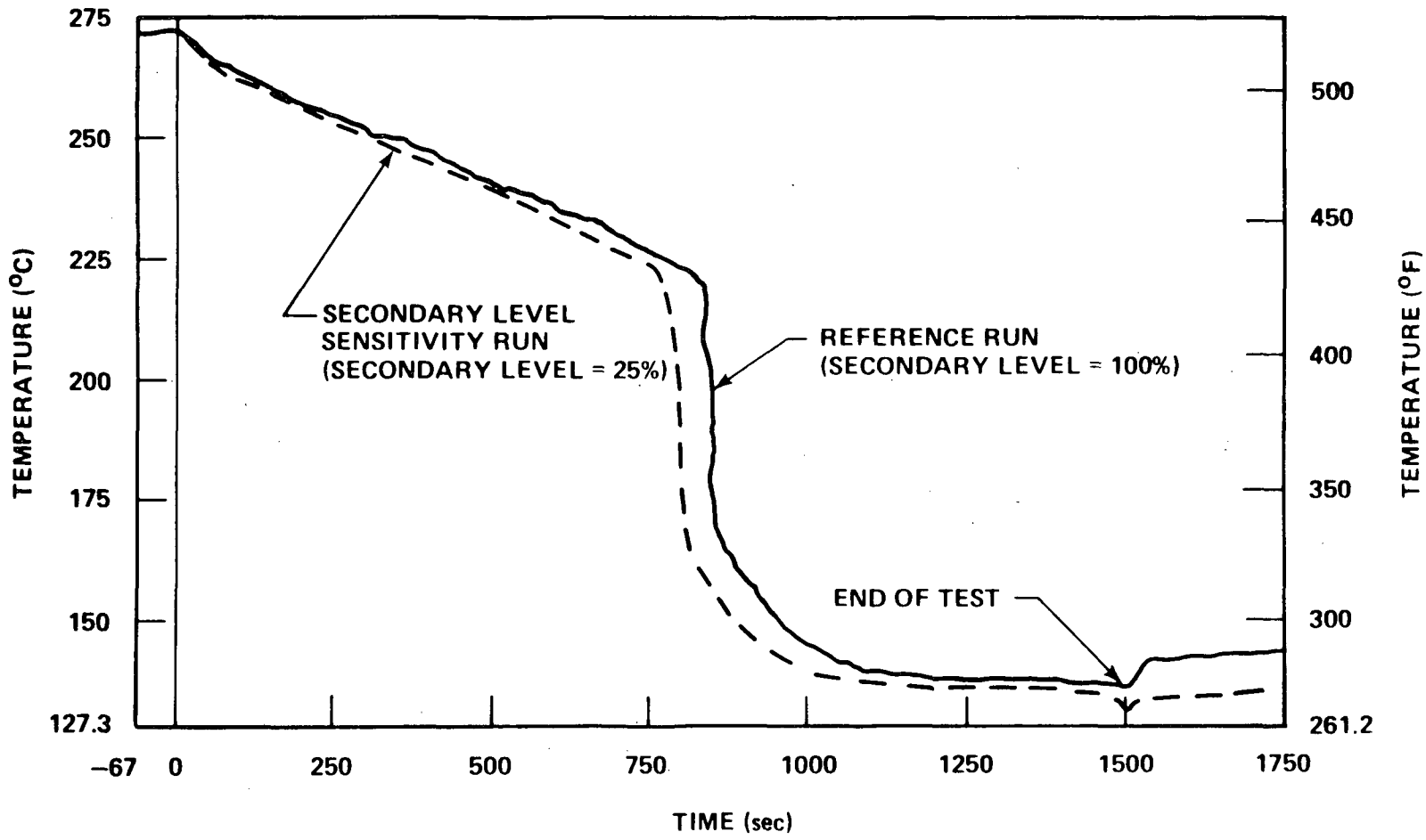


Figure 5-111. Tube Wall Temperatures, Reference and Secondary Level Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

16817-11

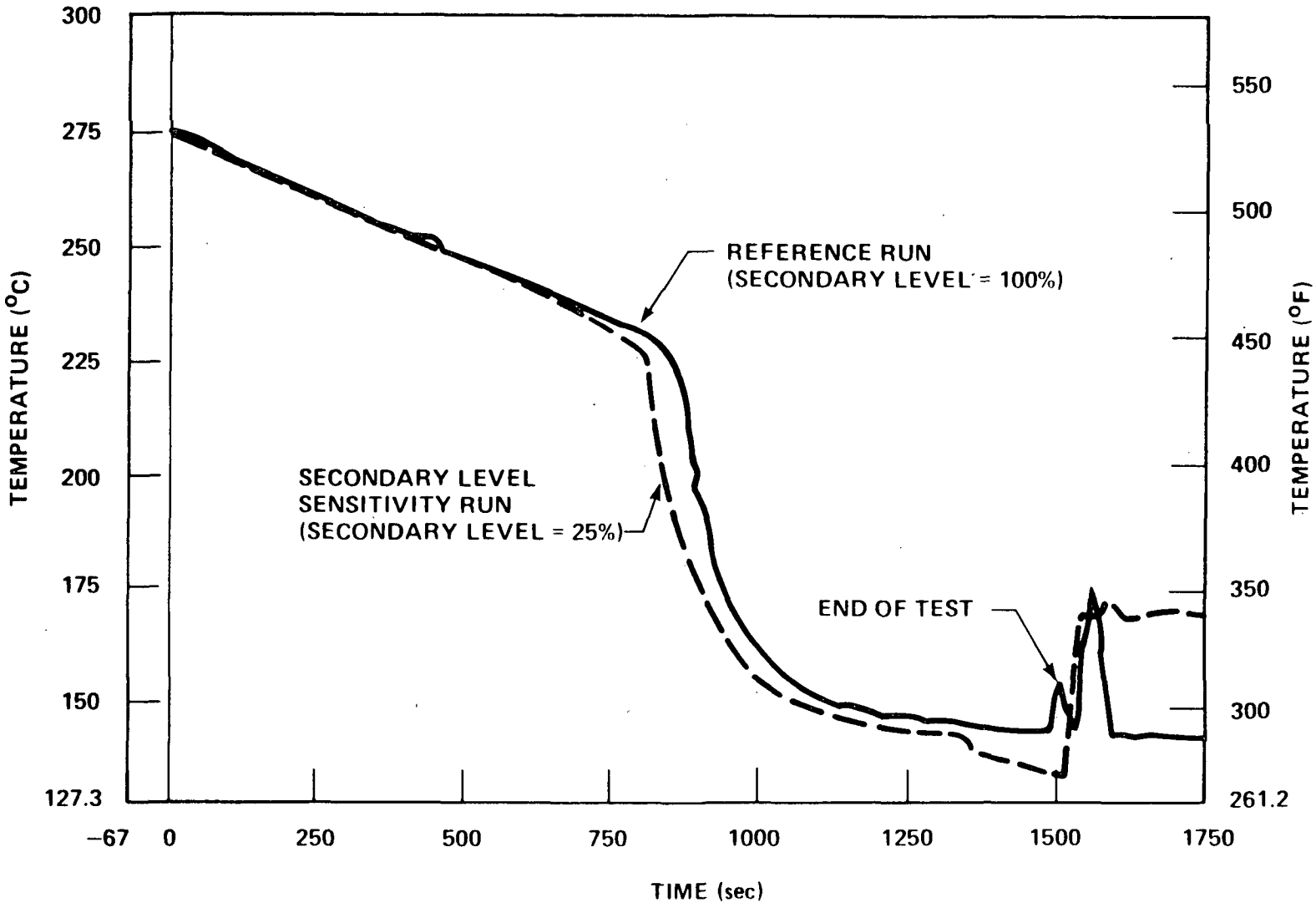


Figure 5-112. Fluid Temperatures, Reference and Secondary Level Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

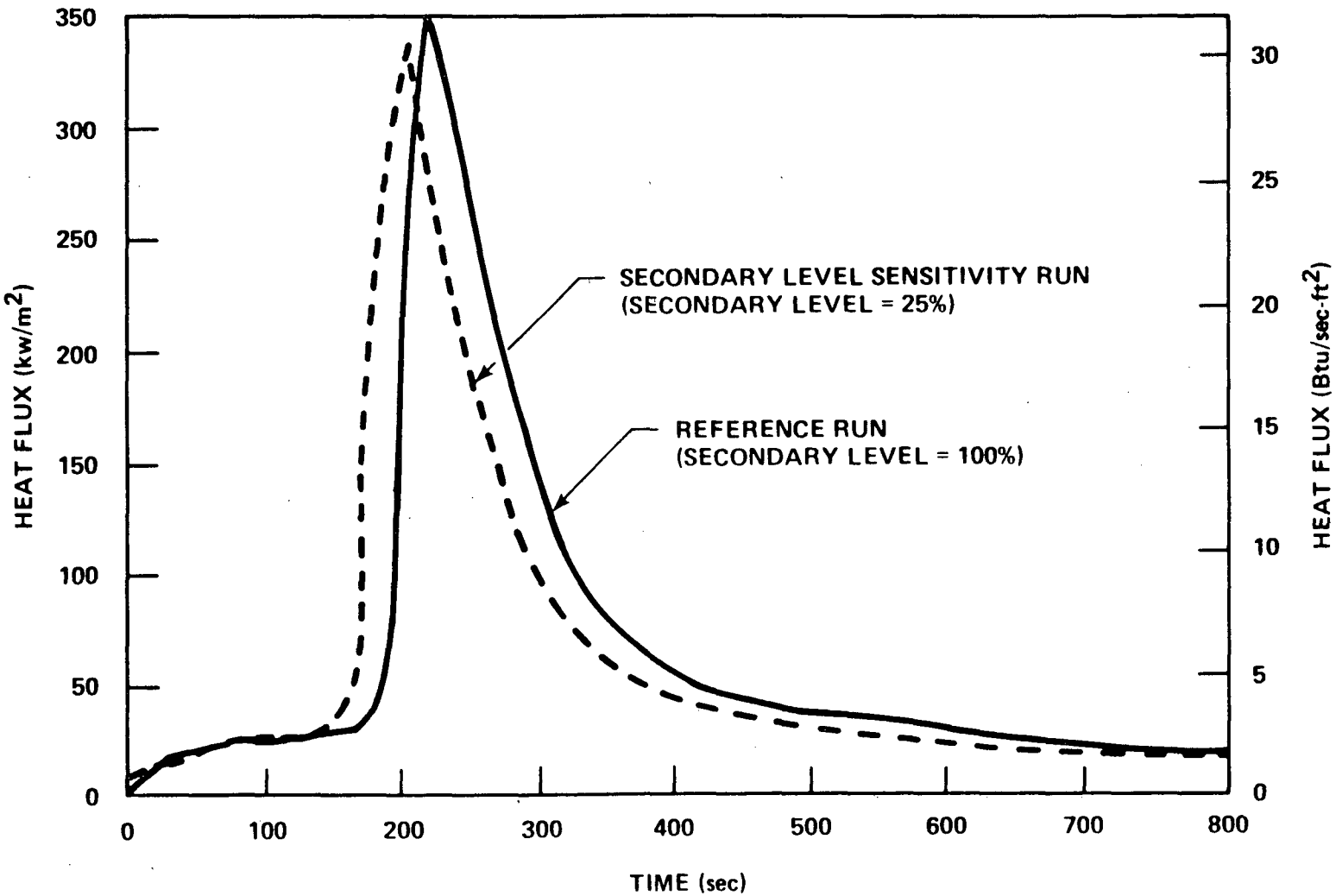


Figure 5-113. Tube Wall Heat Flux, Reference and Secondary Level Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 1

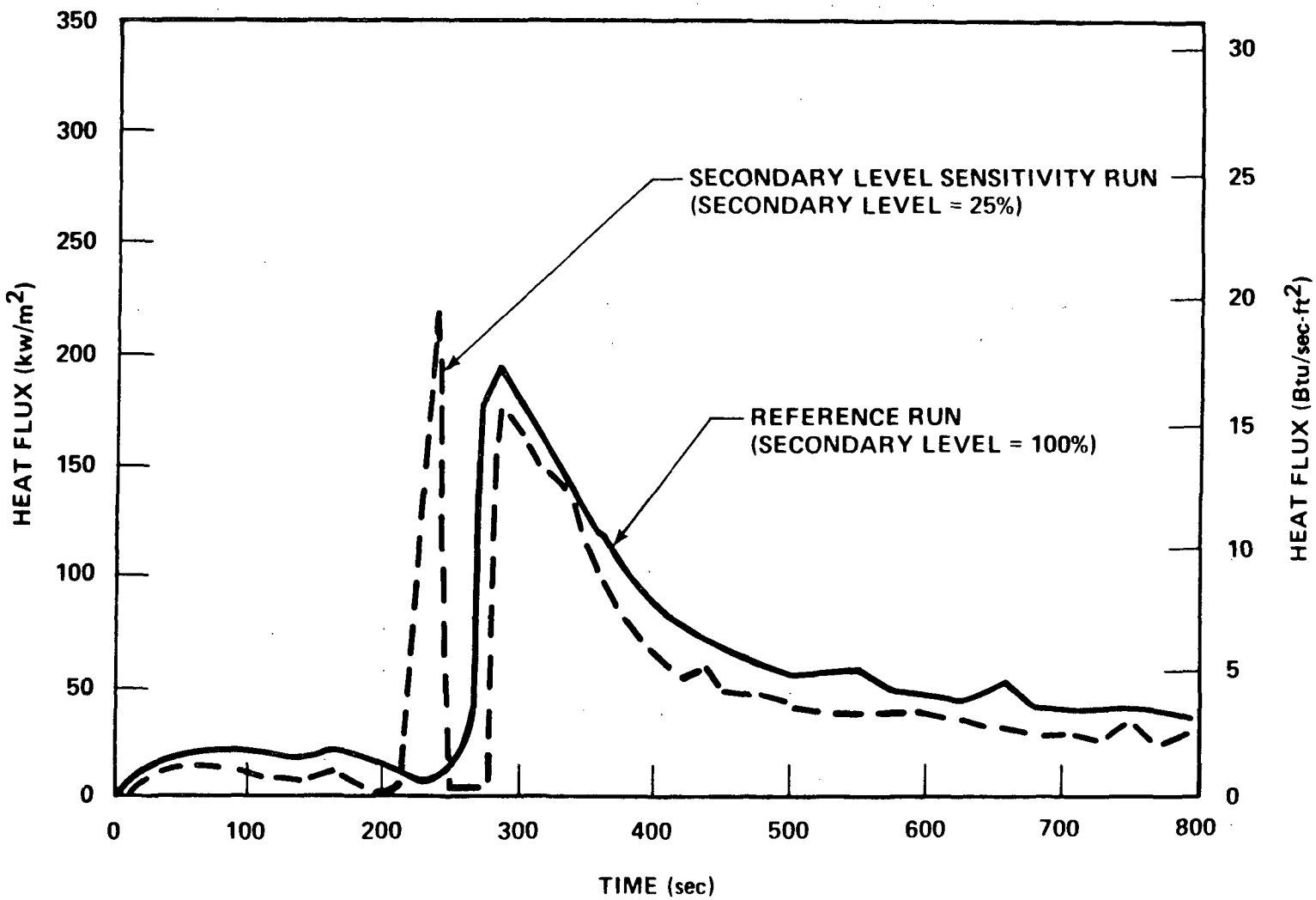


Figure 5-114. Local Heat Flux, Reference and Secondary Level Sensitivity Runs, 0.30 m (1 ft) Elevation, Radial Position 4

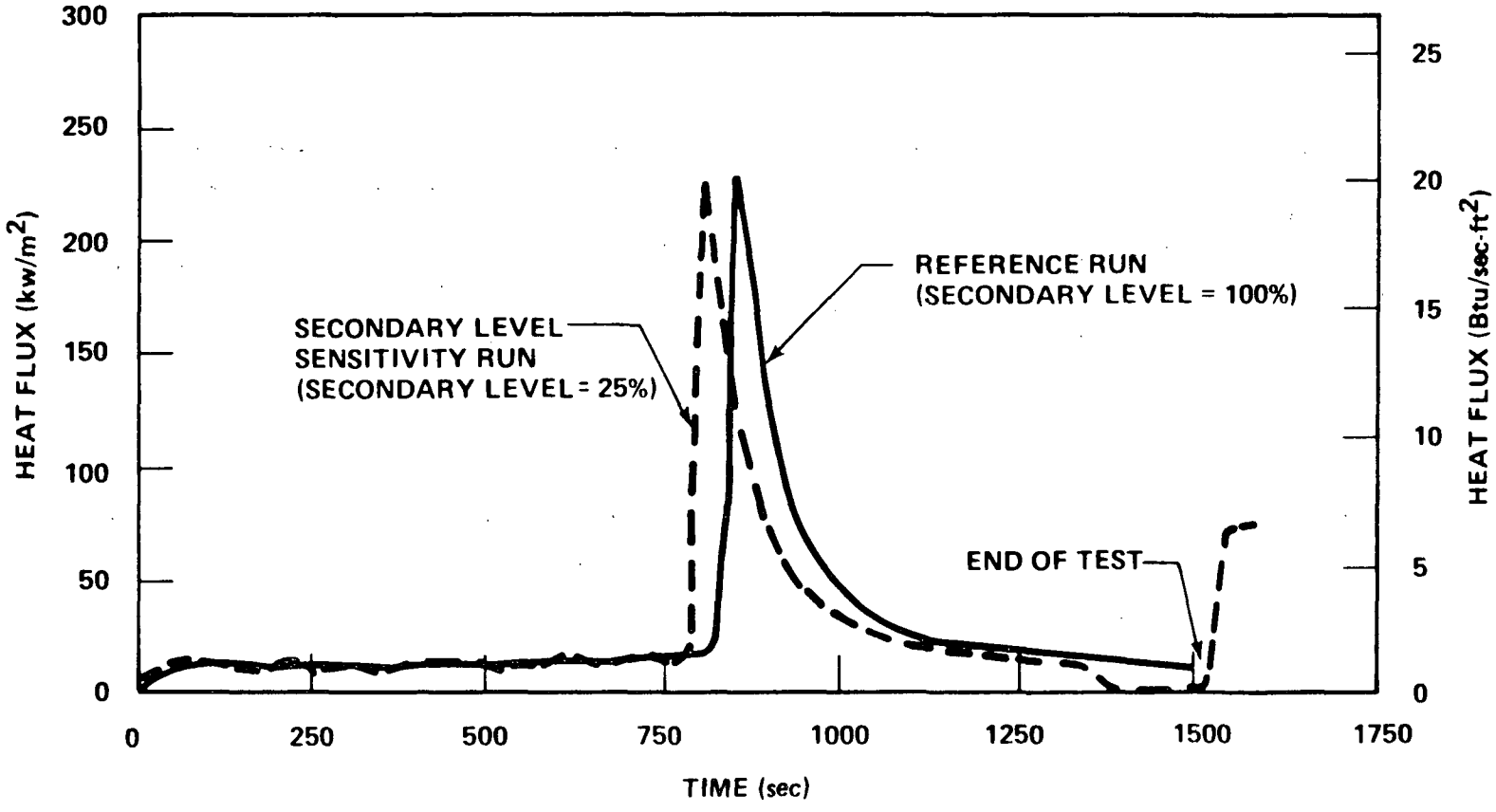


Figure 5-115. Tube Wall Heat Flux, Reference and Secondary Level Sensitivity Runs, 1.22 m (4 ft) Elevation, Radial Position 1

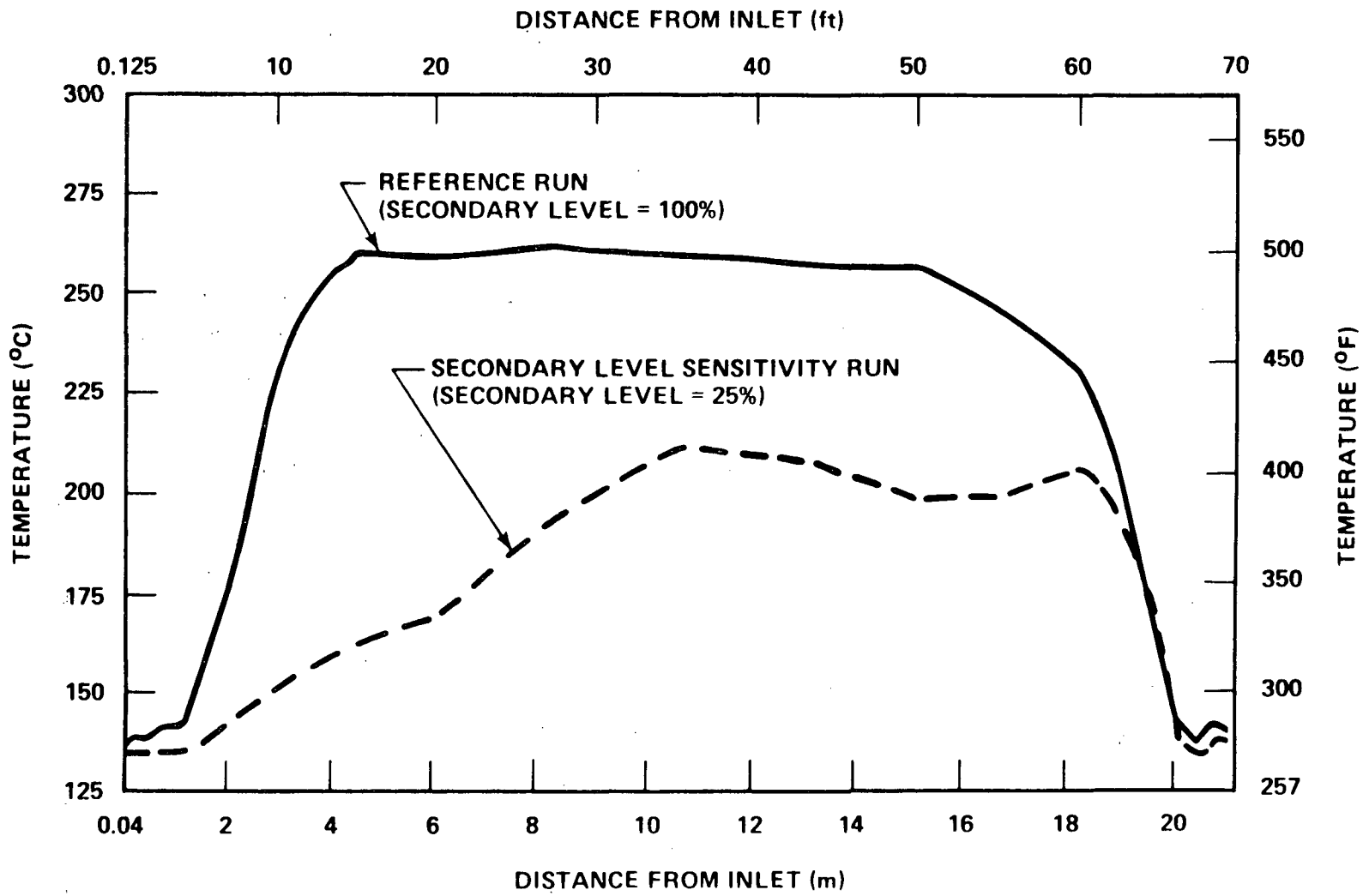


Figure 5-116. Fluid Temperature, Reference and Secondary Level Sensitivity Runs, End of Test, Radial Position 1

16817-29

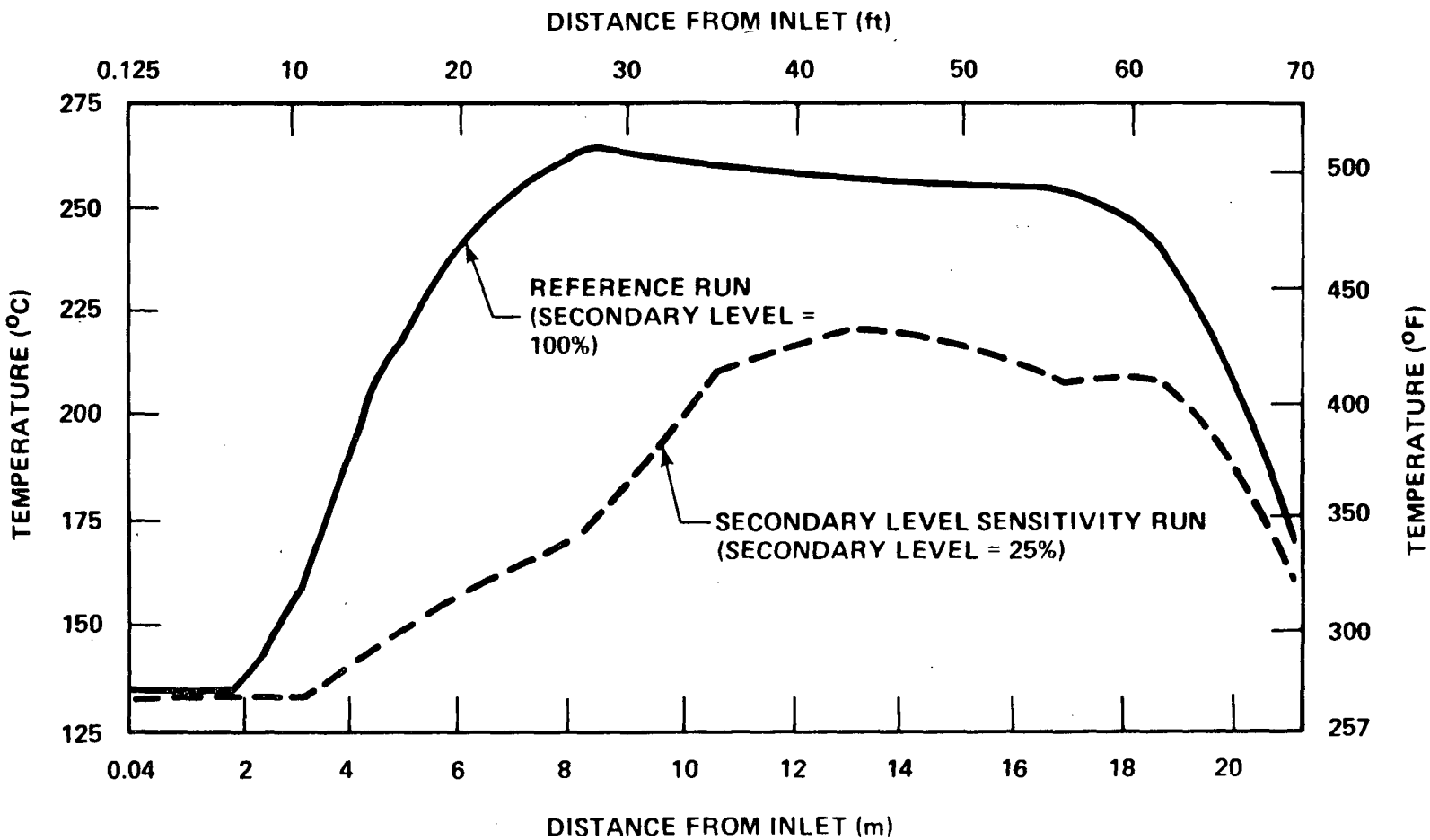


Figure 5-117. Steam Temperature, Reference and Secondary Level Sensitivity Runs, End of Test, Radial Position 1

16817-28

atures shown in figure 5-117 also indicate that the steam temperatures were significantly lower in the low secondary water level run.

Figure 5-118 illustrates the outlet plenum liquid collection in the two runs, as measured by the outlet plenum liquid collecton D/P cell. Also shown in figure 5-118 is the liquid collection in the replicate reference run 21711. As discussed in paragraph 5-3, the liquid collection data in run 22010 (close to the liquid collection from all reference runs and representative of the reference runs) are believed to be more accurate than the liquid collection data in run 22701. Therefore the data trend in figure 5-118 shows that the liquid carryover increased with the reduction in the secondary liquid level. This trend is consistent with the steam probe data trend shown in figure 5-117. The lower steam temperature evaporated a smaller fraction of the entrained drop above the quench front, resulting in more liquid in the outlet plenum.

The average outlet plenum quality, based on the figure 5-118 data for run 22608, was 98.7 percent. This quality is not significantly different from the 99 percent outlet plenum quality during the reference run.

Figures 5-119 and 5-120 show the sensitivity of the overall bundle pressure drop and heat transfer to secondary level. Both of these parameters are essentially independent of the secondary level variation over the range of 25 to 100 percent.

5-10. TUBESHEET LIQUID-PHASE FLOW DISTRIBUTION EFFECTS

In the test matrix (table 4-1), runs 12, 13, 14, and 15 had the same boundary conditions as the reference run and the flow and quality sensitivity runs. However, the liquid injection spray nozzle was located in the inlet plenum at a distance 0.25 m (10 in.) below the tube bundle entrance. A small diffusing screen was attached to the spray nozzle to homogenize the liquid drops in the inlet plenum as much as possible. By comparing runs 12, 13, 14, and 15 with the corresponding test with the spray nozzle upstream of the inlet plenum, the effect of the radial distribution of the liquid phase at the tubesheet can be evaluated. The air/water inlet plenum flow distribution tests described in appendix B of Report No. 4 include tests with the spray nozzle in the same configuration in the inlet plenum as in runs 12, 13, 14, and 15.

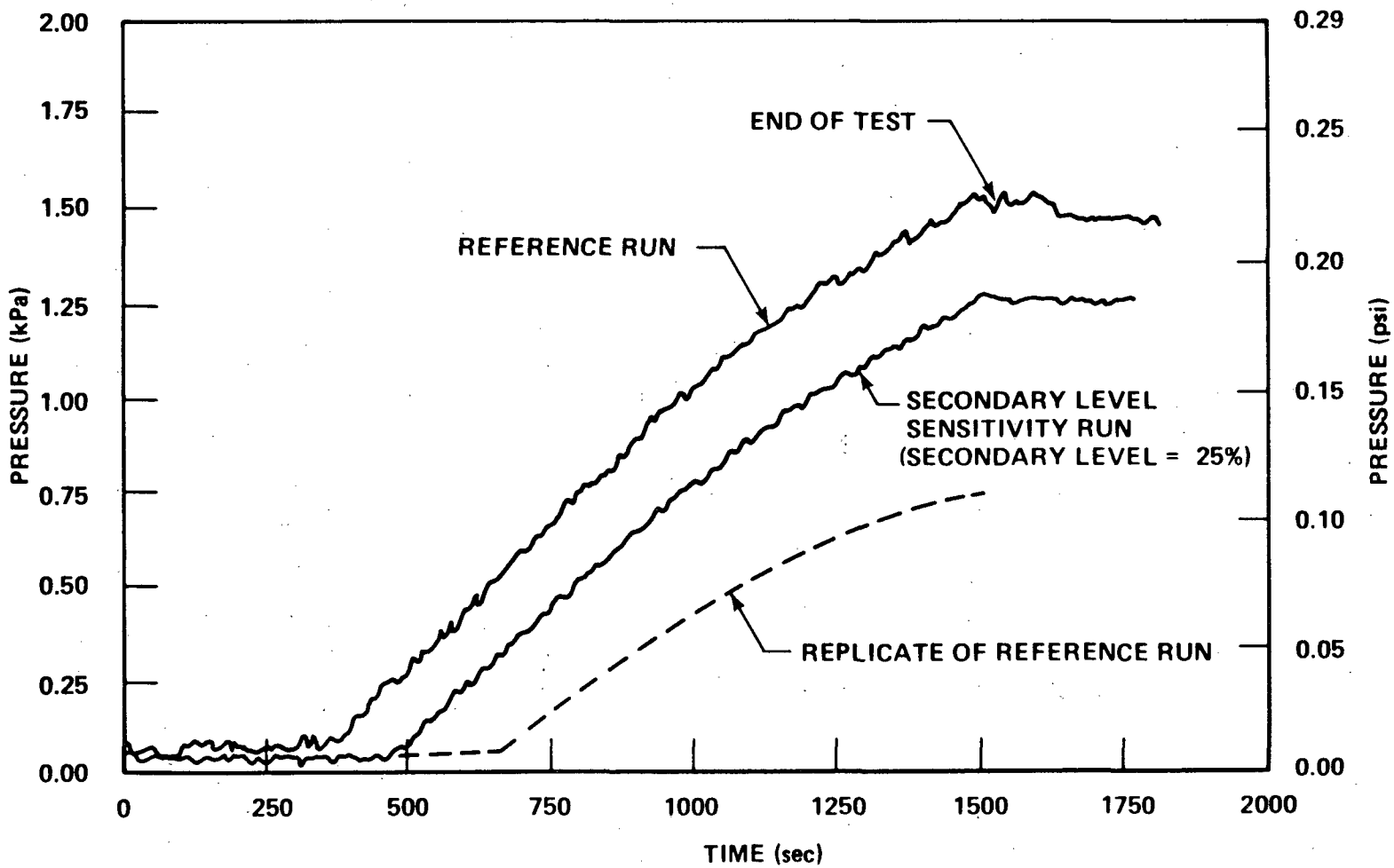


Figure 5-118. Outlet Plenum Liquid Collection, Reference, Replicate, and Secondary Level Sensitivity Runs

16817-55

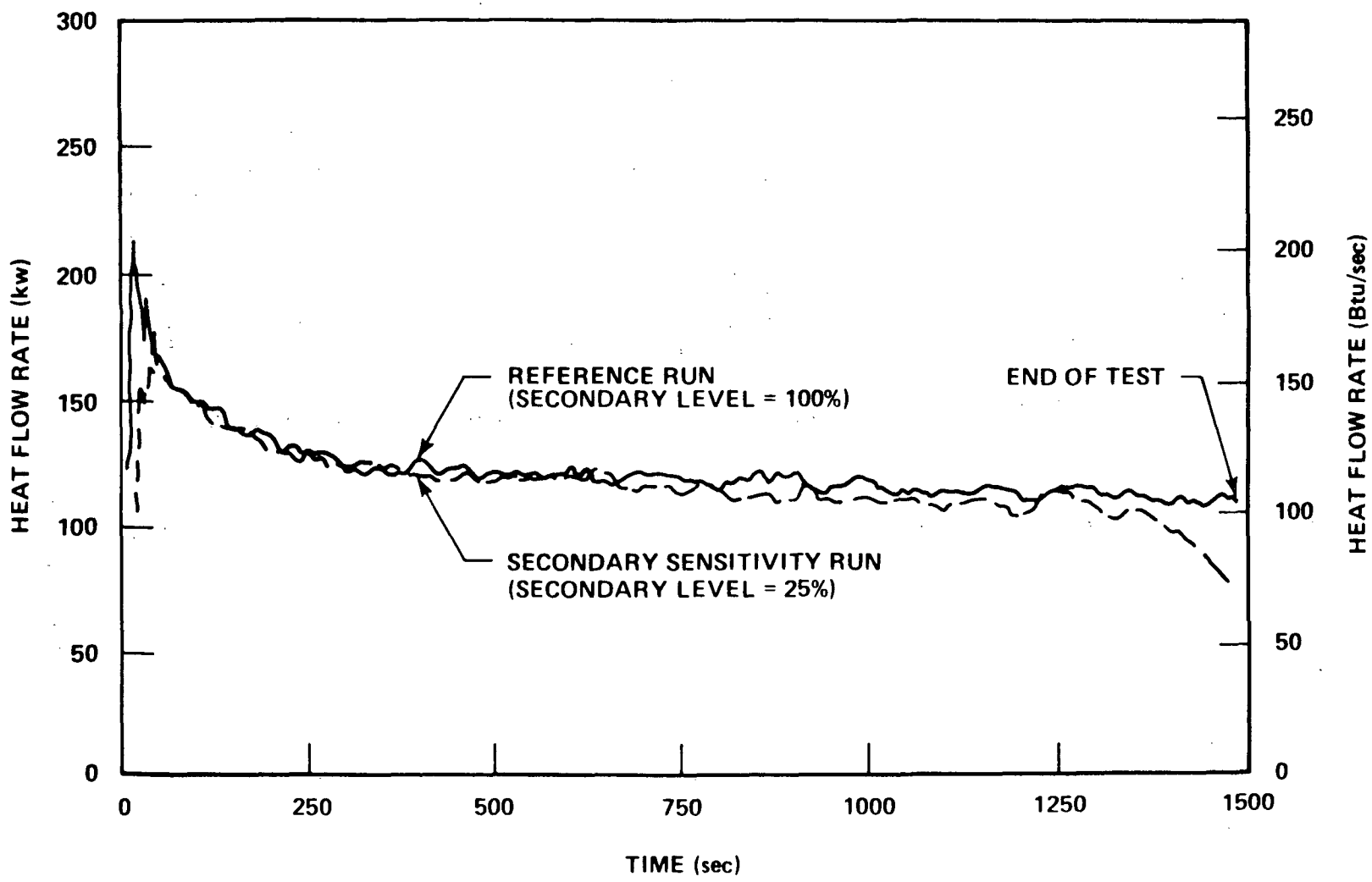


Figure 5-119. Overall Bundle Heat Transfer, Reference and Secondary Level Sensitivity Runs

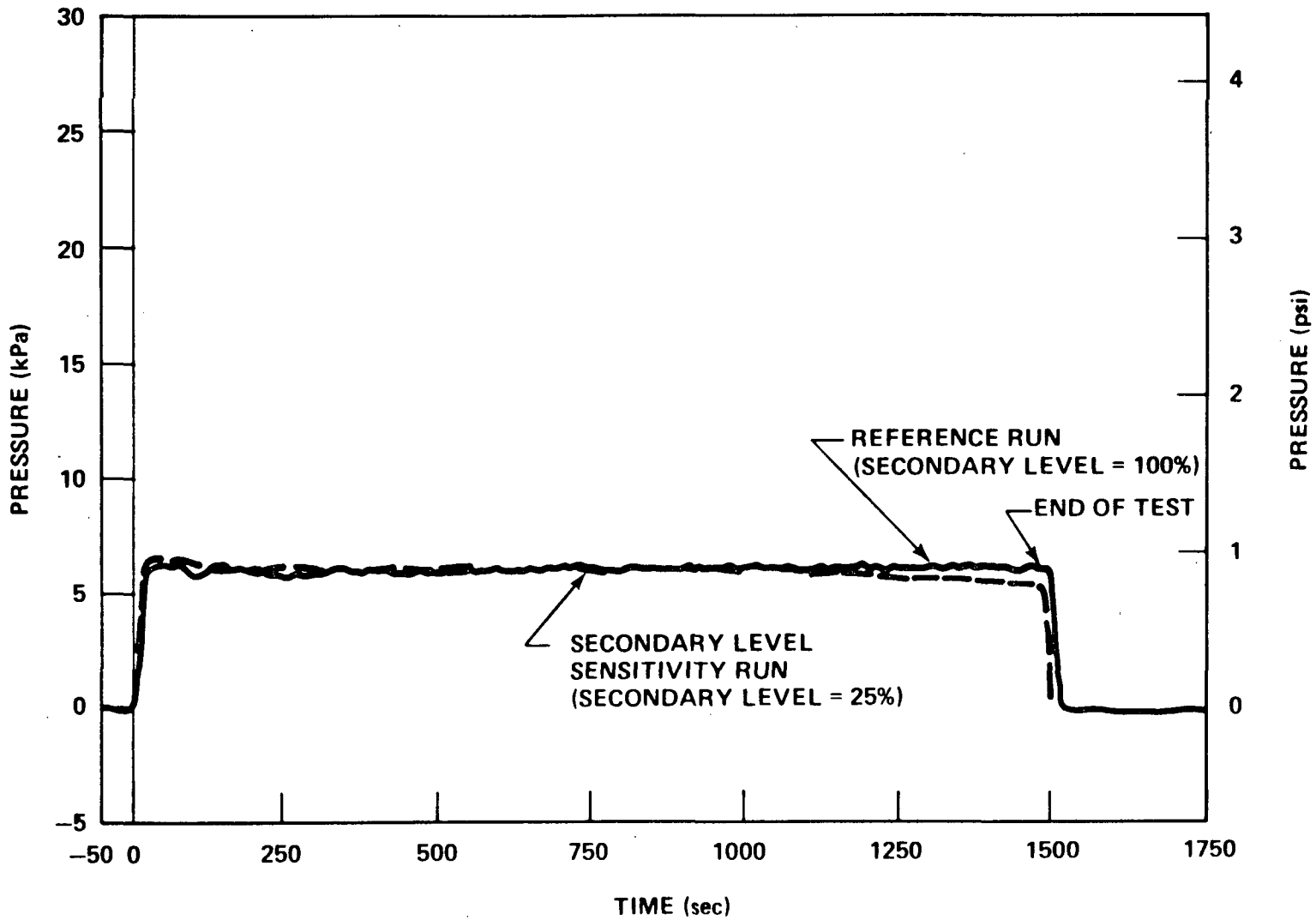


Figure 5-120. Overall Bundle Pressure Drop, Reference and Secondary Level Sensitivity Runs

16817-59

In table 5-9 the effects of the spray nozzle location on the outlet plenum liquid collection, the 1.22 m (4 ft) quench time, and the average bundle heat transfer are compared. These results show that the overall steam generator response is very insensitive to the tubesheet liquid-phase flow distribution.

The local heat flux plots in figures 5-121 through 5-123 can be compared with the local heat fluxes in figures 5-36, 5-38, and 5-39 to compare the two distributions at the reference test boundary conditions. These comparisons show that the radial position 1 fluxes are lower and the radial position 4 fluxes are higher in run 22112 than in the reference run. These trends in the local heat flux distribution imply that the liquid distribution increased in radial position 4 in run 22112. Results from the air/water tests reported in appendix B of Report No. 4 are consistent with these trends. However, the air/water test data for the liquid distribution with the inlet plenum spray nozzle shows radial position 1 with a larger liquid flow rate than radial position 4. The local heat fluxes in figures 5-121 and 5-122 imply that radial position 4 has a higher liquid flow rate than radial position 1.

Figures 5-124 through 5-126 illustrate the local tube wall heat flux for radial positions 1 and 4 at 0.30 m (1 ft) and for radial position 1 at 1.22 m (4 ft) for the flow sensitivity test with the inlet plenum spray nozzle (run 22213). Local fluxes at the 0.30 m (1 ft) elevation with the same boundary conditions without the inlet plenum spray nozzle are plotted in figures 5-77 and 5-78 (run 23402). A comparison of these plots indicates the same trend as the comparison at the reference run boundary condition. The air/water test data have a consistent trend in increasing the liquid flow at radial position 4 when the spray nozzle was relocated to the inlet plenum, although the air/water data with the inlet plenum nozzle continue to indicate a higher relative flow in radial position 1 than in radial position 4.

Possible factors that could account for a discrepancy in the inlet plenum liquid distribution between the air/water tests and the heat transfer tests include the following:

Spray pattern differences between air/water and steam/water test conditions due to evaporation or condensation

TABLE 5-9

TUBESHEET LIQUID-PHASE FLOW DISTRIBUTION EFFECTS

Run Type	Parameter Comparison	Value at Indicated Spray Nozzle Location	
		Hot Leg	Inlet Plenum
Reference[a]	Outlet plenum liquid collection	2.15 kg (4.74 lb)	2.28 kg (5.02 lb)
Flow sensitivity	Outlet plenum liquid collection	4.94 kg (10.9 lb)	0.91 kg (2.0 lb)
Quality sensitivity (x=50%)	Outlet plenum liquid collection	10.1 kg (22.2 lb)	7.98 kg (17.6 lb)
Quality sensitivity (x=20%)	Outlet plenum liquid collection	65.2 kg (143.8 lb)	66.21 kg (146.0 lb)
Reference[a]	Overall heat transfer rate[b]	126 kw (120 Btu/sec)	125 kw (119 Btu/sec)
Flow sensitivity	Overall heat transfer rate[b]	235 kw (223 Btu/sec)	254 kw (241 Btu/sec)
Quality sensitivity (x=50%)	Overall heat transfer rate[b]	236 kw (224 Btu/sec)	236 kw (224 Btu/sec)
Quality sensitivity (x=20%)	Overall heat transfer rate[b]	334 kw (317 Btu/sec)	358 kw (340 Btu/sec)
Reference[a]	1.22 m (4 ft) quench time	800 sec	800 sec
Flow sensitivity	1.22 m (4 ft) quench time	305 sec	300 sec
Quality sensitivity (x=50%)	1.22 m (4 ft) quench time	320 sec	320 sec
Quality sensitivity (x=20%)	1.22 m (4 ft) quench time	330 sec	330 sec

a. Run 21711 used as reference run

b. Heat transfer rate averaged over the 0 to 1000 sec interval

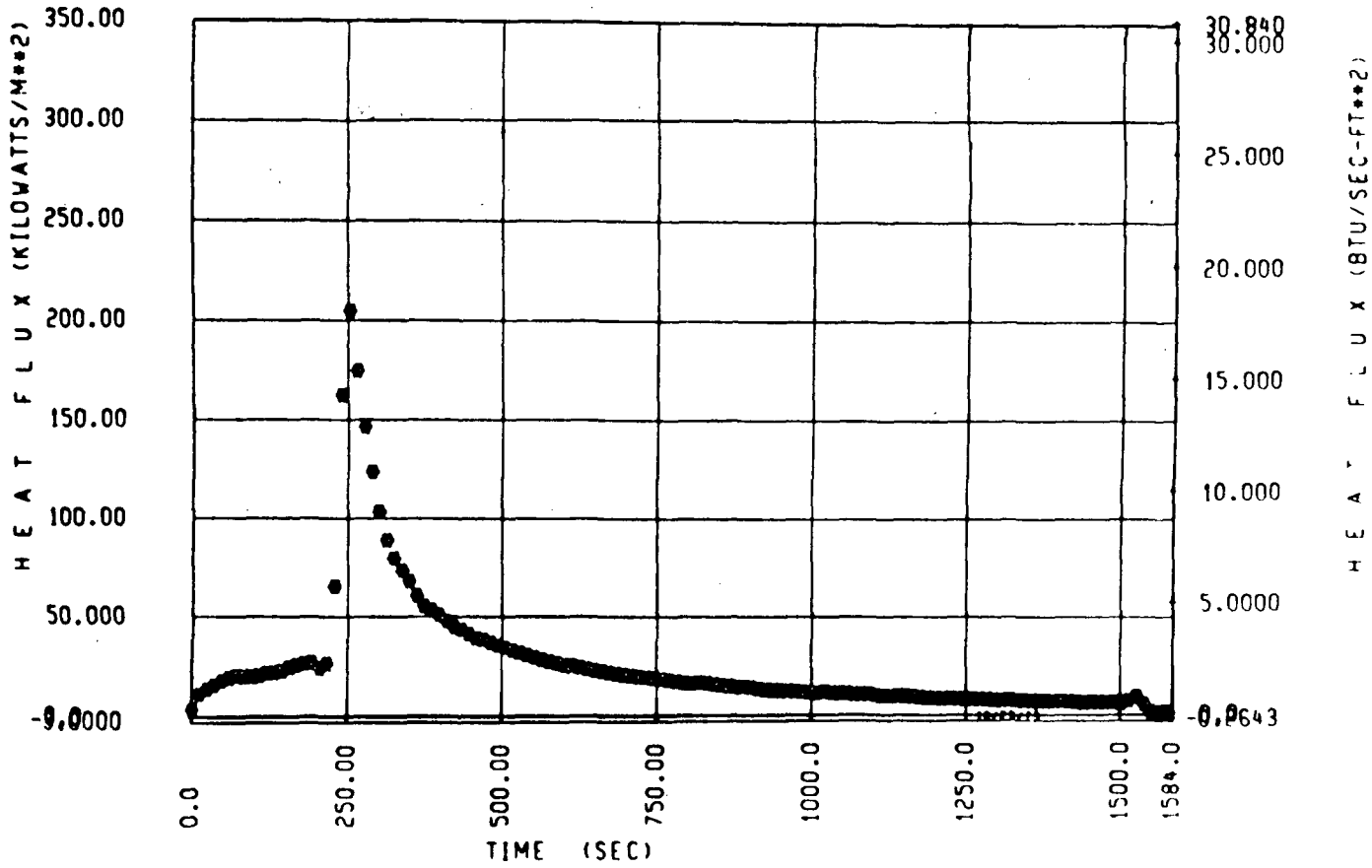


Figure 5-121. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22112, 0.30 m (1 ft) Elevation, Radial Position 1

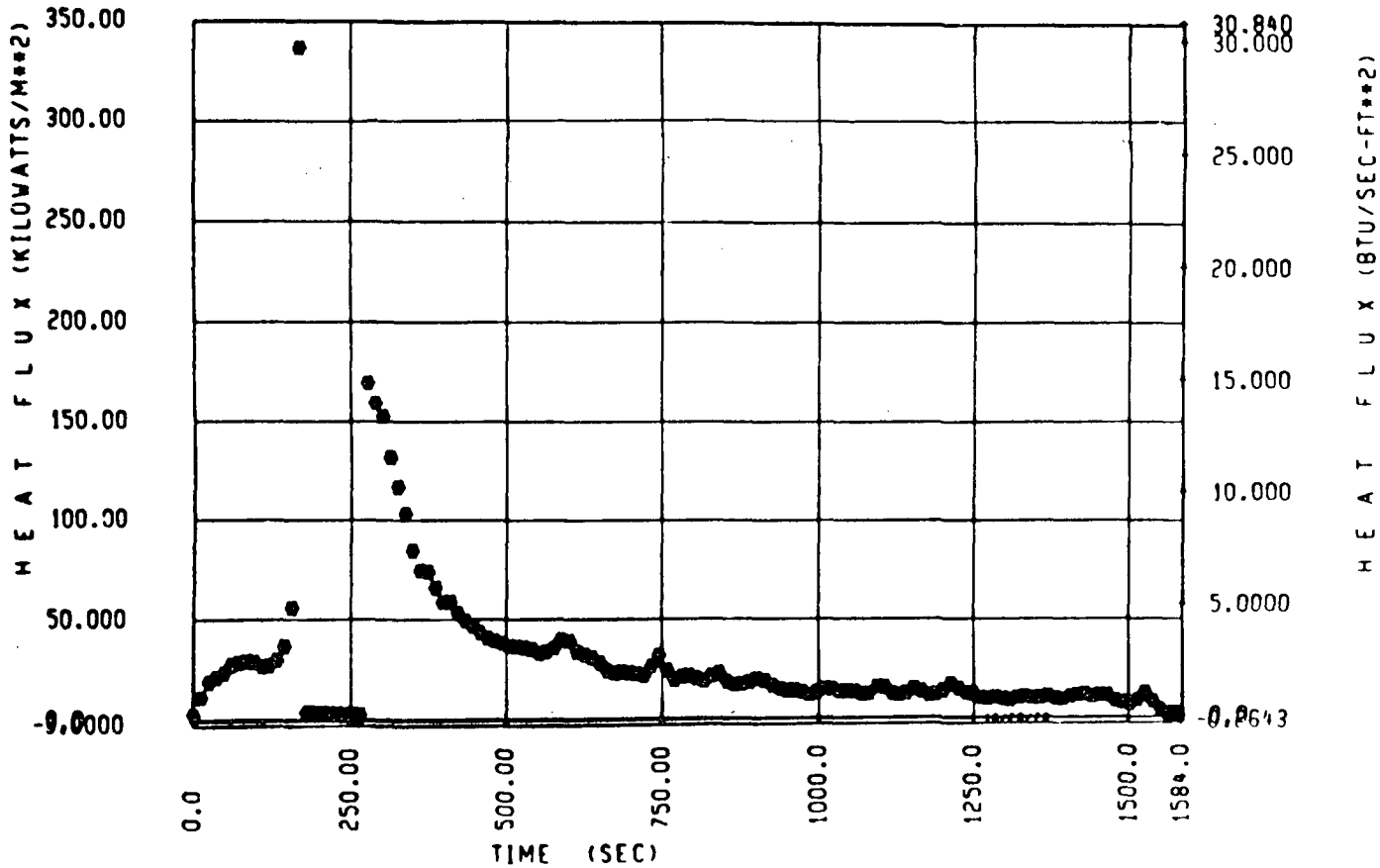


Figure 5-122. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22112, 0.30 m (1 ft) Elevation, Radial Position 4

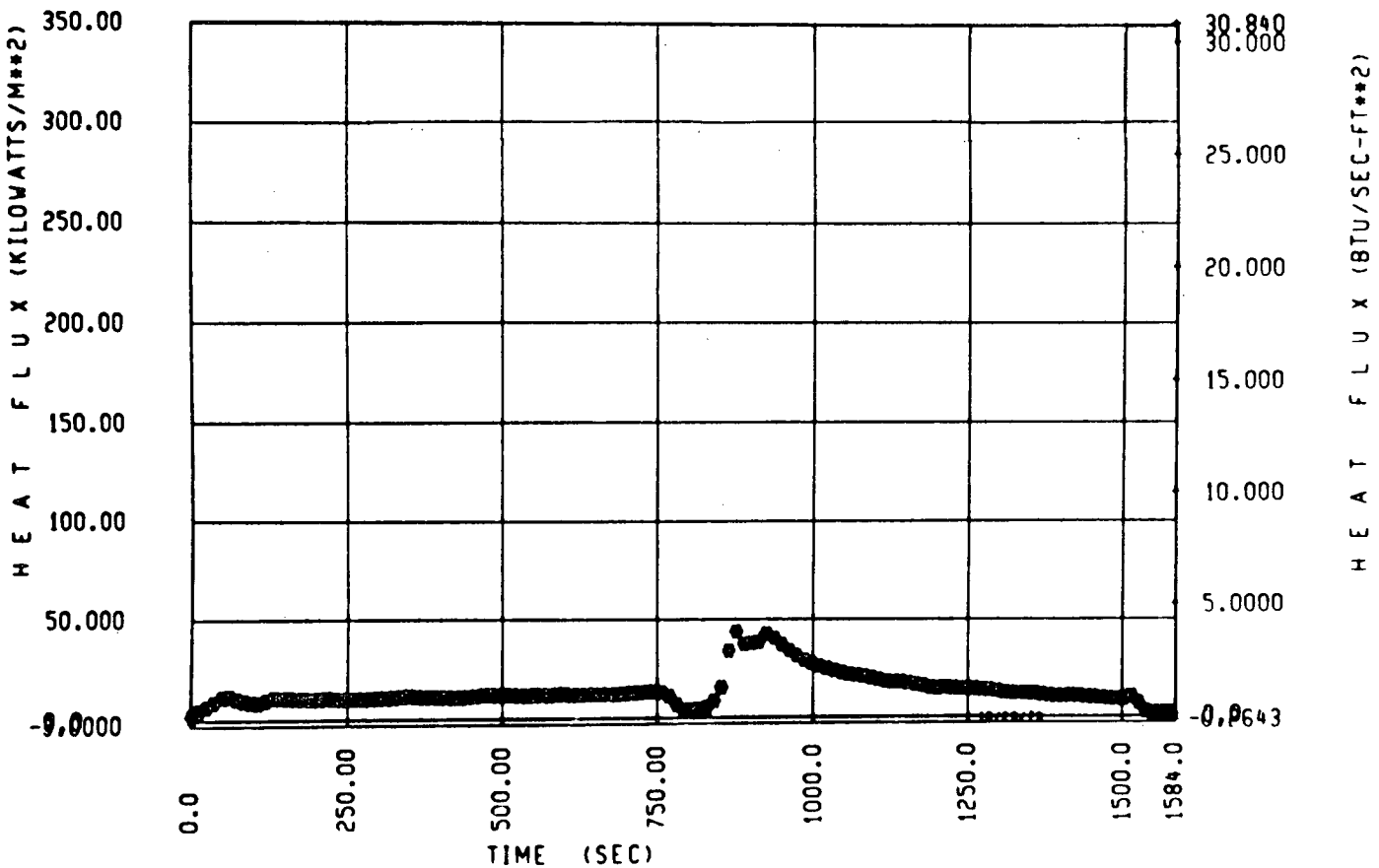


Figure 5-123. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22112, 1.22 m (4 ft) Elevation, Radial Position 1

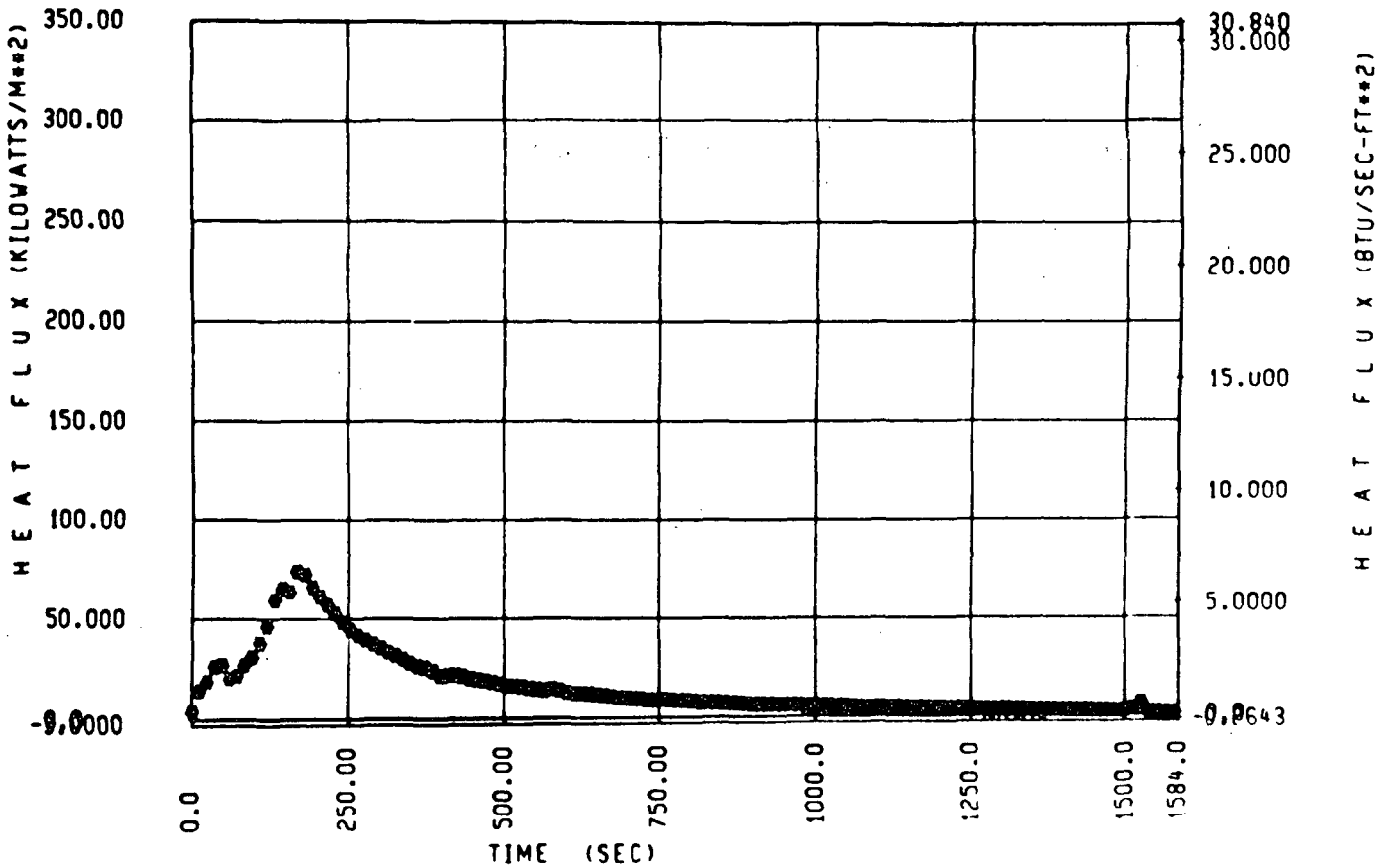


Figure 5-124. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22213, 0.30 m (1 ft) Elevation, Radial Position 1

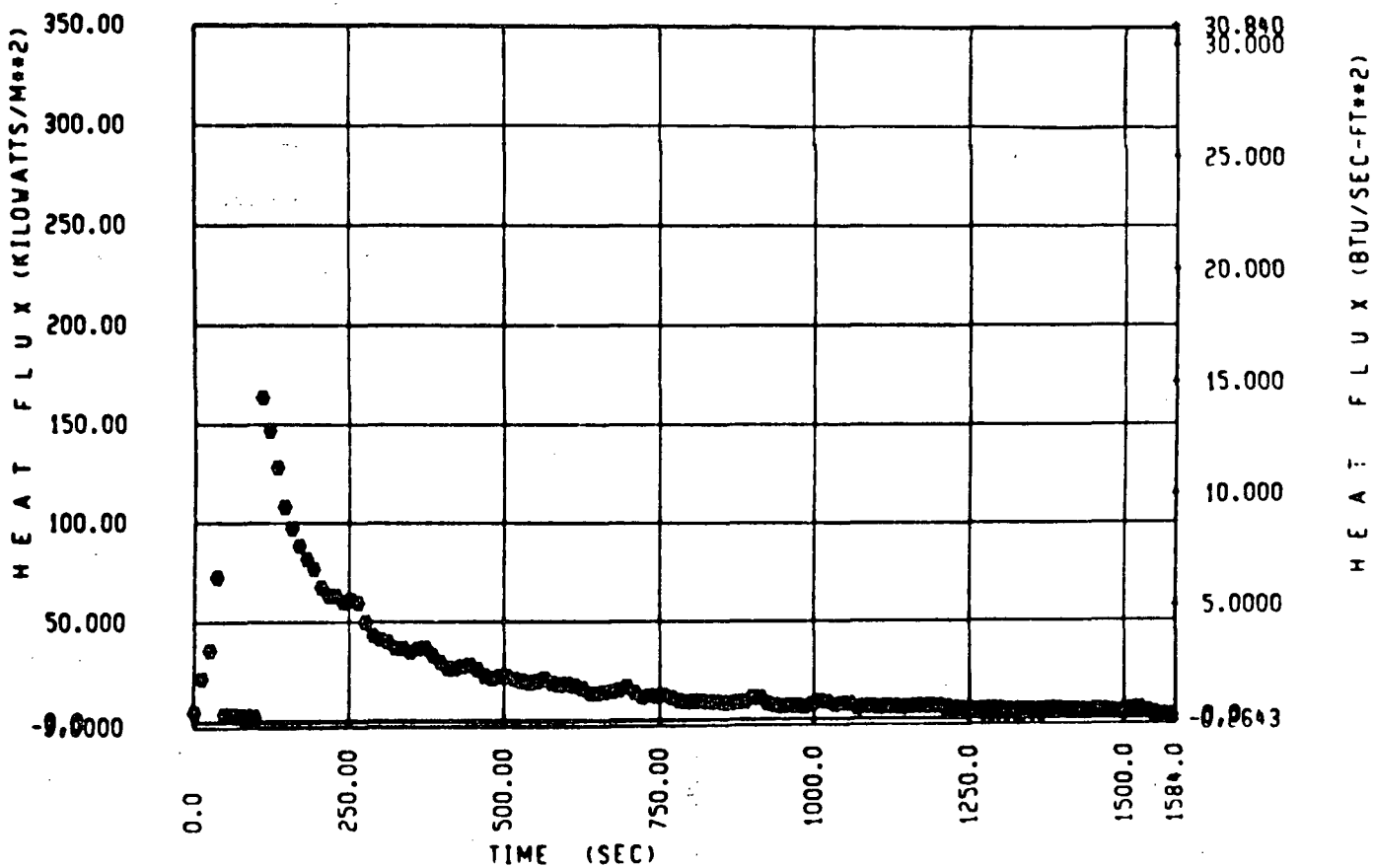


Figure 5-125. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22213, 0.30 m (1 ft) Elevation, Radial Position 4

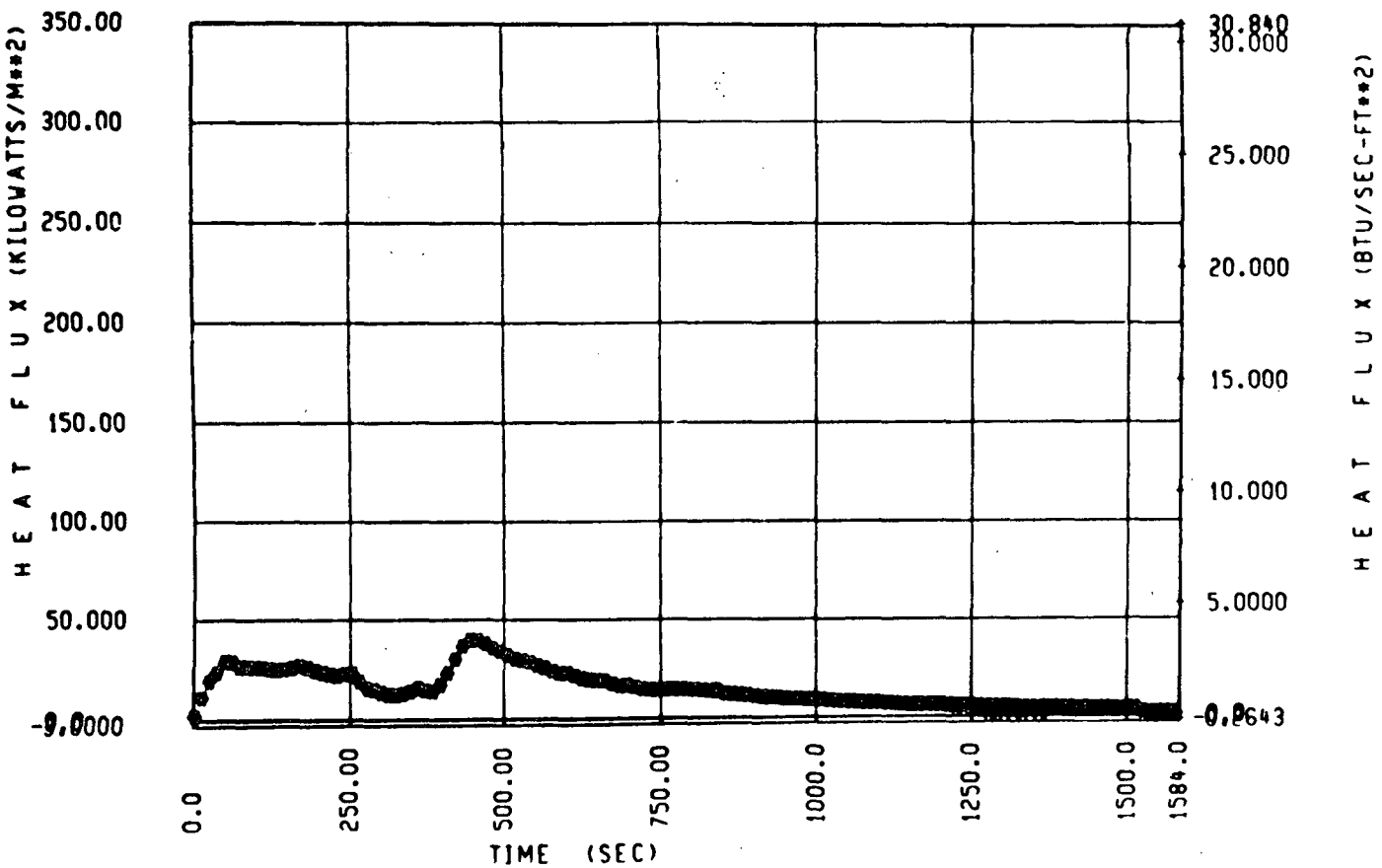


Figure 5-126. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22213, 1.22 m (4 ft) Elevation, Radial Position 1

-- Droplet characteristic changes due to property changes (that is, droplet diameter, drag)

-- Spray distribution differences due to spray nozzle position differences between the air/water test and the heat transfer test

Figures 5-127 through 5-129 are plots of the local flux for radial positions 1 and 4 at the 0.30 m (1 ft) elevation and radial position 1 at the 1.22 m (4 ft) elevation. These figures show the local flux for the 50-percent inlet quality boundary condition with the inlet plenum spray nozzle. These plots also indicate that the radial position 4 liquid flow rate increases when the spray nozzle is mounted in the inlet plenum.

Figures 5-130 through 5-132 show the local flux for the same three locations as for the 20-percent inlet plenum quality boundary condition. The same trends are present. Higher flux peaks in radial position 4 imply a higher liquid flow in radial position 4 than in radial position 1. The flux plot in figure 5-132 appears to have two flux peaks, one at 250 seconds and a second at 850 seconds. The second peak is caused by a peculiar step increase in the secondary fluid temperature at 850 seconds. The 1.22 m (4 ft) inlet fluid thermocouples were recorded on data channels 308, 309, 310, and 311. In run 22415, only channel 308 was operational and from run 22920 on, channel 308 was also identified as a bad channel. The response of channel 308 in run 22415 is characteristic of a shorted thermocouple, where the short occurs at a point where the sheath is hotter than the junction. After the thermocouple lead is shorted to the hot sheath, the indicated temperature represents the average of the temperatures at the junction and at the short. Therefore, the second flux peak shown in figure 5-132 is believed to represent an early indication of the eventual failure of channel 308.

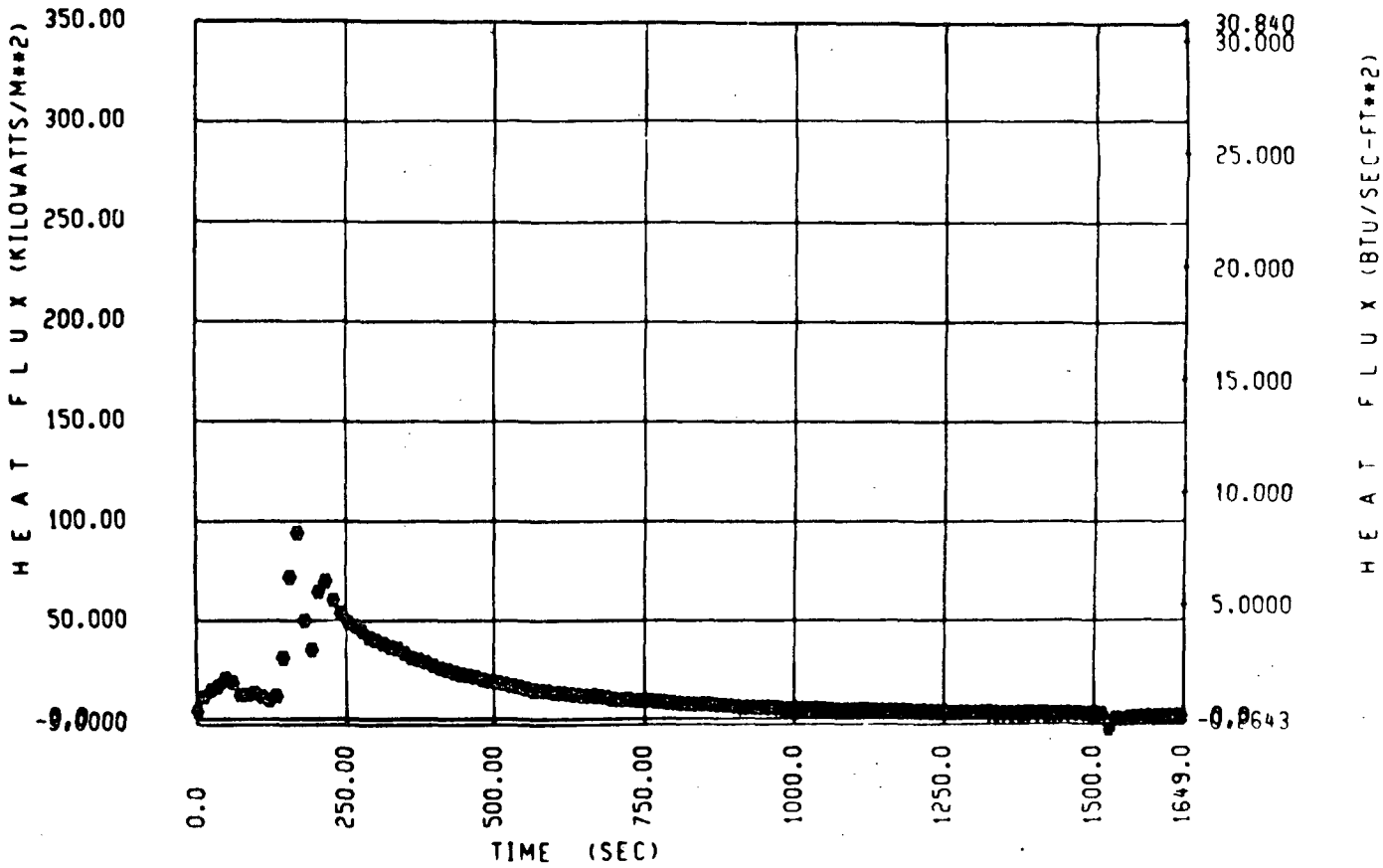


Figure 5-127. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22314, 0.30 m (1 ft) Elevation, Radial Position 1

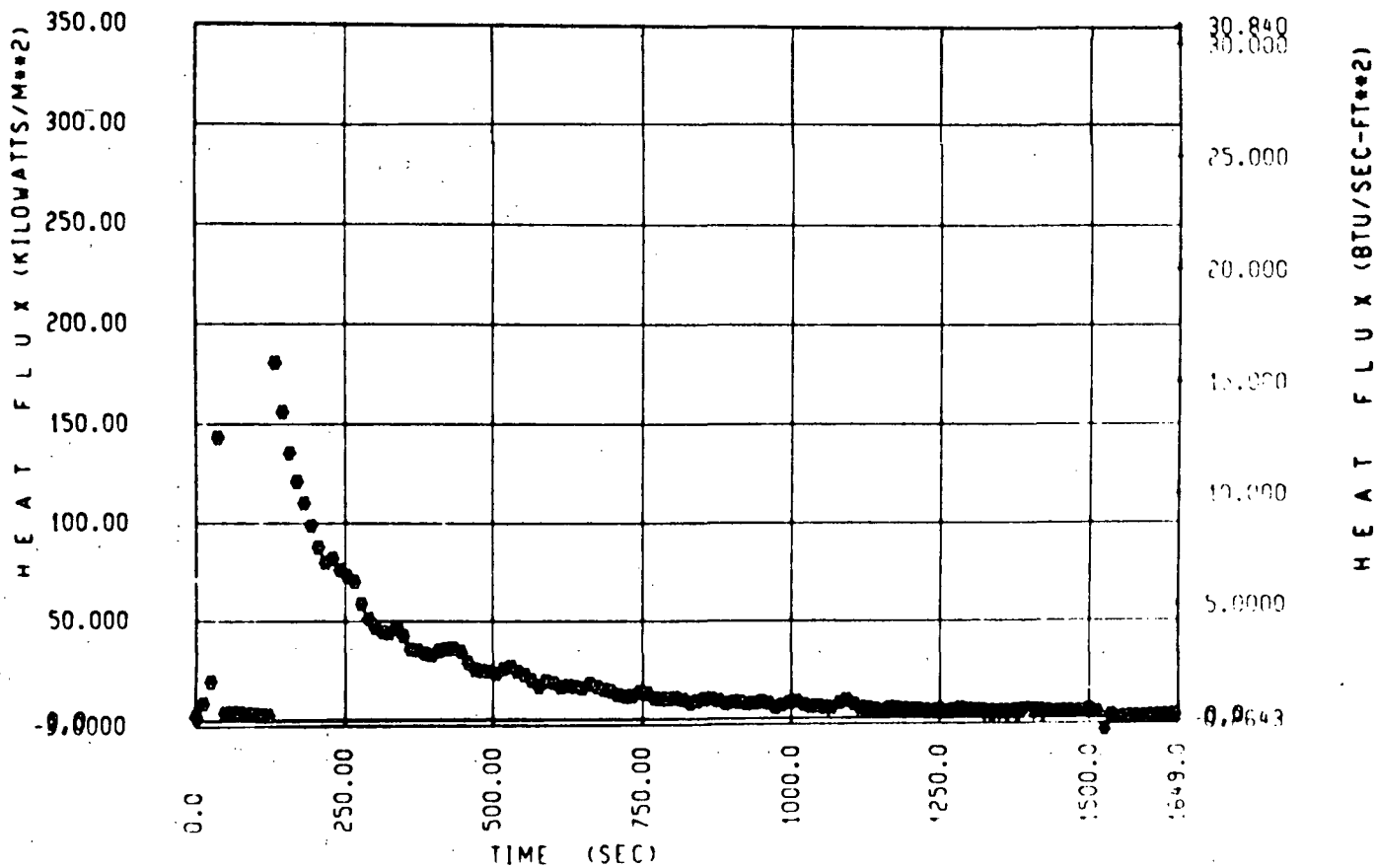


Figure 5-128. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22314, 0.30 m (1 ft) Elevation, Radial Location 4

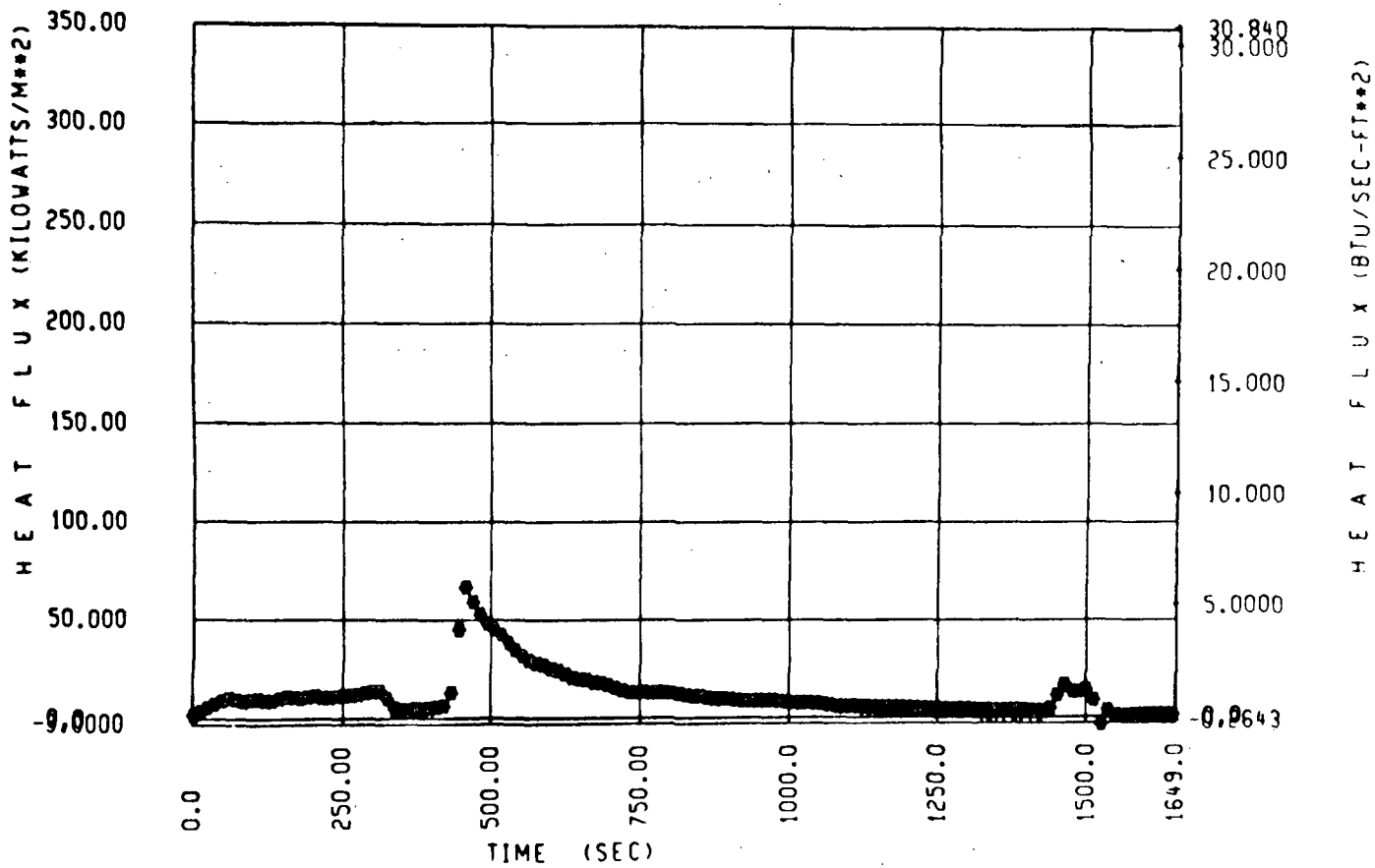


Figure 5-129. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22314, 1.22 m (4 ft) Elevation, Radial Position I

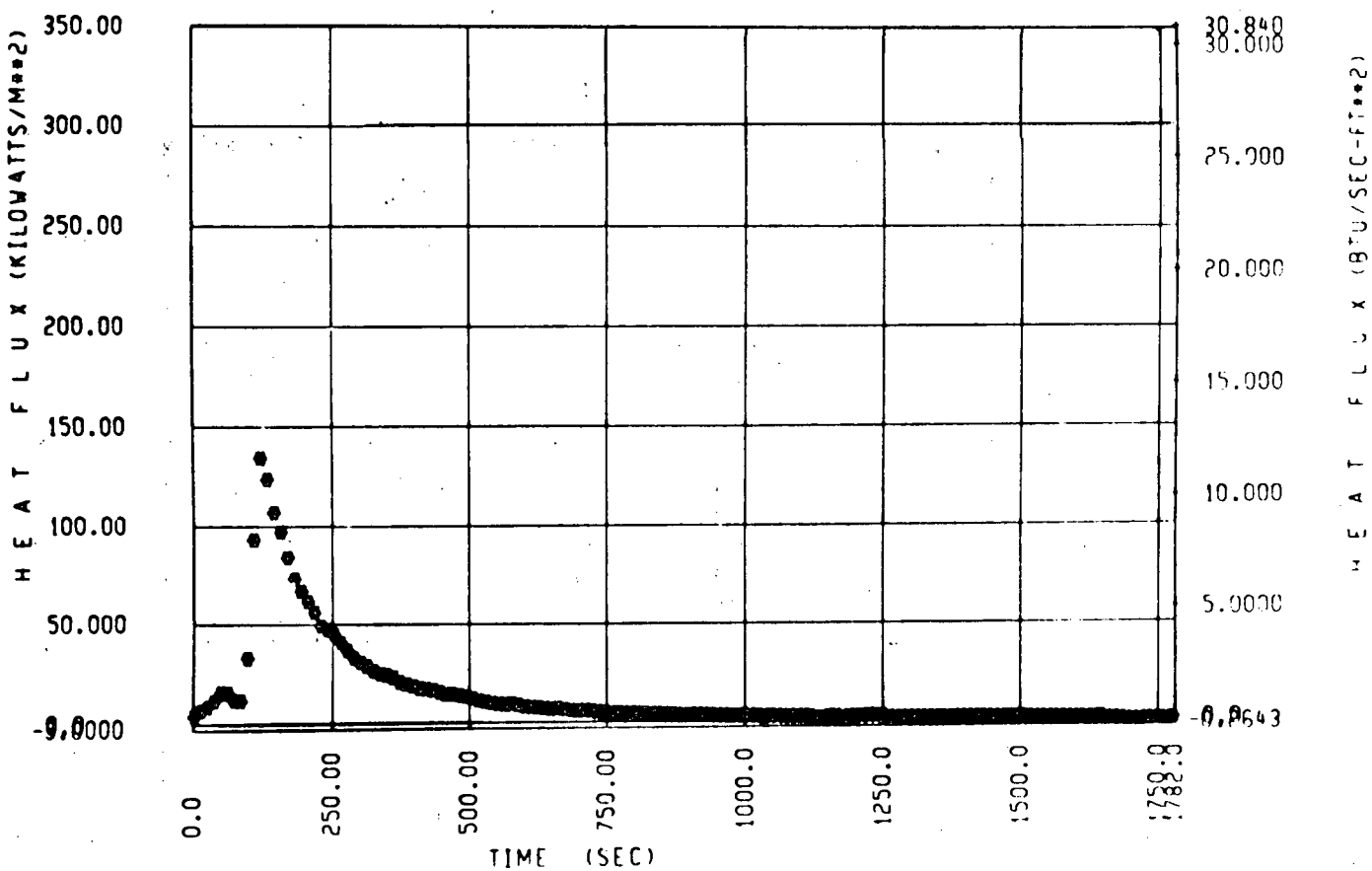


Figure 5-130. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22415, 0.30 m (1 ft) Elevation, Radial Position 1

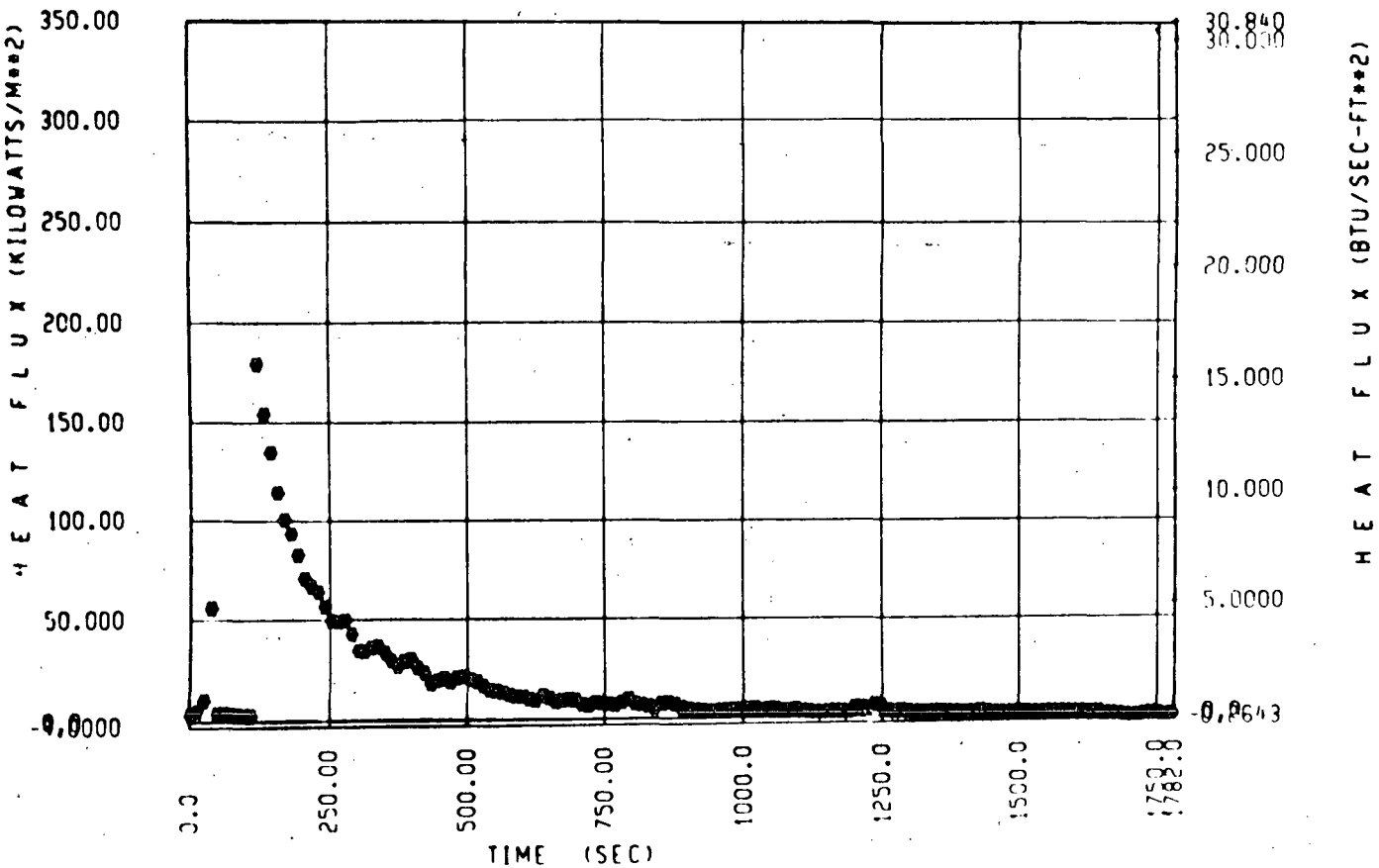


Figure 5-131. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22415, 0.30 m (1 ft) Elevation, Radial Position 4

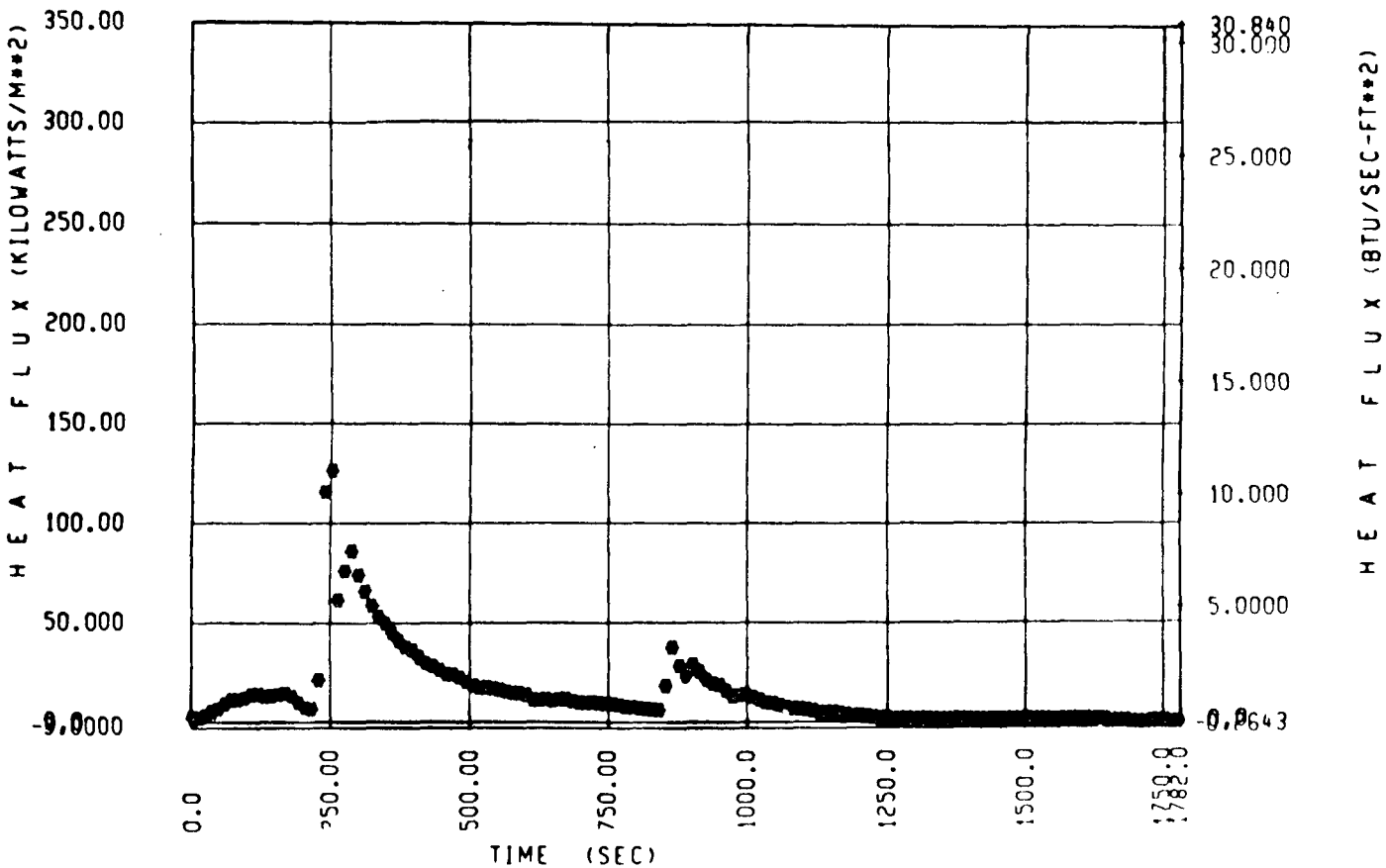


Figure 5-132. Tube Wall Heat Flux With Inlet Plenum Spray Nozzle, Run 22415, 1.22 m (4 ft) Elevation, Radial Position 1

SECTION 6
EVALUATION MODEL

6-1. STEAM GENERATOR EVALUATION MODEL DEVELOPMENT

Several attempts were made to develop a steam generator evaluation model, as described in the following paragraphs.

6-2. Evaluation Model Based on Local Liquid Film Parameters

Development of a mathematical model to describe the steam generator response began with a literature search for methods to predict the quench elevation. A potentially promising reference was found[1] for predicting dryout in a heated vertical tube based on calculations of the liquid film mass flow rate. In this model the flow regime at the tube entrance is assumed to be annular flow with no entrained drops. The liquid flow is depleted because of evaporation and droplet entrainment. Droplet deentrainment, is also calculated. This method calculates the liquid film flow rate and uses correlations to treat film depletion due to droplet entrainment, deentrainment, and evaporation. The dryout position is predicted as the elevation where the film flow rate goes to zero or the film thickness is less than the critical film thickness. The recommended critical film thickness criteria are taken from Zuber and Staub.[2]

A computer program was written following the model described by El-Shanawany, et al., to calculate the dryout elevation on the primary side of the steam generator tube bundle. The results from this computer program for the reference run parameters were that the critical film thickness criteria were exceeded at the tube entrance.

---

1. El-Shanawany, M., et al., "A Model for Predicting the Dry-Out Position for Annular Flow in a Uniformly Heated Vertical Tube," Int. J. Heat Mass Transfer 21, 529-536 (1978).

2. Zuber, N., and Staub, F. W., "Stability of Dry Patches Forming in Liquid Films Flowing Over Heated Surfaces," Int. J. Heat Mass Transfer 9, 897-905 (1966).

Applying the zero film flow criterion resulted in complete evaporation of the liquid film with negligible entrainment of liquid drops into the vapor core. The test data indicate that the liquid film does become established at the tube entrance and migrates up the inside wall of the tube. Also, the recording of liquid accumulation in the outlet plenum shows that the liquid film is not completely evaporated. Because the calculational results do not agree with the known steam generator test results, use of this model for calculating the dryout elevation was discontinued. A review of the data base for the droplet entrainment correlation used in the above model[1] showed that the mass velocities in the entrainment correlation data base were an order of magnitude larger than the tube bundle mass velocities in the steam generator test.

6-3. Evaluation Model Based on Local Critical Heat Flux

In the second attempt to define a mechanistic model to predict the quench elevation, the calculated local tube wall heat flux was tested against a local effects critical heat flux correlation. In this model the local tube wall heat flux was calculated assuming that a wet film existed on the primary side of the tube. The wet film heat transfer coefficient was calculated using the correlation of Dengler and Addoms.[2] This local heat flux was compared to the critical heat flux predicted by Biasi, et al.[3] If the wall heat flux was less than the critical heat flux, the above assumption of a wet film on the tube wall was taken to be true. If the critical heat flux was less than the calculated wall heat flux, the assumption of a wet film was taken to be false and the wall heat flux was recalculated assuming a dry wall film coefficient. On the secondary side of the tube wall, a turbulent-free convection film coefficient from Eckert and Jackson[4]

---

1. Hutchinson and Whalley, "A Possible Characterization of Entrainment in Annular Flow," AEEE, Harwell, 1972.

2. Dengler, C. C., and Addoms, J. N., "Heat Transfer Mechanism for Vaporization of Water in a Vertical Tube," in Heat Transfer - Louisville (Chemical Engineering Progress Symposium Series, Volume 52, Number 18, pp 95-103), AIChE, New York, 1956.

3. Biasi, L., et al., "Studies on Burnout, Part 3. A New Correlation for Round Ducts and Uniform Heating and Its Comparison With World Data," Energ. Nucl. 14, 530-536 (1967).

4. Eckert, E. R. G., and Jackson, T. W., Analysis of Turbulent Free-Convection Boundary Layer on Flat Plate, NACA-1015, 1951.

was used. The secondary fluid was assumed to be stagnant and the heat flux from the secondary fluid to the tube wall was assumed to deplete the stored energy in the secondary fluid. The secondary fluid stored energy was modeled as a lumped parameter with one uniform characteristic secondary fluid temperature defined for each secondary node. The film coefficients and the critical heat flux correlation are presented in table 6-1.

In the calculational nodes where the critical heat flux was not exceeded, the wall heat flux was used to evaporate the primary side liquid. The steam-phase temperature was assumed to remain at the saturation temperature. The evaporating liquid phase causes the quality to increase monotonically with elevation. In the critical heat flux correlation, the quality dependence is in the form (1-x), which causes the critical heat flux to approach zero as the quality approaches 1.0. Therefore eventually an elevation will be reached where the critical heat flux is exceeded. This is the elevation where the wet film terminates and is defined as the quench front elevation in this method.

To calculate axial variation, the tube bundle length was divided into calculational nodes, with the fluid properties leaving a given node used as the inlet conditions for the following node. On the secondary side of a node, the stored energy in the secondary water and tube metal provided the driving force for the tube wall heat flux. At a given elevation, the secondary water stored energy included the water on both the inlet and outlet sides of the tube bundle. The water was assumed to remain stationary and temperature changes were only caused by the tube wall heat flux. Preliminary calculations of the quench elevation change with time for the reference run using the above method are shown in figure 6-1. Also shown in figure 6-1 are the test data from the reference test for the four instrumented tube locations. Although the method appeared capable of predicting the results of the reference run, results of the other runs in the test matrix were not predicted as well as the reference run using this method.

It should also be noted that the U-tube geometry of the tube bundle was not modeled in the calculational result shown in figure 6-1. That is, the tube wall heat flux that exists on the downflow side of the U-tube after some initial cooling of the secondary water has occurred was not accounted for. The direction of this heat flux is from the primary side steam to the secondary water. When this heat flux term was included, the quench velocity was significantly retarded, and the agreement between the model and the test data implied in figure 6-1 disappeared. Therefore this method of calculating the quench velocity was abandoned.

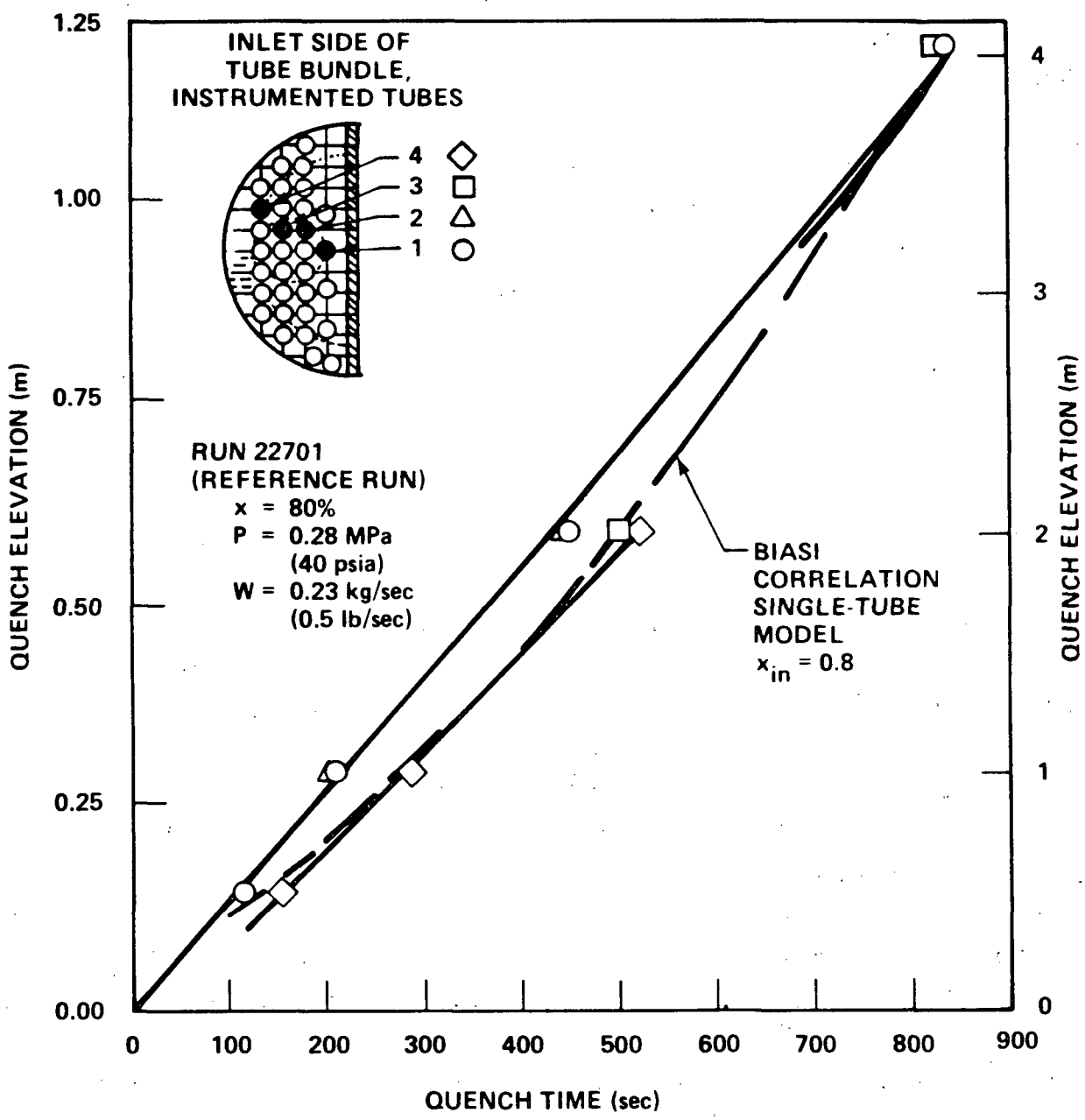


Figure 6-1. Quench Elevation Versus Quench Time, Reference Case, Measured and Preliminary Calculations

TABLE 6-1
STEAM GENERATOR MODEL HEAT TRANSFER COEFFICIENTS

Desired Quantity	Equation
Wet wall primary side film coefficient[a]	$h_{2\phi} = h_{fo}\,(3.5)\,(X_{tt})^{-0.5}$
X_{tt} [b]	$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} (\rho_g/\rho_f)^{0.5} (\mu_f/\mu_g)^{0.10}$
Dry wall primary side film coefficient[c]	$Nu_p = 0.023\,(Re_p)^{0.8}\,(Pr_p)^{0.4}$
Secondary turbulent free-convection film coefficient[d]	$Nu_s = 0.021\,(Gr_s)\,(Pr_s)^{0.40}$
Critical heat flux (Biasi correlation)[b]	$\phi_{CHF} = \frac{1.78 \times 10^3\, h(p)\,(1-x(z))}{D^{\eta} G^{0.6}}$
$h(p)$[b]	$h(p) = -1.159 + 0.149p(-.019p) + \frac{8.99p}{10+p^2}$

where

$h_{2\phi}$	=	two-phase forced convection film coefficient	G_{rs}	=	secondary side Grashof number
h_{fo}	=	forced convection film coefficient assuming all primary flow is liquid	Pr_s	=	secondary side Prandtl number
			ϕ_{CHF}	=	critical heat flux (w/cm^2)
X_{tt}	=	Martinelli parameter	$h(p)$	=	pressure-dependent term in CHF correlation
ρ_g	=	vapor density	$x(z)$	=	local quality in primary side of tube at elevation z
ρ_f	=	fluid density	D	=	tube diameter (cm)
μ_g	=	vapor viscosity	G	=	primary side mass velocity (g/cm^2-sec)
μ_f	=	fluid viscosity	η	=	0.4
Nu_p	=	primary side Nusselt number	p	=	primary side pressure (bars)
Re_p	=	primary side Reynolds number	z	=	distance from tube inlet (cm)
Pr_p	=	primary side Prandtl number			
Nu_s	=	secondary side Nusselt number			

a. Dengler, C. E., and Addoms, J. N., "Heat Transfer Mechanism for Vaporization of Water in a Vertical Tube," in Heat Transfer-Louisville (Chemical Engineering Progress Symposium Series, Volume 52, Number 18, pp 95-103), AIChE, New York, 1956.

b. Collier, J. G., Convective Boiling and Condensation, McGraw-Hill, New York, 1972.

c. Dittus-Boelter correlation

d. Eckert, E. R. G., and Jackson, T. W., Analysis of Turbulent Free-Convection Boundary Layer on Flat Plate, NACA-1015, 1951.

6-4. Evaluation Model Based on Axial Conduction Controlled Rewet

In several analyses of the quenching of a fuel assembly,[1,2,3,4,5] the quench velocity is related to the axial conduction of heat in the fuel rod. In these solutions, the quench velocity can be determined if the boiling curve is specified[3,4] or if the interface temperature between the wet and dry zones is specified.[1,2]

To apply the axial conduction quench velocity concept to the steam generator model, the basic noding scheme described in paragraph 6-3 was retained. A local axial conduction calculation added to the computer program allowed the quench velocity to be calculated. In this calculation, it was assumed that the film coefficients above and below the quench elevation were constant. It was also assumed that in the local region about the quench elevation, the fluid temperatures in the secondary and primary sides of the tube bundle were constant. The axial tube wall temperature is found by solving the differential equation describing the heat conduction process in the axial direction. After an appropriate variable transformation, the quench velocity appears as a coefficient in the differential equation. The derivation is reviewed below:

$$\rho C_p \frac{dT}{dt} + H(T-T_{sat}) = K\delta \frac{d^2 T}{dZ^2} \qquad (6\text{-}1^{(6)})$$

---

1. Yeh, H. C., "An Analysis of Rewetting of a Nuclear Fuel Rod in Water Reactor Emergency Core Cooling," Nucl. Eng. Des. 34, 317-322 (1975).

2. Yamanouchi, A., "Effect of Core Spray Cooling in Transient State After Loss-of-Coolant Accident," J. Nucl. Sci. Technol. 5, 547-558 (1968).

3. Chambre, P., and Elias, E., "Boiling Heat Transfer During Rewetting," Nucl. Eng. Des. 50, 353-363 (1978).

4. Sun, K. H., et al., "Effect of Precursory Cooling on Falling-Film Rewetting," ASME Paper 74-WA/HT-52.

5. Duffey, R. B., and Porthouse, D. T. C., "Experiments on the Cooling of High-Temperature Surfaces by Water Jets and Drops," RD/B. N2386, August 1972.

6. Lahey, R. T., Jr., and Moody, F. J., The Thermal Hydraulics of a Boiling Water Nuclear Reactor, ANS, LaGrange Park, IL, 1977.

If $z = Z - ut$,

$$\rho C_p \delta U \frac{dT}{dz} + K\delta \frac{d^2T}{dz^2} = H(T - T_{sat}) \qquad (6\text{-}2^{(1)})$$

where

ρC_p	=	tube wall heat capacity per unit volume
δ	=	tube wall thickness
K	=	tube wall thermal conductivity
U	=	quench front velocity
z	=	distance below quench front
T	=	tube wall temperature
H	=	tube wall heat transfer coefficient
T_{sat}	=	primary fluid saturation temperature

In this model, equation (6-1) is solved once below the quench elevation using a two-phase forced convection heat transfer coefficient, and a second time above the quench elevation using a single-phase steam forced convection heat transfer coefficient. Boundary conditions for the solution are the tube wall temperature equal to T_{sat} well below the quench elevation and the secondary fluid temperature well above the quench elevation. This upstream wall temperature is defined as the T_∞ in paragraph 5-7. The two solutions are required to have continuity of temperature and temperature gradient at the wet/dry interface. The interface temperature is defined as T_o in paragraph 5-7.

When a value for U in equation (6-2) is assigned, the temperature distribution in the axial direction can be solved. An example of the axial temperature distribution calculated for the reference run at the 1.22 m (4 ft) quench time is shown in figure 6-2. The assumed value for the quench velocity in this calculation was taken from the test data for the 1.22 m (4 ft) quench time (800 seconds for the reference run) and is 1.524 mm/sec (0.005 ft/sec). The temperature at the wet/dry interface in figure 6-2 is 152°C (306°F), which is 22°C (39°F) above the primary side saturation temperature.

---

1. Lahey, R. T., Jr., and Moody, F. J., The Thermal Hydraulics of a Boiling Water Nuclear Reactor, ANS, LaGrange Park, IL, 1977.

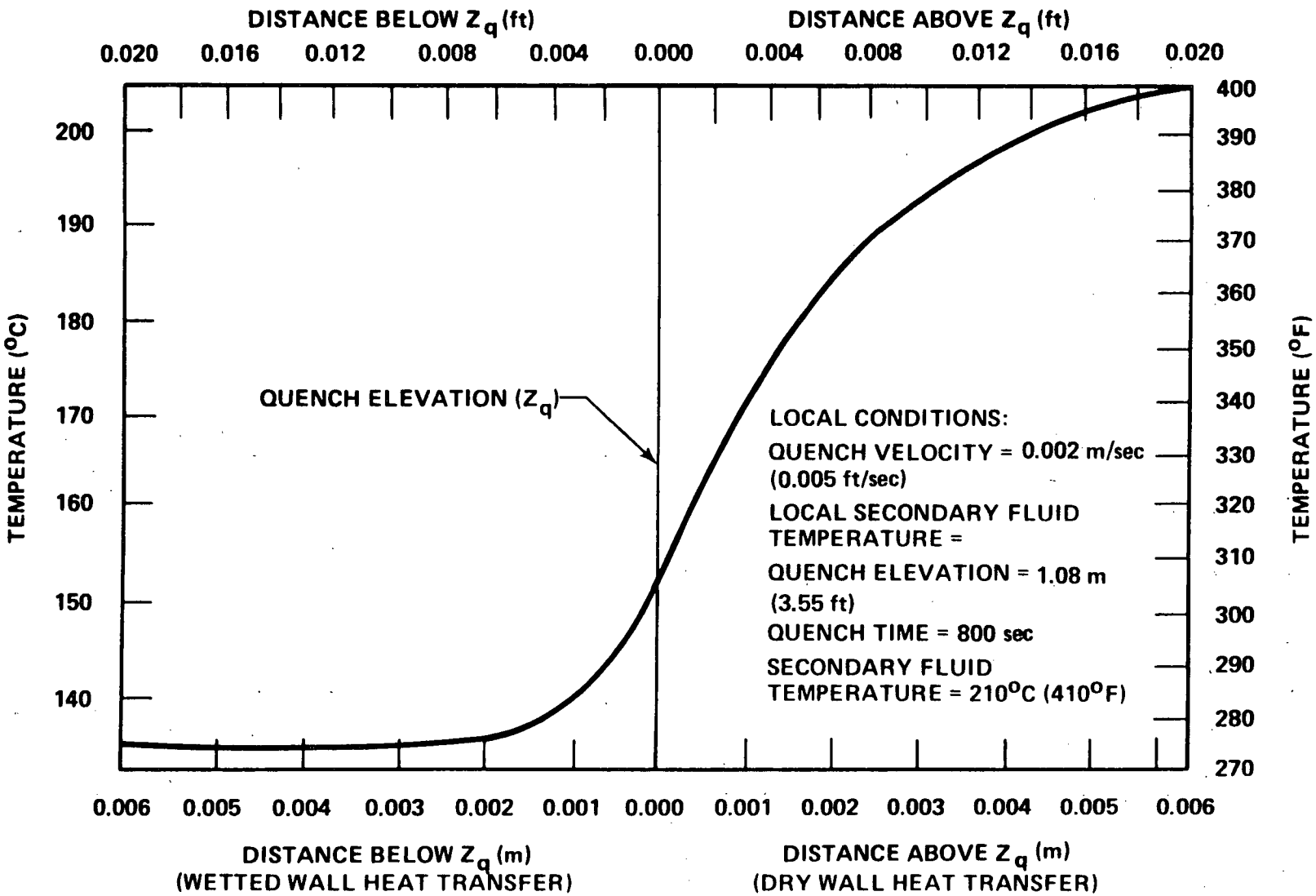


Figure 6-2. Axial Temperature Distribution, Reference Run, 1.22 m (4 ft) Elevation

16817-5

From the boiling curves in figures 5-44 and 5-45, the tube wall superheat at the point of maximum tube wall heat flux is in the 17°C to 25°C (30°F to 45°F) temperature range.

To use the axial conduction calculation to calculate the quench front velocity, the temperature at the wet/dry interface must be known. Because the quench velocity appears as a coefficient in the above equation, to use this equation to solve for the quench velocity requires an iterative technique. The above equation can be solved for several assumed quench velocities, and a plot of quench velocity versus interface temperature can be constructed. From this plot, the unique quench velocity corresponding to the known interface temperature can be determined.

The steam generator mathematical model was expanded to include the axial conduction calculation described above. In this model, the wet/dry interface temperature is defined and the corresponding quench velocity is calculated. That is, in the program several quench velocities were generated as guesses, the axial temperature was calculated, and a table of quench velocity versus interface temperature was constructed. An example of the results of this calculation is shown in figure 6-3. From the table of quench velocity versus interface temperature, the quench velocity corresponding to a given interface temperature is found.

In this calculation the interface temperature was defined by the following equation:

$$T_{int} = T_{sat} + \frac{\phi_{CHF}}{H_{2\phi}} + \Delta T \qquad (6\text{-}3)$$

where

T_{int} = interface temperature

T_{sat} = primary side saturation temperature

ϕ_{CHF} = critical heat flux at the wet/dry interface

$H_{2\phi}$ = two-phase forced convection heat transfer coefficient

ΔT = arbitrary constant used to force calculation to agree with test results

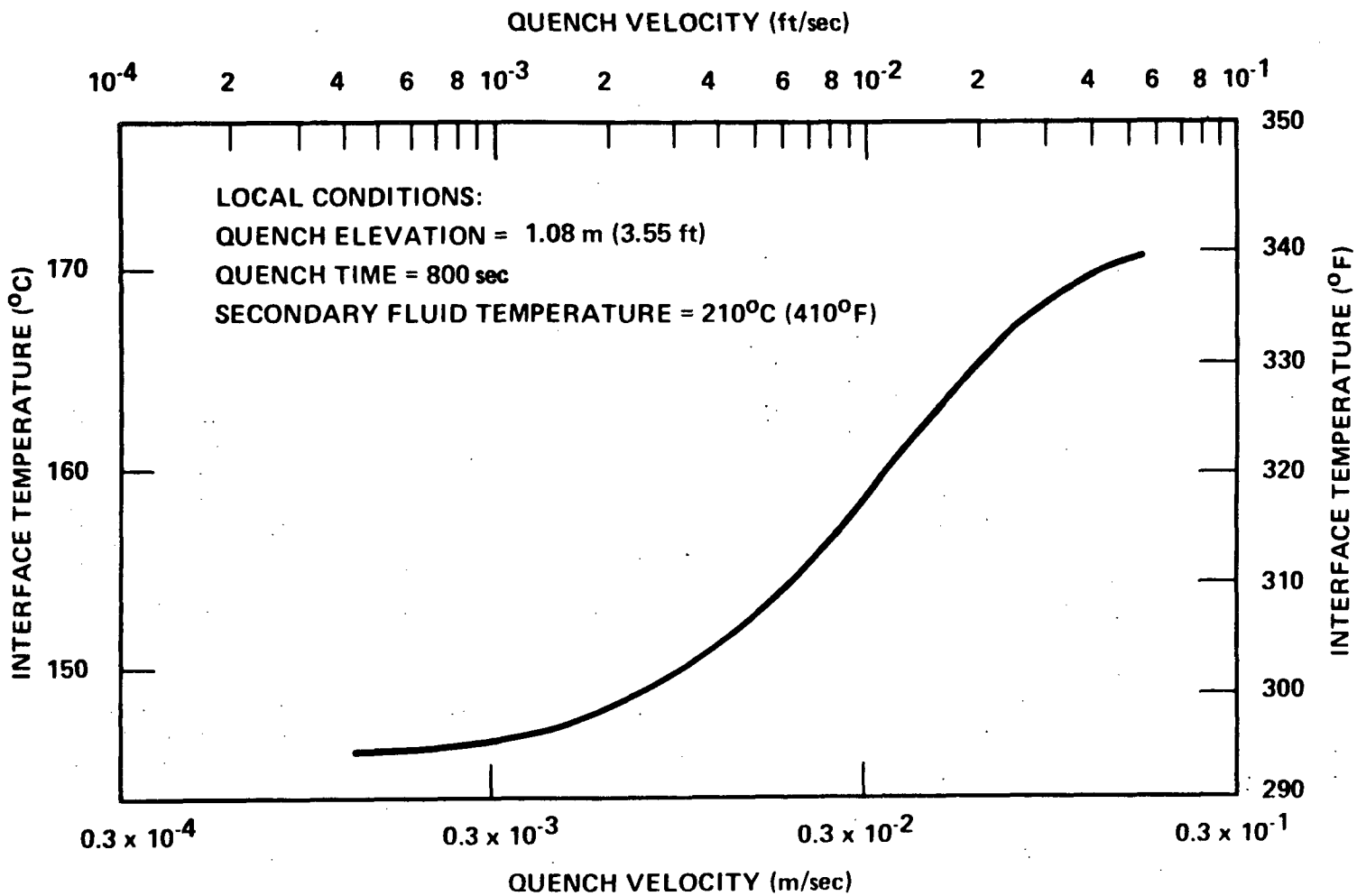


Figure 6-3. Quench Velocity Versus Interface Temperature, Reference Run

16817-6

The local conditions critical heat flux correlation of Biasi in table 6-1 was used to determine the critical heat flux.

For the reference run, it was found that the above method using 5.5°C (10°F) as ΔT in equation (6-3) comes close to matching the test data. The results of this calculation are shown in figure 6-4.

The calculational procedure described above was repeated on the single-parameter variation runs. The calculated time for the quench elevation to reach 1.22 m (4 ft) is reported in table 6-2. The measured time for the quench elevation to reach 1.22 m (4 ft) is also reported, along with the interface temperature used in the axial heat conduction calculation. The results show that the model predicts the reference case, high primary pressure, low secondary temperature, and the 50-percent quality runs reasonably well. The results of the high flow, low pressure, and the lowest quality run quench velocities were not accurately predicted by the model.

6-5. Evaluation Model Based on an Empirical Quench Velocity Correlation

To determine the quench velocity accurately for the whole range of parameter variations in the test matrix, an empirical fit of the 1.22 m (4 ft) quench times was formulated. The 1.22 m (4 ft) quench times shown in figure 5-74 were fit with the following function:

$$t_{q_{4\,ft}} = 0.2154\,(40/P)^{0.25}\,0.20/(1-x)^{0.84}\,(5.0/G)^{1.32}\,(T-267)^{1.4803} \qquad (6\text{-}4)$$

where

$t_{q_{4\,ft}}$	=	1.22 m (4 ft) quench time (sec)
P	=	primary system pressure (psia)
x	=	primary side inlet quality
G	=	primary side mass velocity (lb/sec-ft)
T	=	initial secondary side temperature

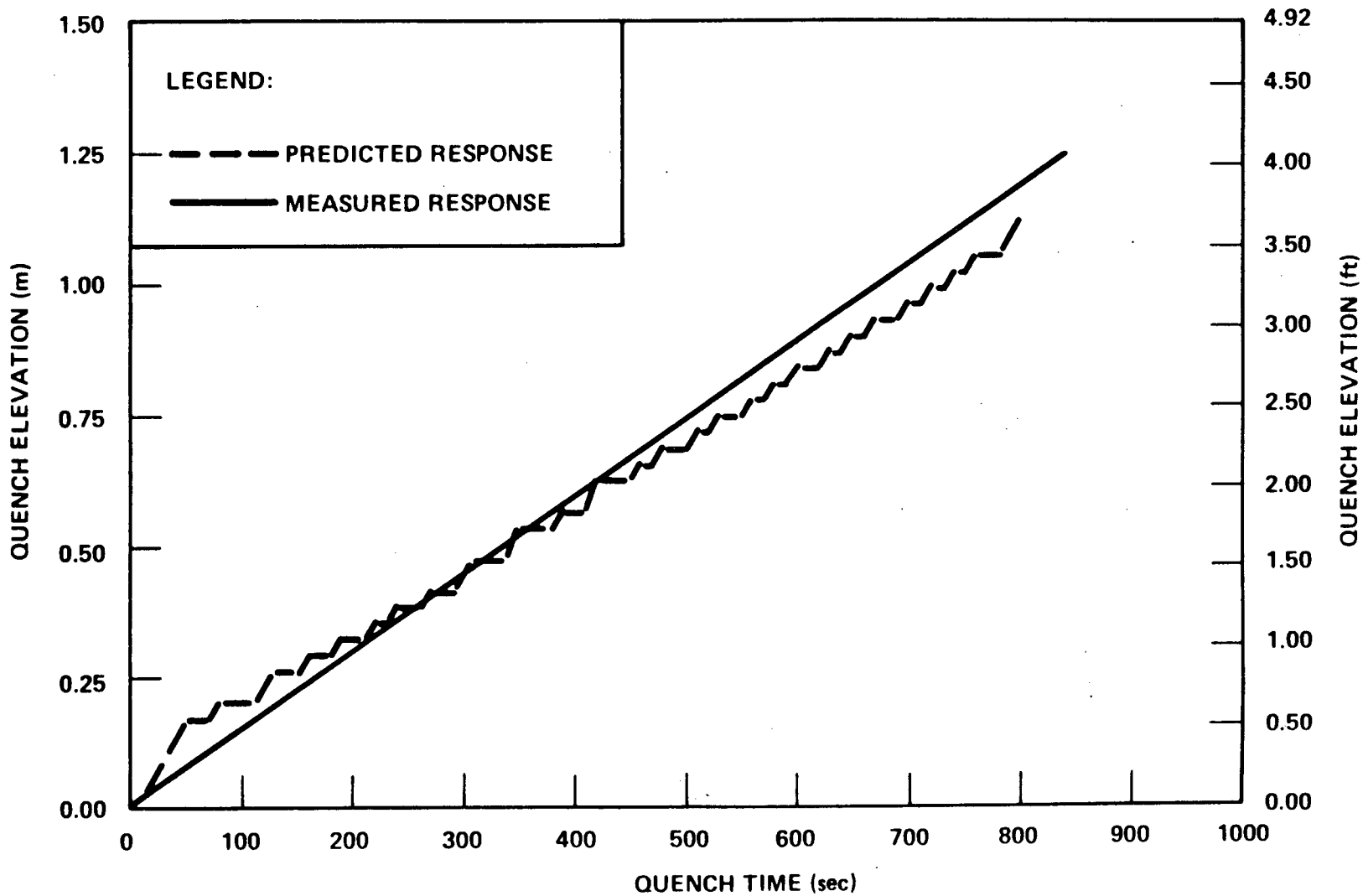


Figure 6-4. Quench Velocity Calculated From Axial Conduction Model With Differential Temperature = 5.5°C (10°F)

16817-86

TABLE 6-2

IMPLICIT CALCULATION OF QUENCH TIME,

1.22 m (4 ft) ELEVATION

Run No.	Axial Conduction Interface ΔT[a]	Quench Time at 1.22 m (4 ft) (sec)	
		Calculated	Measured
22701	0°C (0°F)	1000	825
	5.5°C (10°F)	900	825
23402	5.5°C (10°F)	900	300
22503	5.5°C (10°F)	> 1000 [b]	950
20904	5.5°C (10°F)	700	720
23605	5.5°C (10°F)	240	320
21806	5.5°C (10°F)	120	325
23207	5.5°C (10°F)	340	300
21909	5.5°C (10°F)	40	70

a. Z_q = 0.14 m (0.45 ft) at t = 1000 sec, calculation terminated.

In metric units, the equation is

$$t_{q_{4\ ft}} = 0.2154\,(0.276/P)^{0.25}\,0.20/(1-x)^{0.84}(24.41/G)^{1.32}(1.8T-235)^{1.4803} \quad (6\text{-}5)$$

where

P = primary pressure (MPa)

G = mass velocity (kg/m^2-sec)

T = secondary initial temperature (°C)

The $t_{q_{4\ ft}}$ correlation is used to calculate the quench velocity by dividing $t_{q_{4\ ft}}$ into 1.22 m (4 ft). The quench velocity is assumed to be constant with time and the quench elevation is found by multiplying the quench velocity by time.

A comparison between the above equation and the 1.22 m (4 ft) quench time data is presented in table 6-3.

The correlation for $t_{q_{4\ ft}}$ provides a constant quench velocity for the constant inlet plenum parameters in the matrix tests. This correlation could also be applied to problems with time-varying boundary conditions by simply calculating the instantaneous quench velocity from the $t_{q_{4\ ft}}$ correlation (quench velocity equals 4 ÷ $t_{q_{4\ ft}}$) and integrating the quench velocity to get the quench elevation. To check this method, a test run with time-varying boundary conditions would have to be run. No transient tests were run in the steam generator separate effects test facility. However, the only parameter within the steam generator that could affect the quench velocity is the axial temperature distribution. If different test runs resulted in the same secondary fluid temperature distribution for the same quench elevation, the steady-state correlation should predict the transient test quench velocity very accurately. An estimate of the axial temperature distribution dependence on the inlet plenum boundary conditions at the same quench elevation was developed from the test data by comparing the secondary fluid temperature at the 1.22 m (4 ft) elevation at the 1.22 m (4 ft) quench time. This comparison is presented in table 6-4 for all tests with the same initial temperature. The data in table 6-4 show that, for the wide range of test

TABLE 6-3
EMPIRICAL CALCULATION OF QUENCH TIME,
1.22 m (4 ft) ELEVATION

Run No.	Quench Time at 1.22 m (4 ft) (sec)	
	Calculated[a]	Measured
22701	800	825
23402	320	300
22503	951	950
20904	723	720
23605	370	320
21806	250	325
23207	300	300
21909	90	70

a. From equation (6-4)

TABLE 6-4

SECONDARY FLUID TEMPERATURE AT 1.22 m (4 ft) ELEVATION AT 1.22 m (4 ft) QUENCH TIME

Run No.	Quench Time at 1.22 m (4 ft), $t_{q_{4\ ft}}$ (sec)	Secondary Fluid Temperature at 1.22 m (4 ft) at $t_{q_{4\ ft}}$ [°C (°F)]	
22701	825	232	(450)
23402	300	243	(470)
22503	950	216	(420)
20904	720	238	(460)
23605	320	254	(490)
21806	325	243	(470)
23207	800	227	(440)
21909	70	266	(510)
Average secondary temperature		240	(464)
Standard deviation		16	(28)

parameters in the test matrix, the axial temperature distribution correlates fairly closely with the quench elevation. That is, for any given boundary condition at the inlet plenum, when the quench front reaches the same elevation the secondary fluid temperature distribution is about the same. This observation supports the assumption that the empirical correlation for the quench velocity is valid for transients even though, in the test data base, all tests were run with constant primary loop parameters.

6-6. Evaluation Model Droplet Entrainment and Evaporation

Once the quench elevation has been determined, the liquid mass flow at that elevation is assumed to be dispersed into drops and completely entrained in the continuous steam phase. The assumed drop size distribution, taken from Hewitt and Hall-Taylor,[1] is reproduced in table 6-5. The drops are distributed into 10 groups, with each group having an equal volume of drops. The number of drops per pound of two-phase mixture can be calculated from the following equation:

$$Ni = \frac{\alpha_i[1 - x(z)]}{\rho_\ell V_i} \qquad (6\text{-}6)$$

where

N_i = number of drops in group i per pound of two-phase mixture

α_i = volume fraction of drops in group i

V_i = volume of a drop in group i (ft^3)

$x(z)$ = local quality at elevation z

ρ_ℓ = liquid density (lbm/ft^3)

To calculate the droplet steam heat exchange, an initial drop size distribution was assumed, a steam to drop heat transfer coefficient was defined, and the rate at which the drops evaporate was calculated. Heat transfer to the drops occurs because of steam to drop heat transfer and because of radiation directly from the tube wall.

---

1. Hewitt, G. F., and Hall-Taylor, N. S., Annular Two-Phase Flow, Pergamon Press, New York, 1970.

TABLE 6-5

DROP SIZE DISTRIBUTION

Group No.	Drop Diameter [mm (ft)]
1	1.14 (0.00375)
2	0.686 (0.00225)
3	0.457 (0.00150)
4	0.357 (0.00117)
5	0.28 (0.00092)
6	0.22 (0.00071)
7	0.16 (0.00054)
8	0.13 (0.00042)
9	0.088 (0.00029)
10	0.040 (0.00013)

The droplet film coefficient is calculated from the following equations:[1]

$$Nu_{drop} = 2 + 0.55\,(Re_d)^{0.5}\,(Pr_v)^{0.33} \qquad (6\text{-}7)$$

$$Re_d = \left\{0.292\; d_i/\mu_g\,[g_c \rho_g\,(\rho_\ell - \rho_g)]\,d_i^{\;0.5}\right\}^{1.725} \qquad (6\text{-}8)$$

$$Re_d = [4 g_c\,(\rho_\ell - \rho_g)\,d_i / 3 \rho_g\, C_D)]^{0.5}\;\rho_g\, d_i/\mu_g \qquad (6\text{-}9)$$

where

Nu_{drop}	=	droplet Nusselt number
Re_d	=	droplet Reynolds number
Pr_v	=	vapor Prandtl number
d_i	=	diameter of a drop in group i (ft)
μ_g	=	vapor viscosity (lbm/ft-sec)
ρ_g	=	vapor density (lbm/ft^3)
ρ_ℓ	=	liquid density (lbm/ft^3)
C_D	=	drag coefficient, taken as 0.50
g_c	=	gravitational constant (ft/sec^2)

The droplet Reynolds number in equation (6-7) is determined from considering the terminal velocity of a single drop. The terminal velocity is dependent on the drag coefficient, the droplet diameter, and the densities of steam and water. By starting with the force balance equation and using the defining equation for the droplet Reynolds number, the following equation for the droplet Reynolds number, in terms of the droplet diameter, drag coefficient, and fluid properties, was derived:

$$Re_d = [4 g_c (\rho_\ell - \rho_g)\, d_i \;/(3\, C_D \rho_g)]\;\frac{\rho_g d_i}{\mu_g} \qquad (6\text{-}10)$$

---

1. Equation (6-7) from Lee, K., and Ryley, D. J., "The Evaporation of Water Droplets in Superheated Steam," J. Heat Transfer 90, ASME, 445-451 (1968).

Equation (6-10) can be used to solve for the droplet Reynolds number if the drag coefficient is known. Generally, the drag coefficient is expressed as a function of the droplet Reynolds number. In this study, the drag coefficient dependence on the Reynolds number is defined by the following equation:

$$C_D = (27/Re_d)^{0.84} \tag{6-11}$$

This expression can be substituted into equation (6-10) to yield

$$Re_d = \left\{ [0.292\ (d_i/\mu_g\ [g_c \rho_g (\rho_\ell - \rho_g) d_i]^{0.5} \right\}^{1.725} \tag{6-12}$$

As the droplet Reynolds number increases, the drag coefficient decreases asymptotically to a constant value. The asymptotic drag coefficient in this study is taken to be 0.50. The corresponding droplet Reynolds number is calculated by solving equation (6-10) for Re, assuming C_D is 0.50 and also solving equation (6-12) for Re_d. The correct drag coefficient is the larger value between 0.50 and the drag coefficient determined from equation (6-11). Since the drag coefficient appears in the denominator of equation (6-10), the correct droplet Reynolds number will be the smaller Re value between equations (6-10) and (6-12).

Wall to droplet radiation is calculated following the method described by Sun, et al.:[1]

$$Q_e = F_{w\ell}\, \sigma\, (T_w^4 - T_{sat}^4) \tag{6-13}$$

and

$$F_{w\ell} = \frac{1}{R_2\left(1 + \frac{R_3}{R_1} + \frac{R_3}{R_2}\right)}$$

$$R_1 = \frac{1 - \varepsilon_v}{\varepsilon_v (1 - \varepsilon_v\, \varepsilon_\ell)}$$

---

1. Sun, K. H., et al., "Calculations of Combined Radiation and Convection Heat Transfer in Rod Bundles Under Emergency Cooling Conditions," ASME-AIChE, 15th National Heat Transfer Conference, August 1975.

$$R_2 = \frac{1 - \varepsilon_\ell}{\varepsilon_\ell (1 - \varepsilon_v \varepsilon_\ell)}$$

$$R_3 = \frac{1}{1 - \varepsilon_v \varepsilon_\ell} + \frac{1 - \varepsilon_w}{\varepsilon_w}$$

where

Q_e	=	heat flux absorbed by a drop
σ	=	Stefan-Boltzmann constant
T_w	=	absolute wall temperature
T_{sat}	=	absolute saturation temperature
$\varepsilon_v, \varepsilon_\ell, \varepsilon_w$	=	emissivity of vapor, liquid, and tube wall, respectively

In the calculation of radiation to the drops, the wall and liquid emissivities were set equal to 1.0 and the vapor emissivity was set equal to zero.

In summary, the model described above to calculate the steam generator heat transfer uses an empirical correlation derived from the test data to predict the quench velocity [equation (6-4) or (6-5)]. The quench elevation is calculated by integrating the quench velocity. Heat transfer below the quench elevation is calculated by assuming that the applicable primary side heat transfer regime is two-phase forced convection. Above the quench elevation, the applicable heat transfer regime is assumed to be single-phase forced convection to steam. At the quench elevation, the liquid mass flow rate is assumed to be dispersed into drops and entrained in steam-phase flow. Steam-to-drop convective heat transfer and wall-to-drop radiation heat transfer is modeled above the quench elevation.

The secondary side heat release is modeled by defining one common axial node at any given elevation which includes the secondary water in both the inlet and outlet regions of the tube bundle. This treatment of the secondary water will result in a secondary temperature distribution with axial variation but no radial variation. The observed secondary temperature distribution in all of the matrix tests showed large axial temperature gradients but virtually uniform temperatures in the radial direction.

At a given elevation, the secondary fluid node can transfer heat to the primary fluid in the upflow inlet region of the tube bundle and also in the downflow outlet region of the tube bundle. Therefore, the number of primary nodes will equal twice the number of secondary nodes. Heat transfer will always be from secondary fluid to primary fluid in the upflow region of the tube bundle, but can be in either direction in the downflow region of the bundle, depending on the relative magnitudes of the primary and secondary fluid temperatures.

At a given elevation, the heat transfer rates from the upflow inlet side of the tube bundle and the downflow outlet side of the tube bundle are summed together to determine the net energy depletion from the common secondary node.

Initial comparisons of the prediction model described above with test data showed that the outlet plenum liquid flow rate was overpredicted. To enhance liquid evaporation, the drop size distribution was changed to include only the five smallest groups in the distribution in table 6-5. That is, α_i for groups 1 through 5 was set to zero and α_i for groups 6 through 10 was set to 0.20.

With this modification, the droplet diameters range from 0.22 to 0.040 mm (0.00071 to 0.000040 ft). Studies of drop sizes ejected from a liquid drop in contact with a heated wall are reported by Cumo and Farello.[1] These studies report that the drop size distributions tend to peak at droplet diameters less than 0.3 mm (0.00098 ft). The data are qualitatively consistent with the adjustment in the drop size distribution discussed above.

6-7. EVALUATION MODEL COMPARISON WITH TEST DATA

The reference run test data and the steam generator response predicted by the above model, using equation (6-4) to calculate the quench velocity, were compared with the test data by superimposing the calculated data on the test data plots.

---

1. Cumo, M., and Farello, G. E., "Heated Wall-Droplet Interaction for Two-Phase Flow Heat Transfer in Liquid-Deficient Region," in Symposium on Two-Phase Flow Dynamics, European Atomic Energy Community, Eindhoven, September 1967.

In figures 6-5, 6-6, and 6-7, the outlet plenum steam temperature, outlet plenum liquid collection, and the overall bundle heat transfer are compared. These comparisons of the overall bundle response show that the model predicts all the data trends correctly, although the overall bundle heat transfer is somewhat overestimated by the prediction model. The comparisons show that the model described above, which uses an empirical correlation to determine the quench velocity, correctly predicts the overall data trends in the steam generator response. Figure 6-8 shows the agreement between the quench elevation test data and the empirical correlation used to predict the quench elevation.

In figures 6-9, 6-10, and 6-11, the axial variation in the primary side steam temperature and secondary side fluid temperature at three discrete times (300, 600, and 900 seconds) are shown. All three plots show that the steam temperature is somewhat under-predicted in the midregion of the bundle, but the agreement in steam temperature at the bundle exit is good.

The secondary fluid temperature plot comparisons in figures 6-9 through 6-11 show that the data trends are correctly predicted. The 600-second and 900-second fluid plots show an oscillation in the inlet region below the 6.10 m (20 ft) elevation. These oscillations are the result of the data interpolation in the zone of high axial temperature gradients. The fluid thermocouples were located at the 1.22, 3.05, and 6.10 m (4, 10, and 20 ft) elevations (figure 3-5); at these specific locations the fluid temperatures are in agreement. Elevations where data interpolation was used to find the secondary fluid temperature, from figure 4-3, include 0.81, 1.83, 2.44, 3.66, and 6.10 m (2.65, 6, 8, 12, and 20 ft). In figure 6-10, the temperature overshoot occurs in the 1.22 to 3.05 m (4 to 10 ft) region. In both of these regions, interpolated temperature data are plotted.

The calculated secondary fluid temperature profile shown in figure 6-11 illustrates an abrupt change in slope at the quench elevation. The test data, also plotted in figure 6-11, show a more gradual transition in the secondary fluid temperatures below and above the quench elevation. The response in the calculated secondary fluid temperature profile is due to the assumption in the model that no mixing occurs in the axial direction. The predicted secondary fluid temperature profile in figure 6-11 would agree more closely with the test data if some axial mixing were allowed.

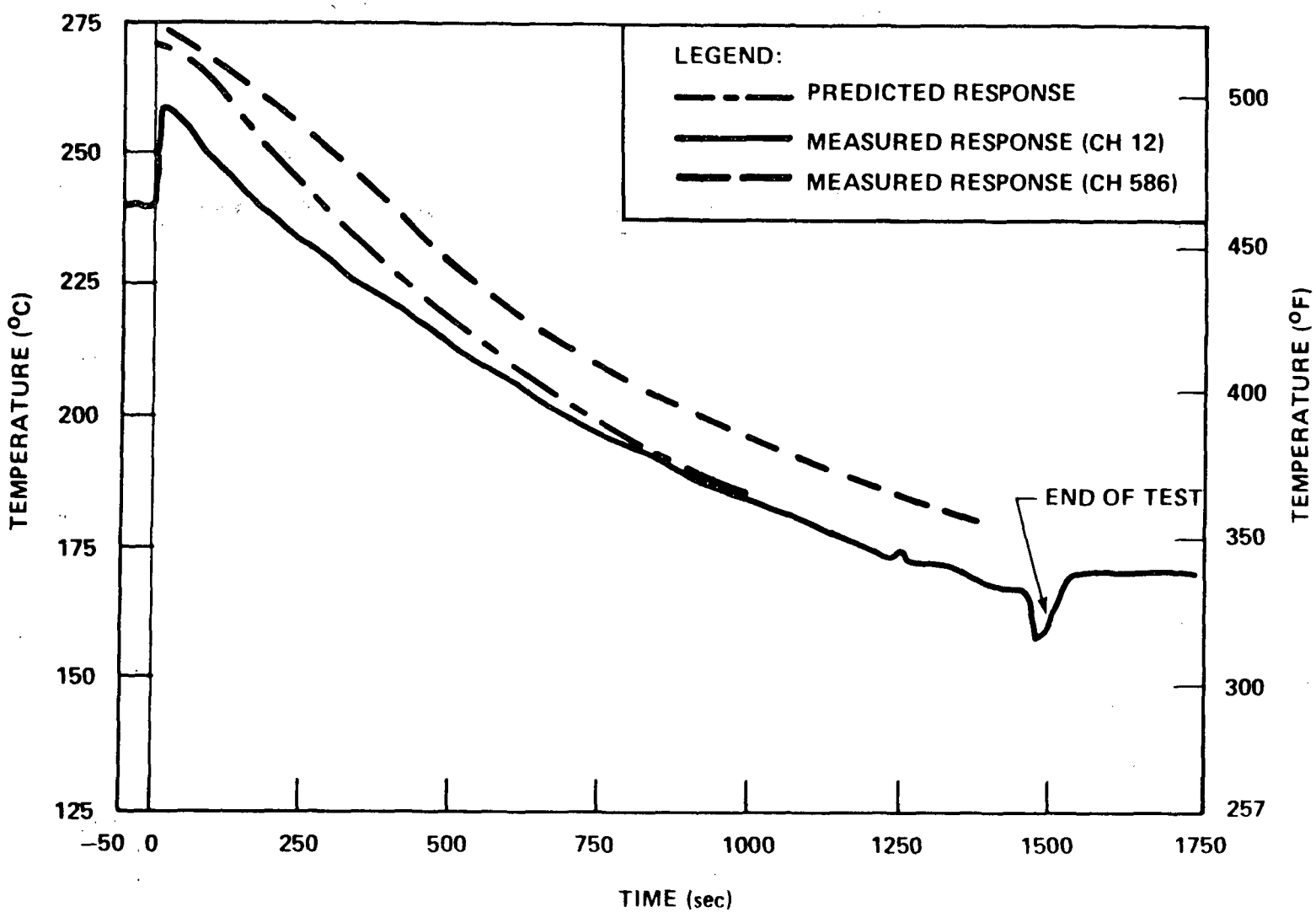


Figure 6-5. Reference Run Prediction Versus Data, Outlet Plenum Steam Temperature

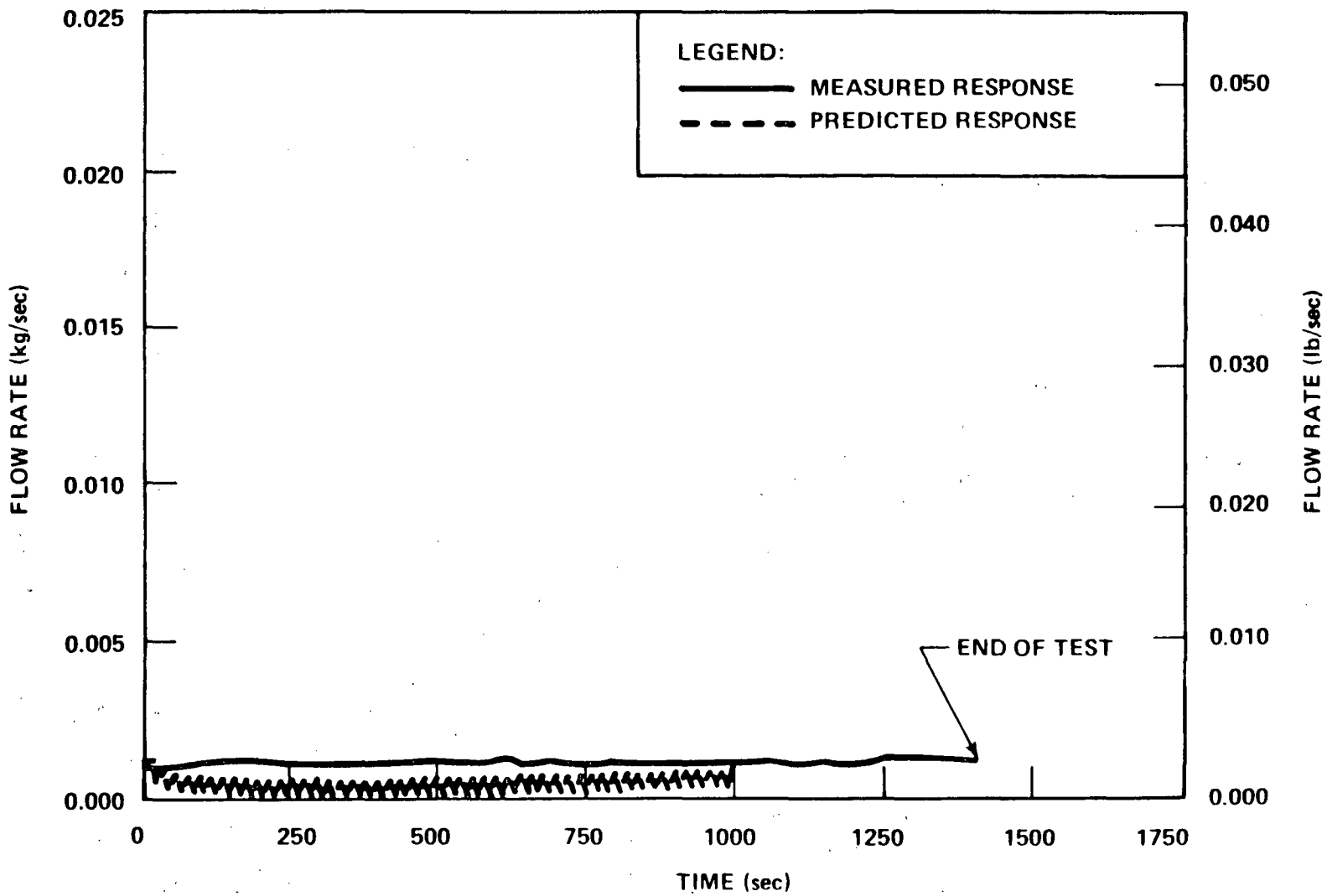


Figure 6-6. Reference Run Prediction Versus Data, Outlet Plenum Liquid Flow Rate

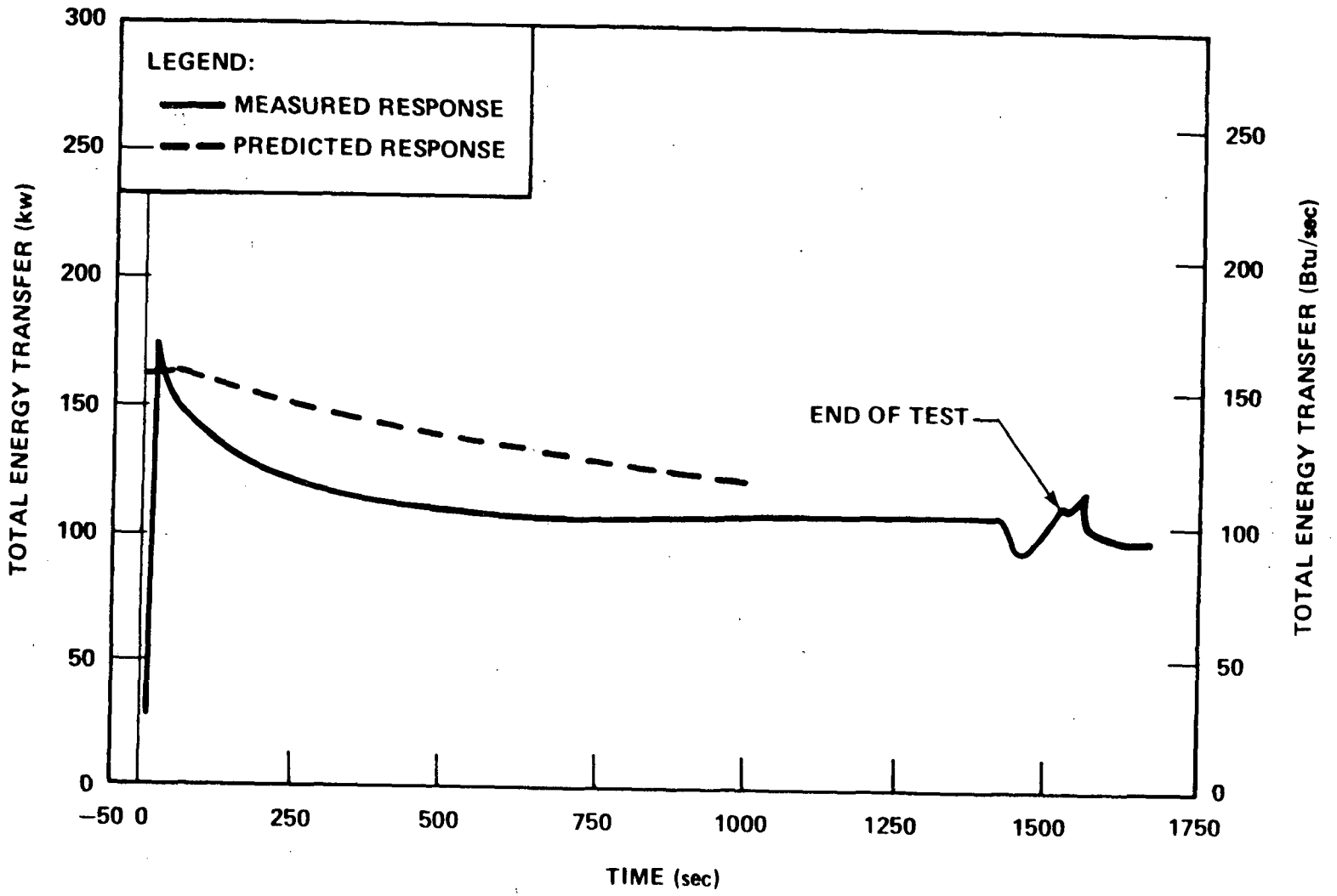


Figure 6-7. Reference Run Prediction Versus Data, Total Energy Transfer

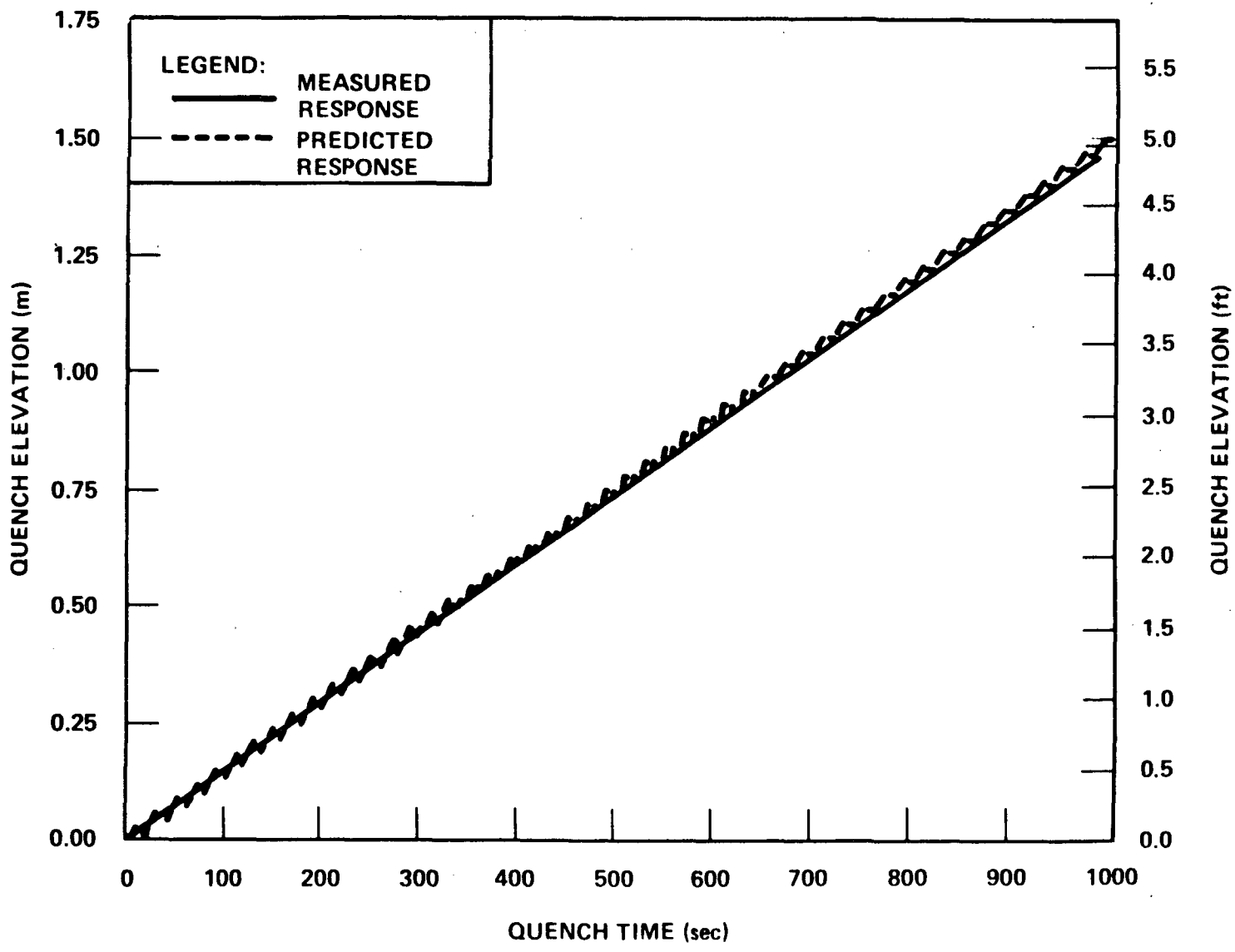
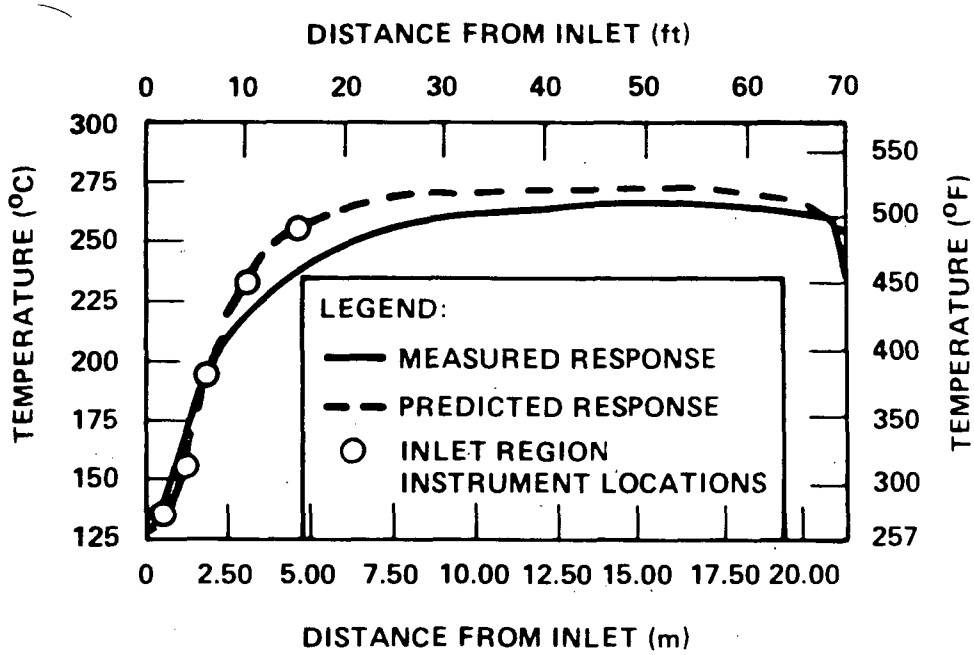


Figure 6-8. Reference Run Prediction Versus Data, Quench Elevation (Empirical Correlation)

16817-85



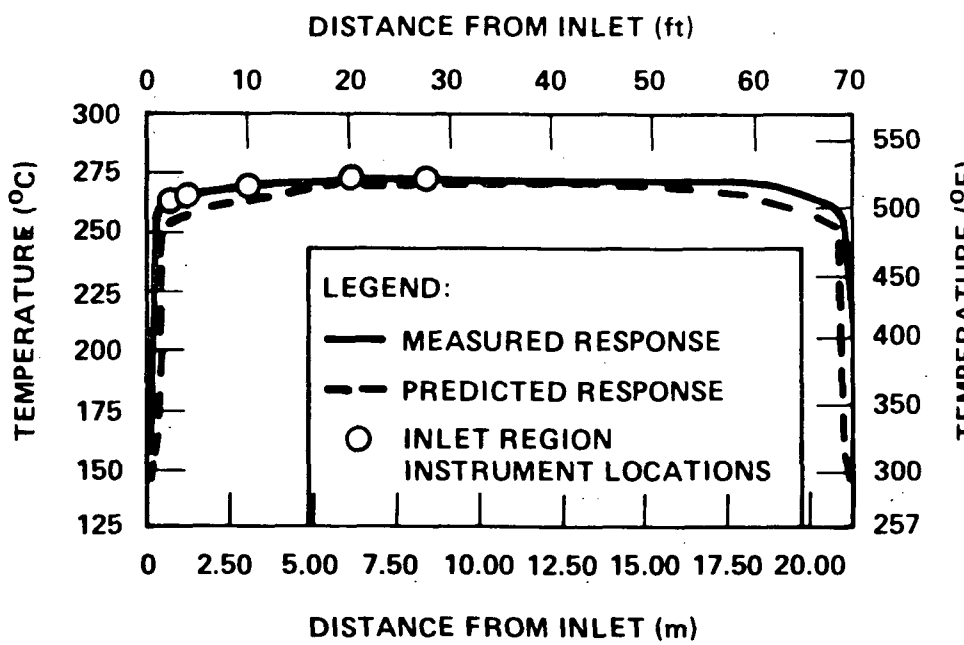
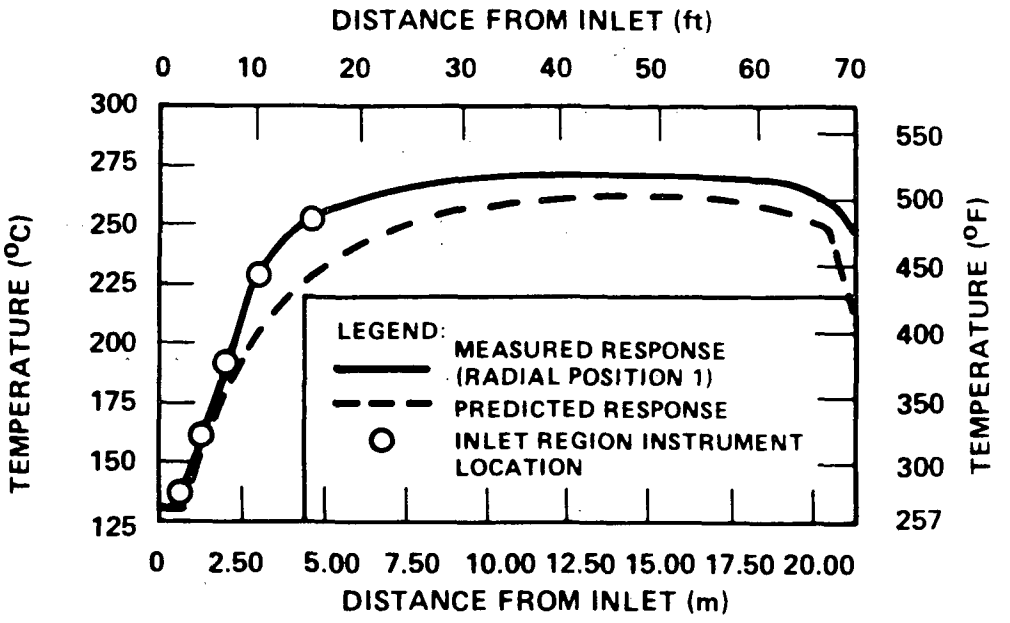
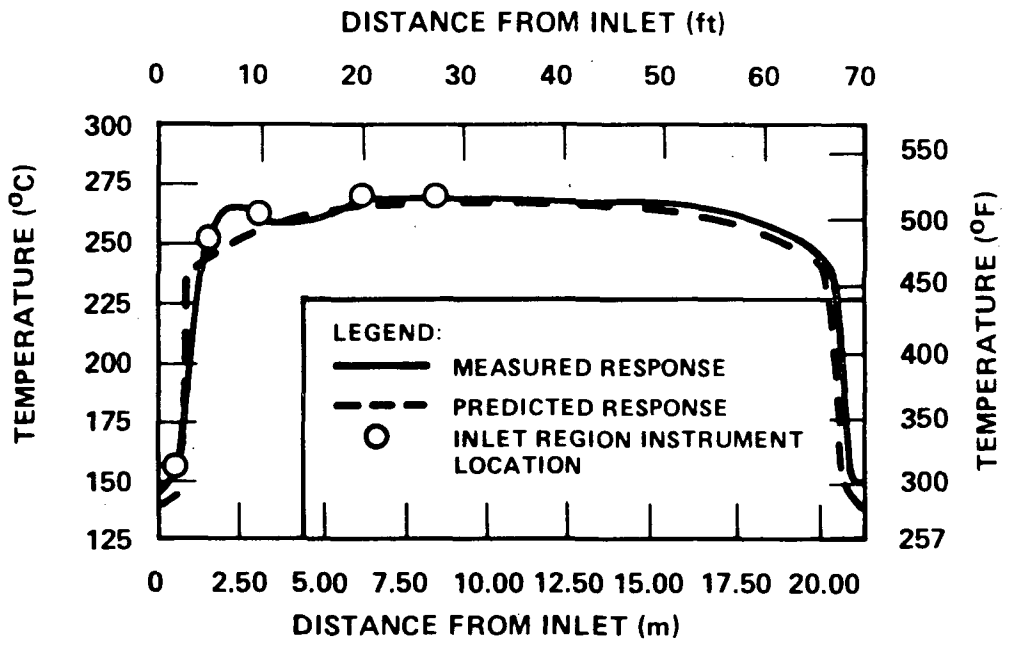


Figure 6-9. Reference Run Prediction Versus Data, Primary Steam and Secondary Fluid Temperatures, t=300 sec

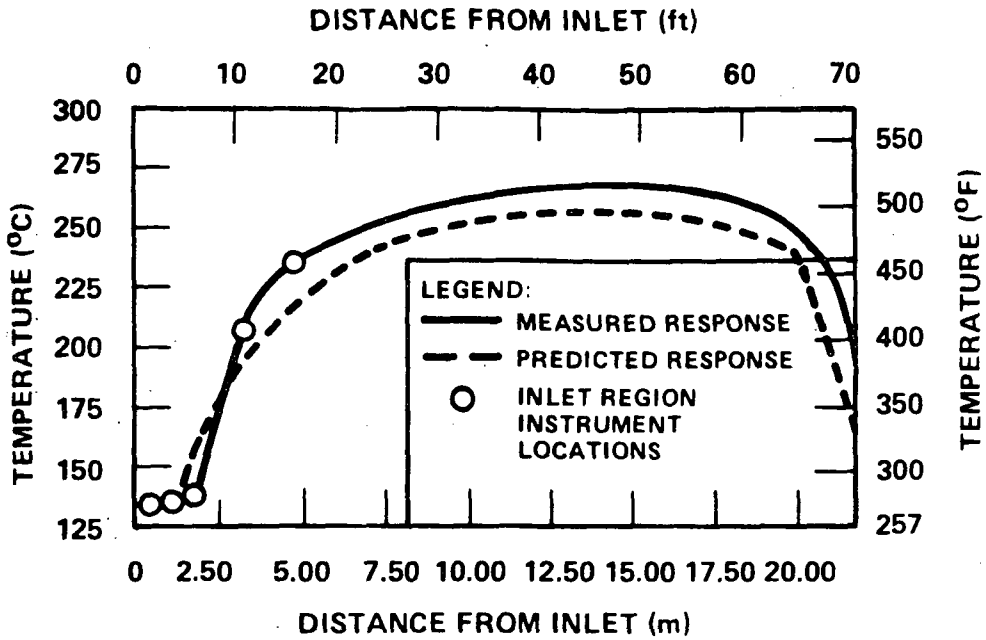


PRIMARY SIDE STEAM PHASE TEMPERATURES

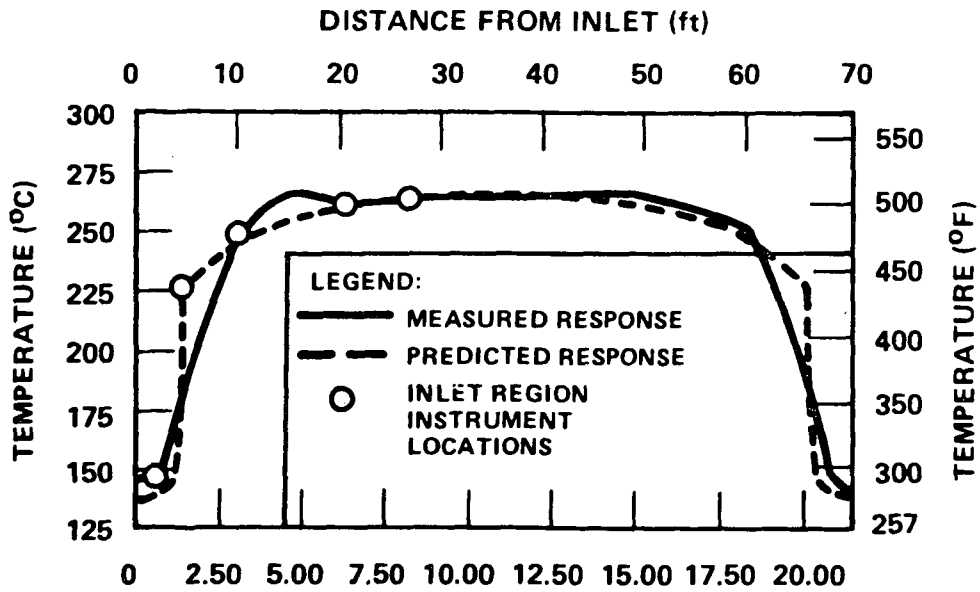


SECONDARY FLUID TEMPERATURES

Figure 6-10. Reference Run Prediction Versus Data, Primary Steam and Secondary Fluid Temperatures, t=600 sec



PRIMARY SIDE STEAM PHASE TEMPERATURES

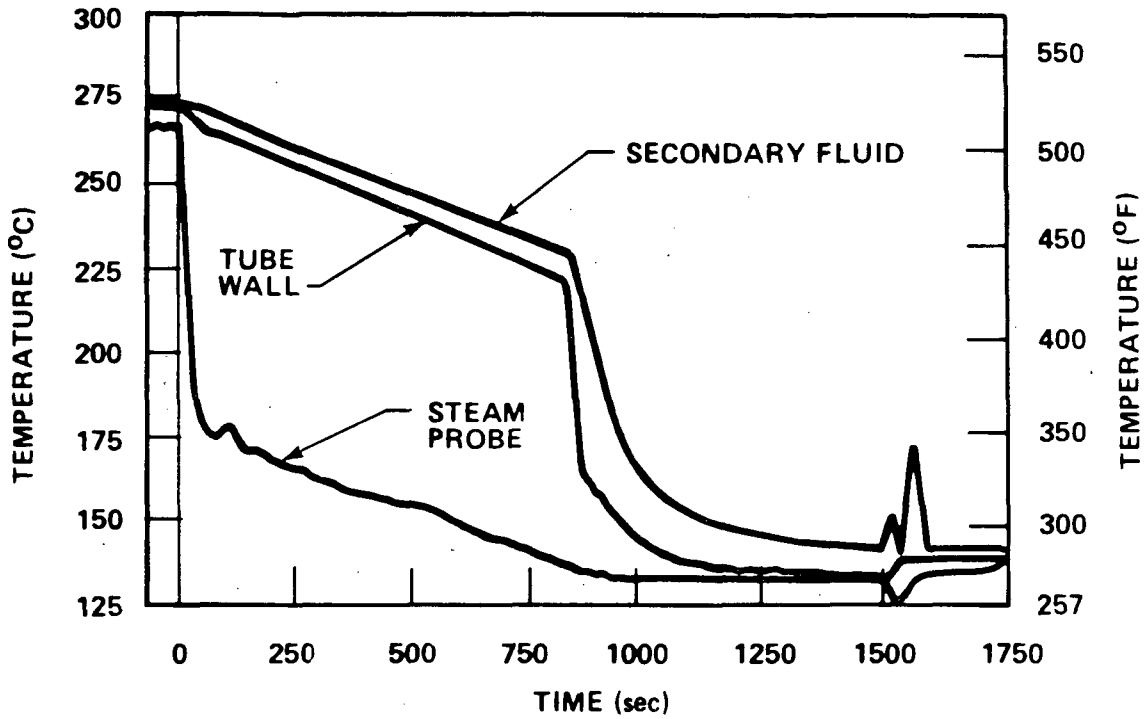


SECONDARY FLUID TEMPERATURES

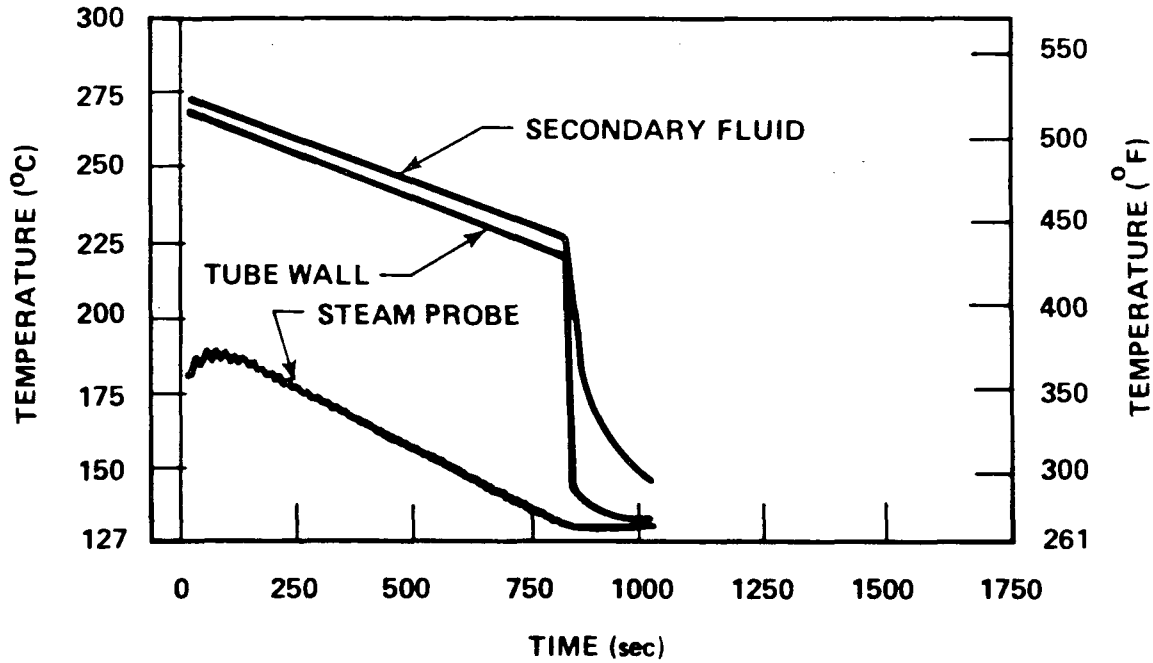
Figure 6-11. Reference Run Prediction Versus Data, Primary Steam and Secondary Fluid Temperatures, t=900 sec

Figures 6-12 and 6-13 compare measured and predicted local temperatures at the 1.22 m (4 ft) elevation. In figures 6-12 and 6-13 the inlet and outlet region temperatures, respectively, are shown. In both cases the observed data trends are closely predicted. Figure 6-14 compares the predicted and measured local tube wall heat flux at the 1.22 m (4 ft) elevation. The plot shows good agreement.

Figures 6-15 through 6-35 show measured and calculated outlet plenum temperature, liquid mass flow, and secondary fluid axial temperature distribution in the bundle when the quench elevation is within the highly instrumented region from zero to 1.22 m (4 ft). These comparison plots show that the model predicts all the observed data trends. The poorest agreement is in the outlet plenum liquid flow rate for the 10-percent quality run (run 9 in table 4-1).

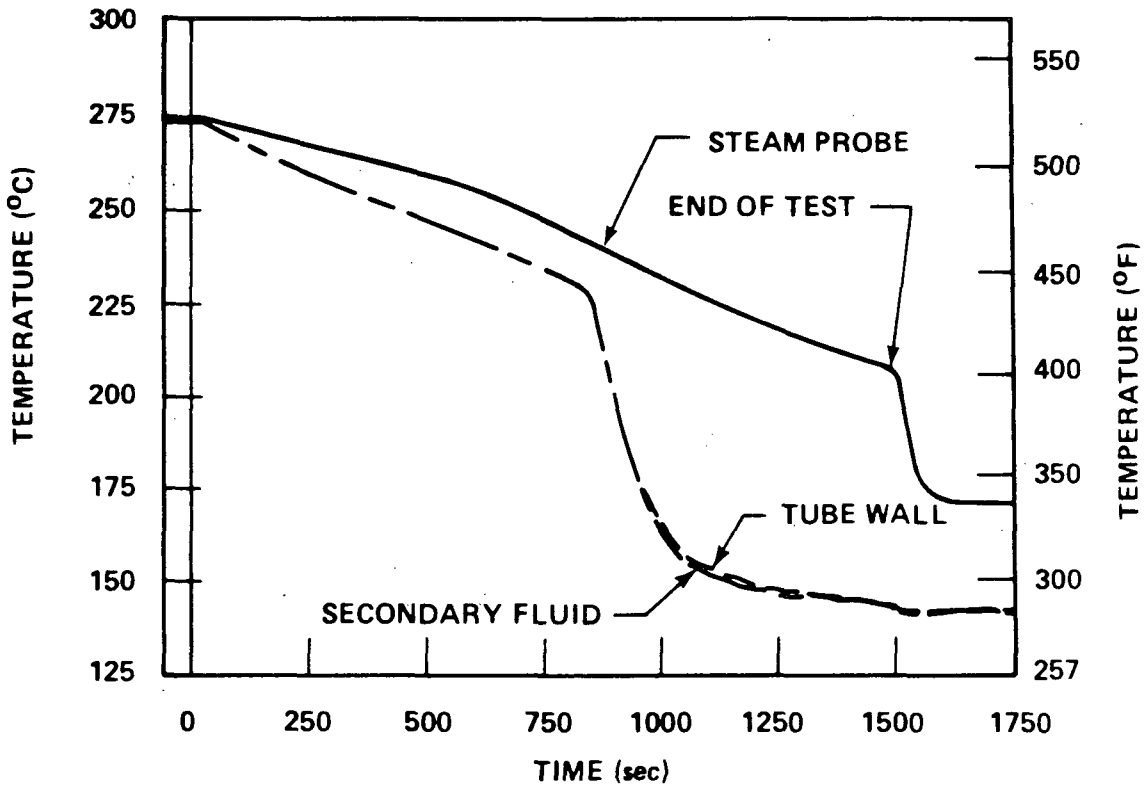


MEASURED RESPONSE

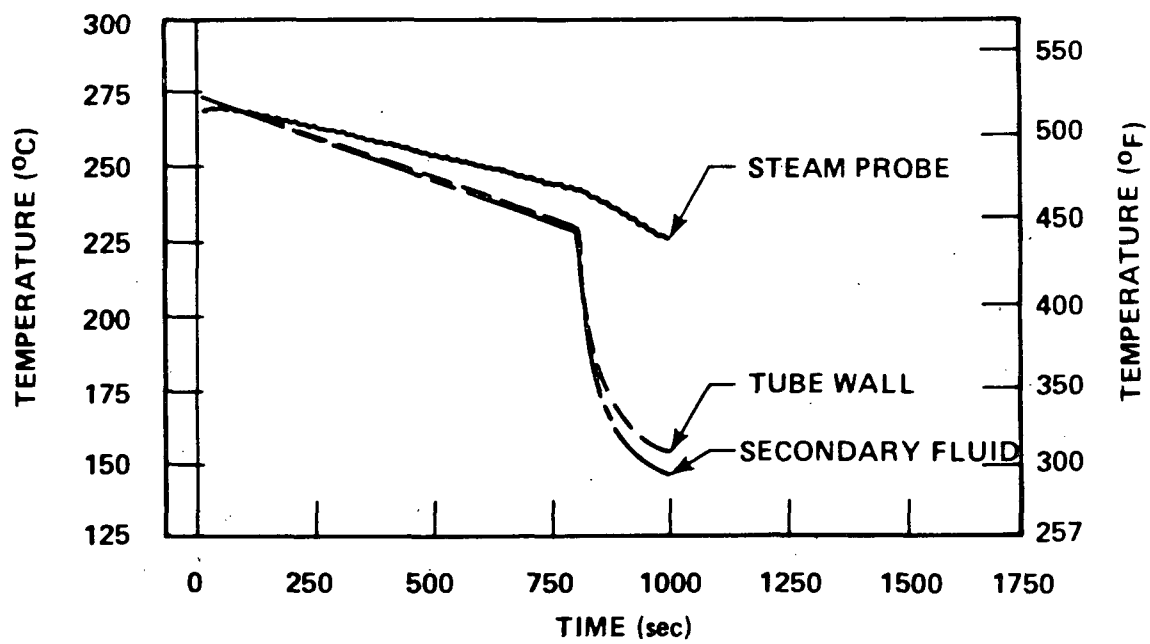


PREDICTED RESPONSE

Figure 6-12. Reference Run Prediction Versus Data, Inlet Region Local Temperature



MEASURED RESPONSE



PREDICTED RESPONSE

Figure 6-13. Reference Run Prediction Versus Data, Outlet Region Local Temperature

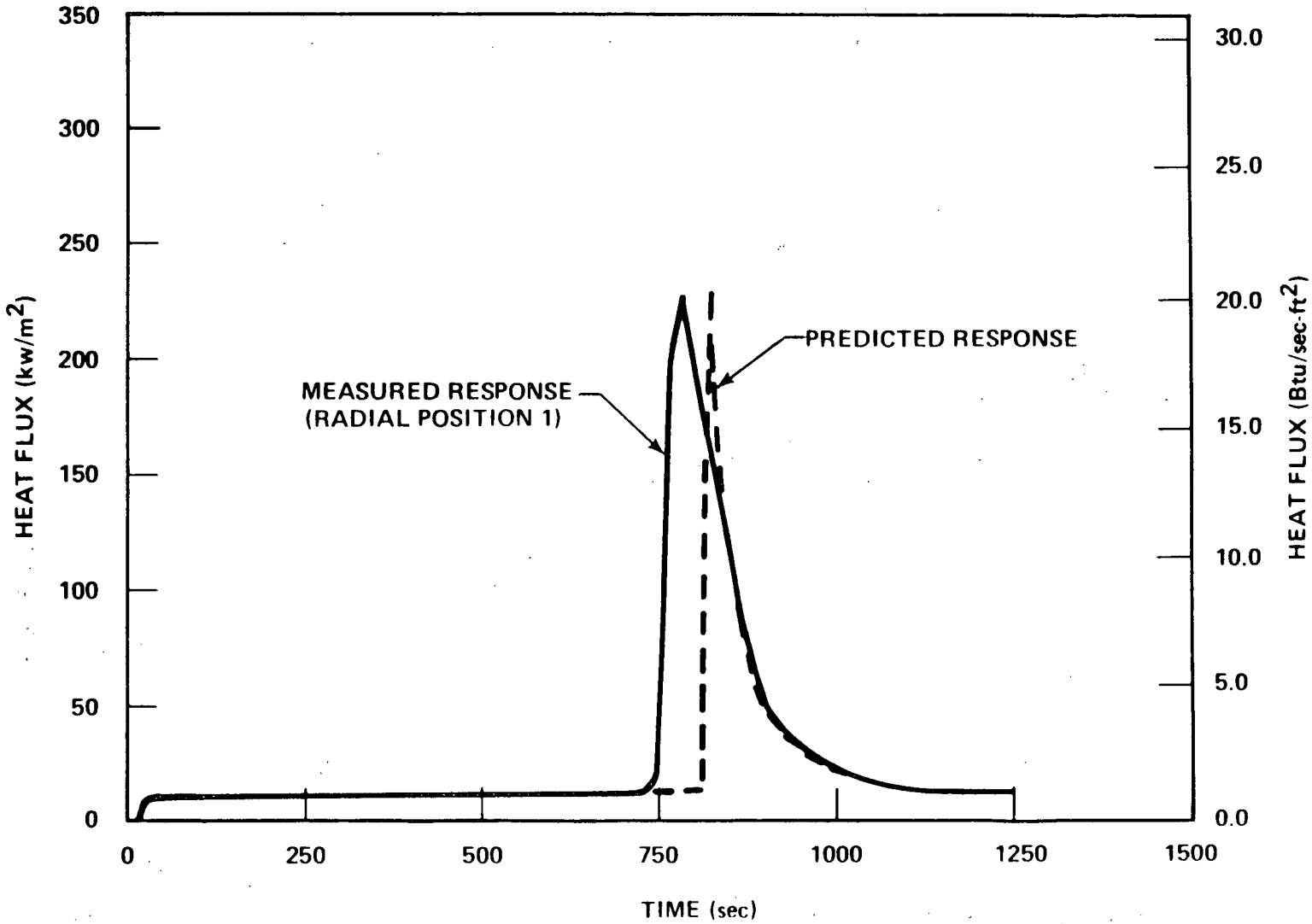


Figure 6-14. Reference Run Prediction Versus Data, Tube Wall Heat Flux, 1.22 m (4 ft) Elevation

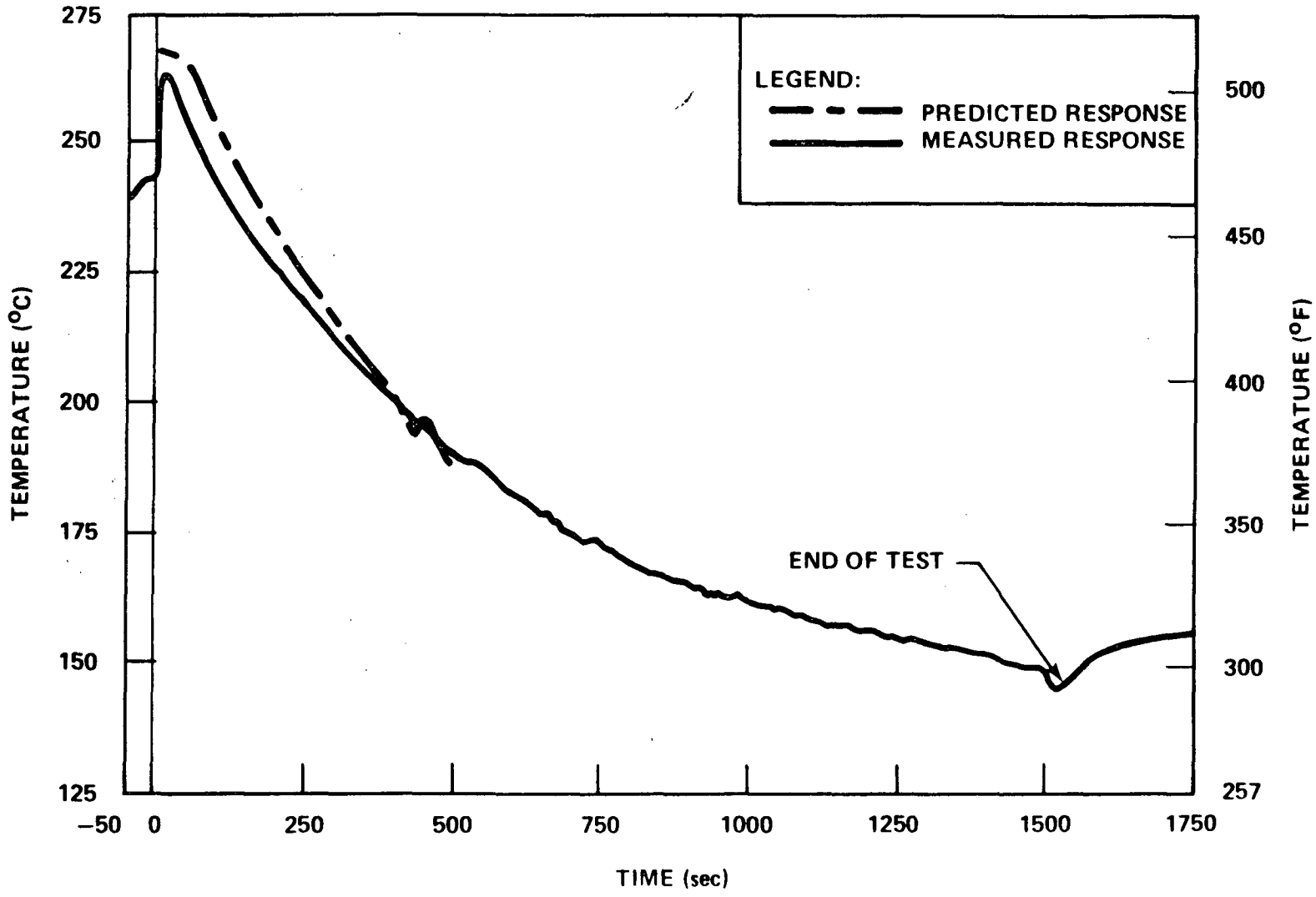


Figure 6-15. Flow Sensitivity Run Prediction Versus Data, Outlet Plenum Steam Temperature

16817-21

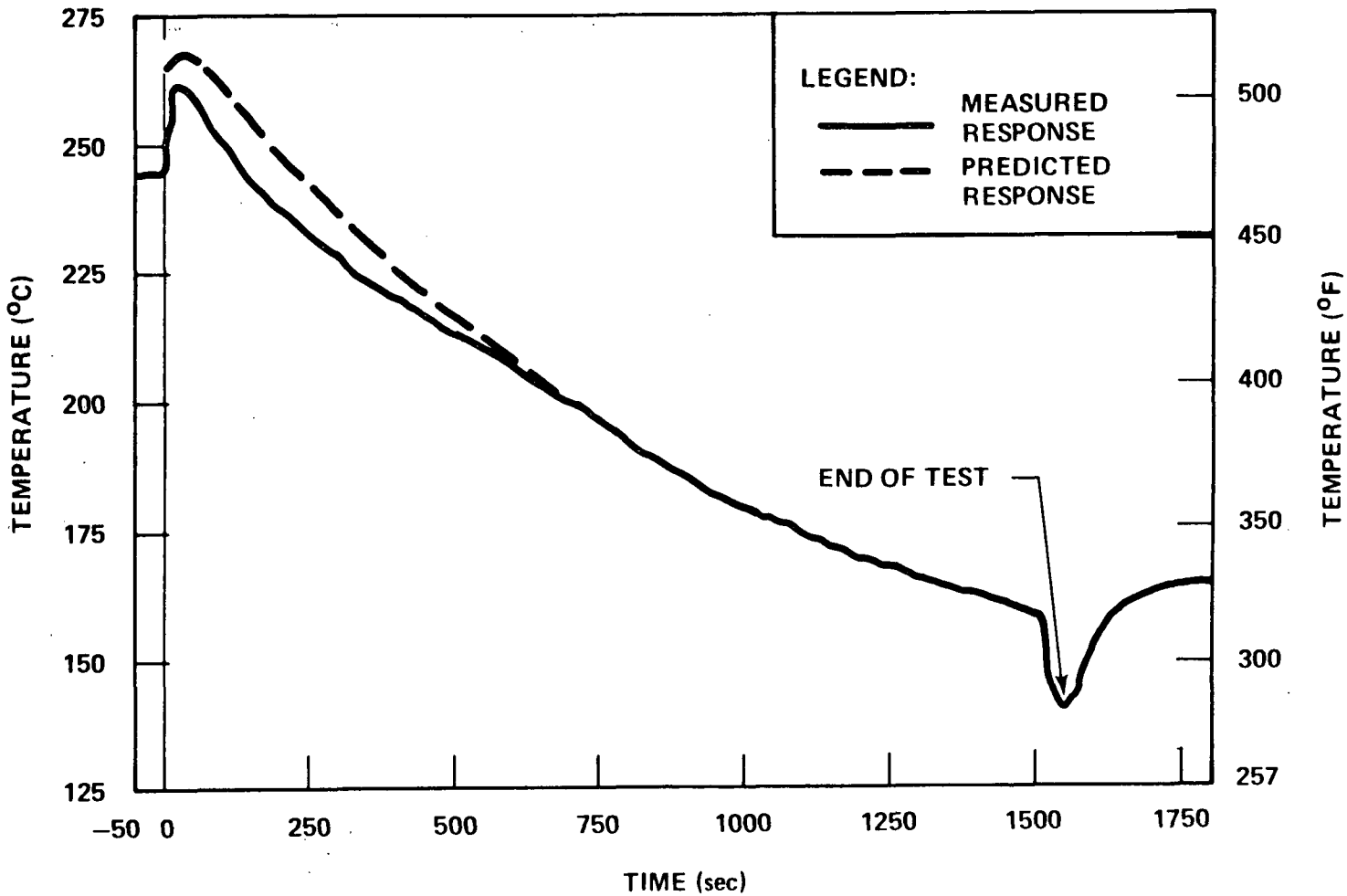


Figure 6-16. Pressure Sensitivity Run [0.14 MPa (20 psia)] Prediction Versus Data, Outlet Plenum Steam Temperature

16817-22

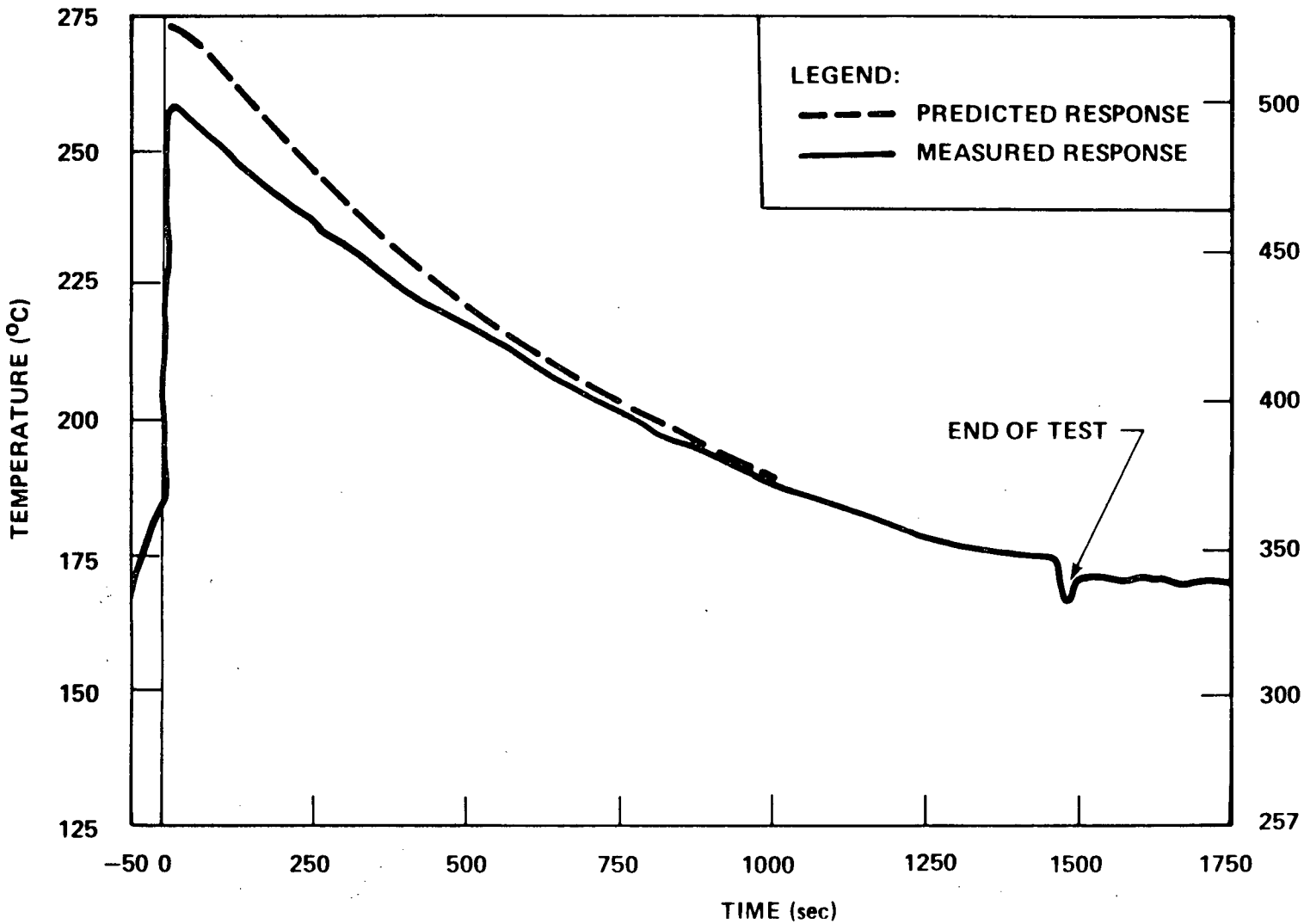


Figure 6-17. Pressure Sensitivity Run [0.41 MPa (60 psia)] Prediction Versus Data, Outlet Plenum Steam Temperature

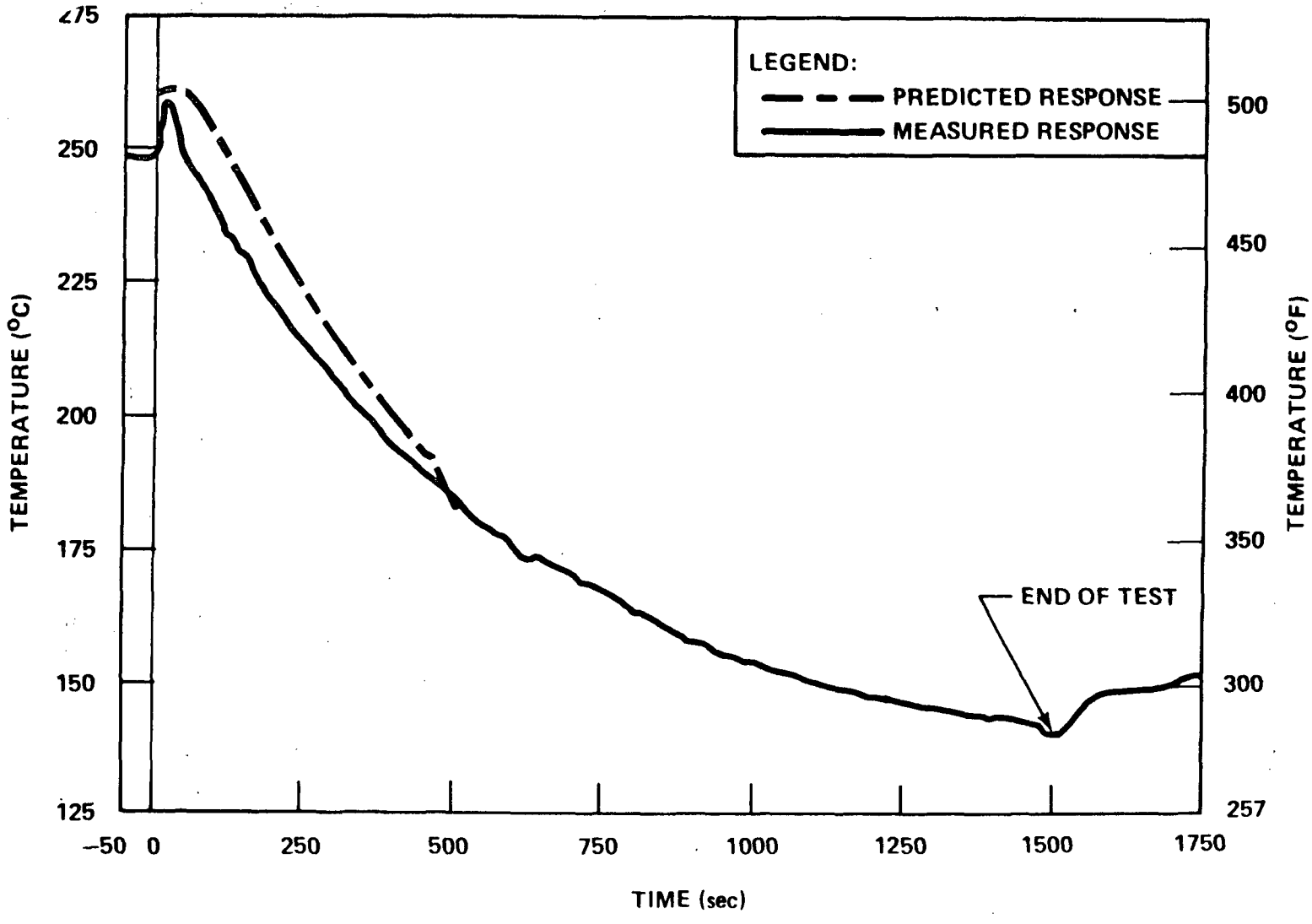


Figure 6-18. Quality Sensitivity Run (x=0.5) Prediction Versus Data, Outlet Plenum Steam Temperature

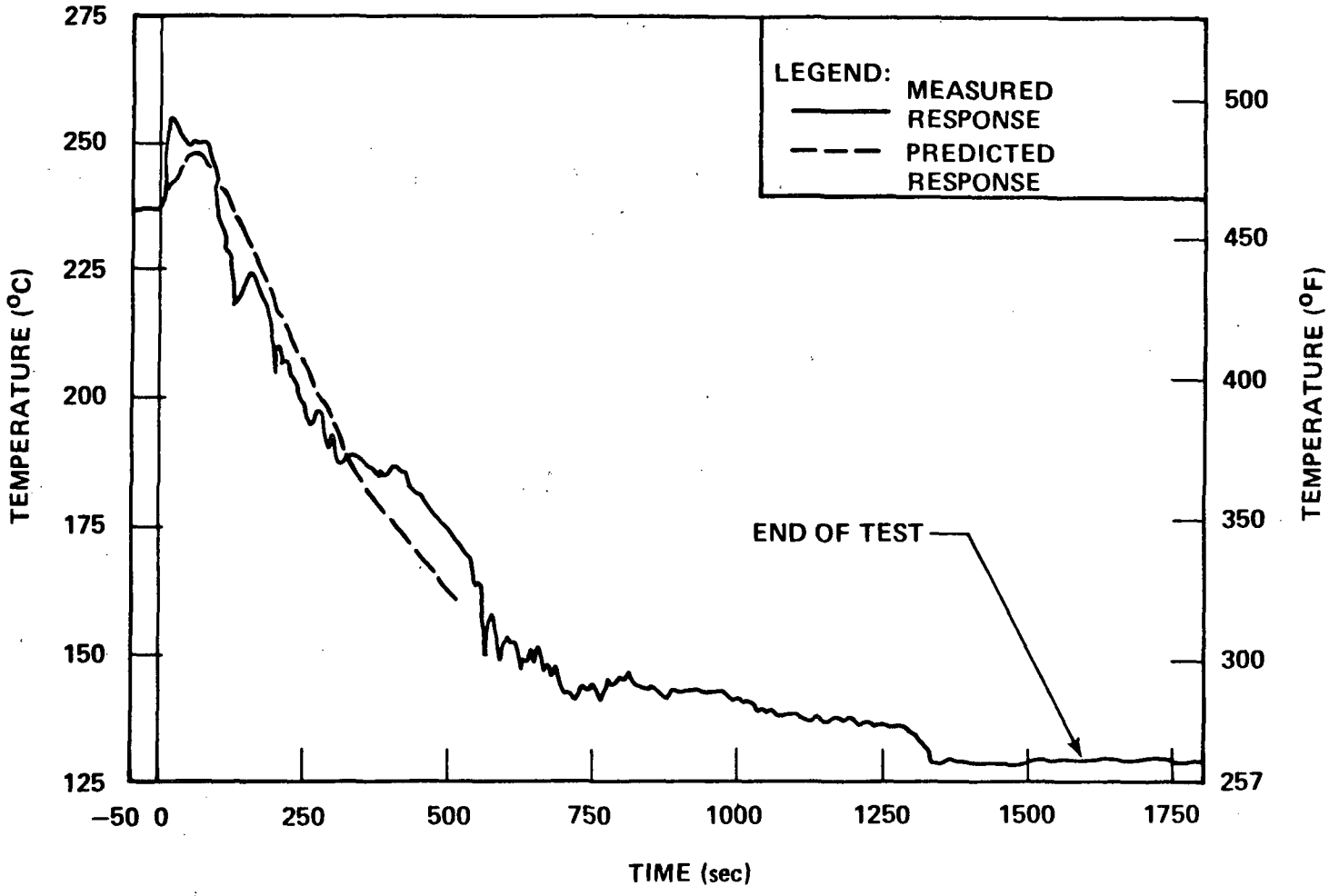


Figure 6-19. Quality Sensitivity Run (x=0.2) Prediction Versus Data, Outlet Plenum Steam Temperature

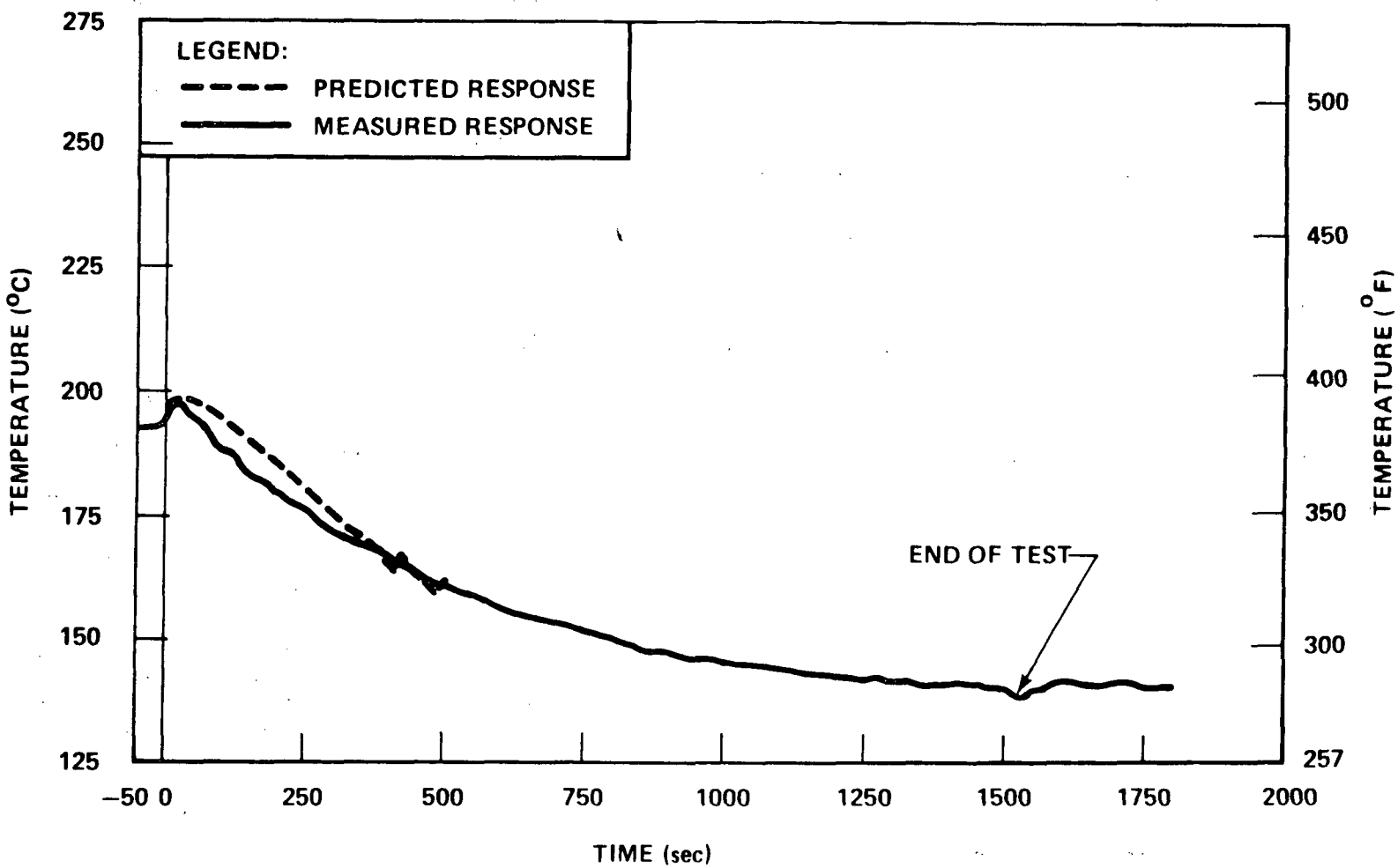


Figure 6-20. Secondary Temperature Sensitivity Run [204°C (400°F)] Prediction Versus Data, Outlet Plenum Steam Temperature

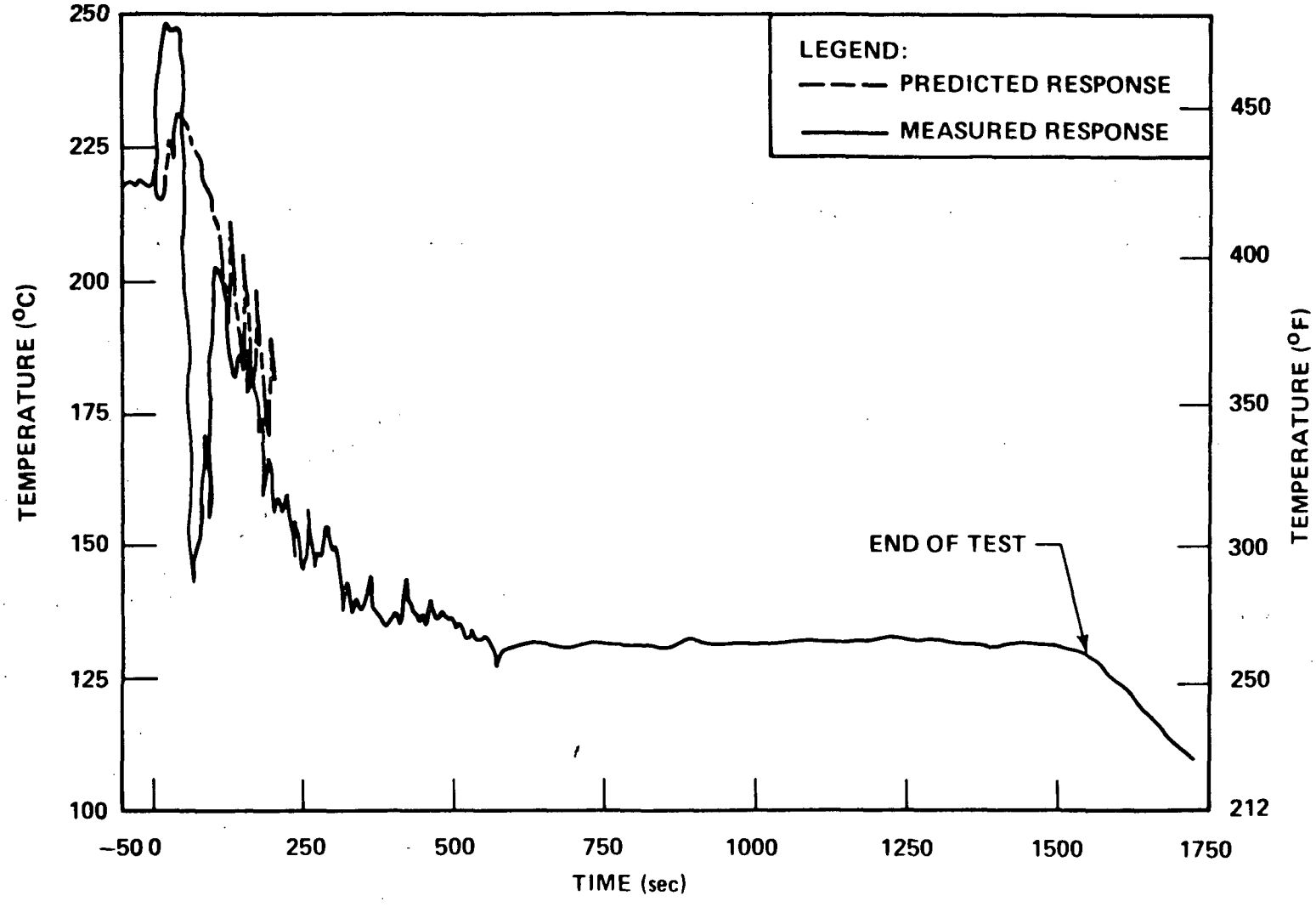


Figure 6-21. Postbundle Quench Run [x=0.10, Flow Rate = 0.45 kg/sec (1.0 lb/sec)] Prediction Versus Data, Outlet Plenum Steam Temperature

16817-27

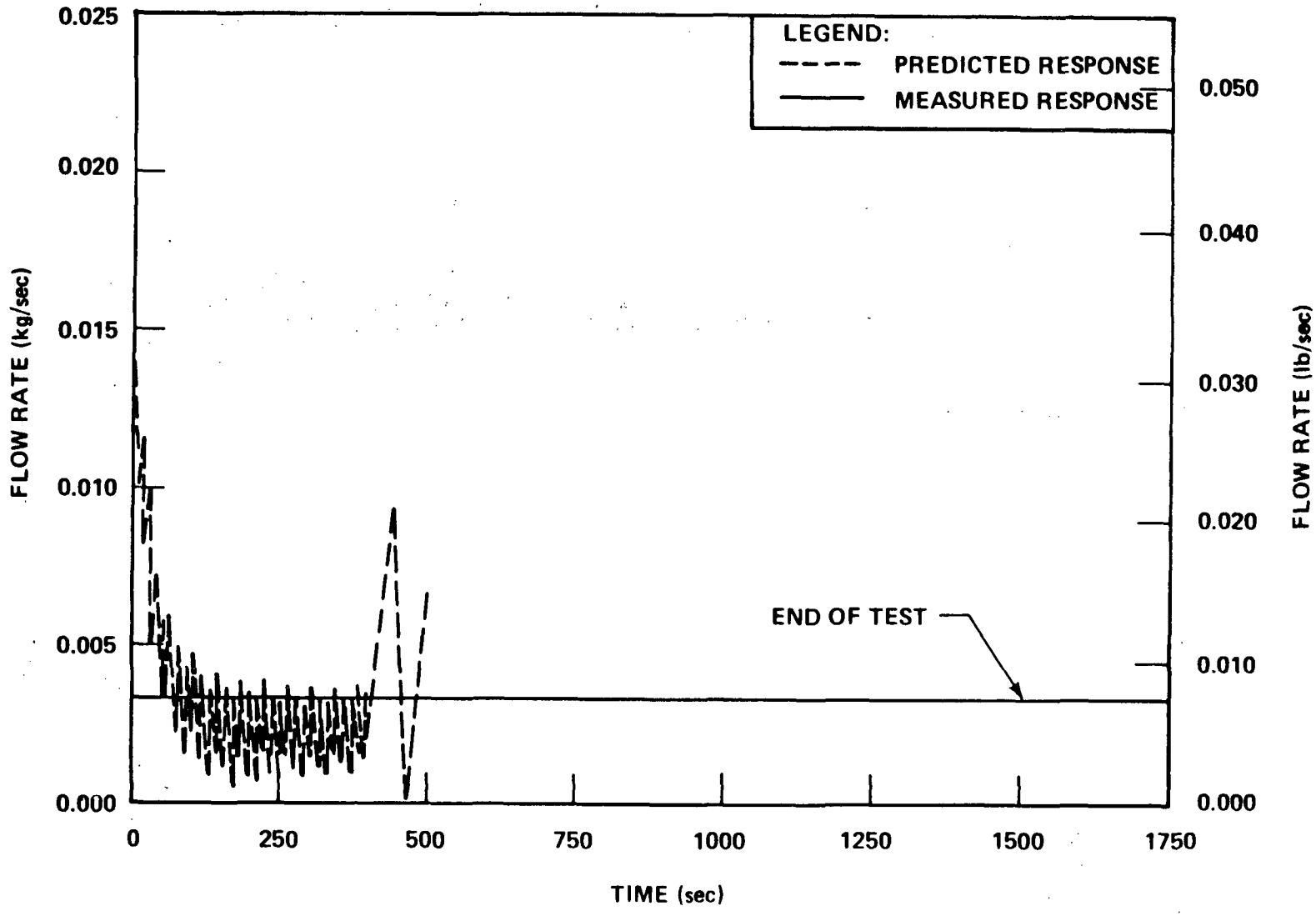


Figure 6-22. Flow Sensitivity Run Prediction Versus Data, Outlet Plenum Liquid Flow

16817-77

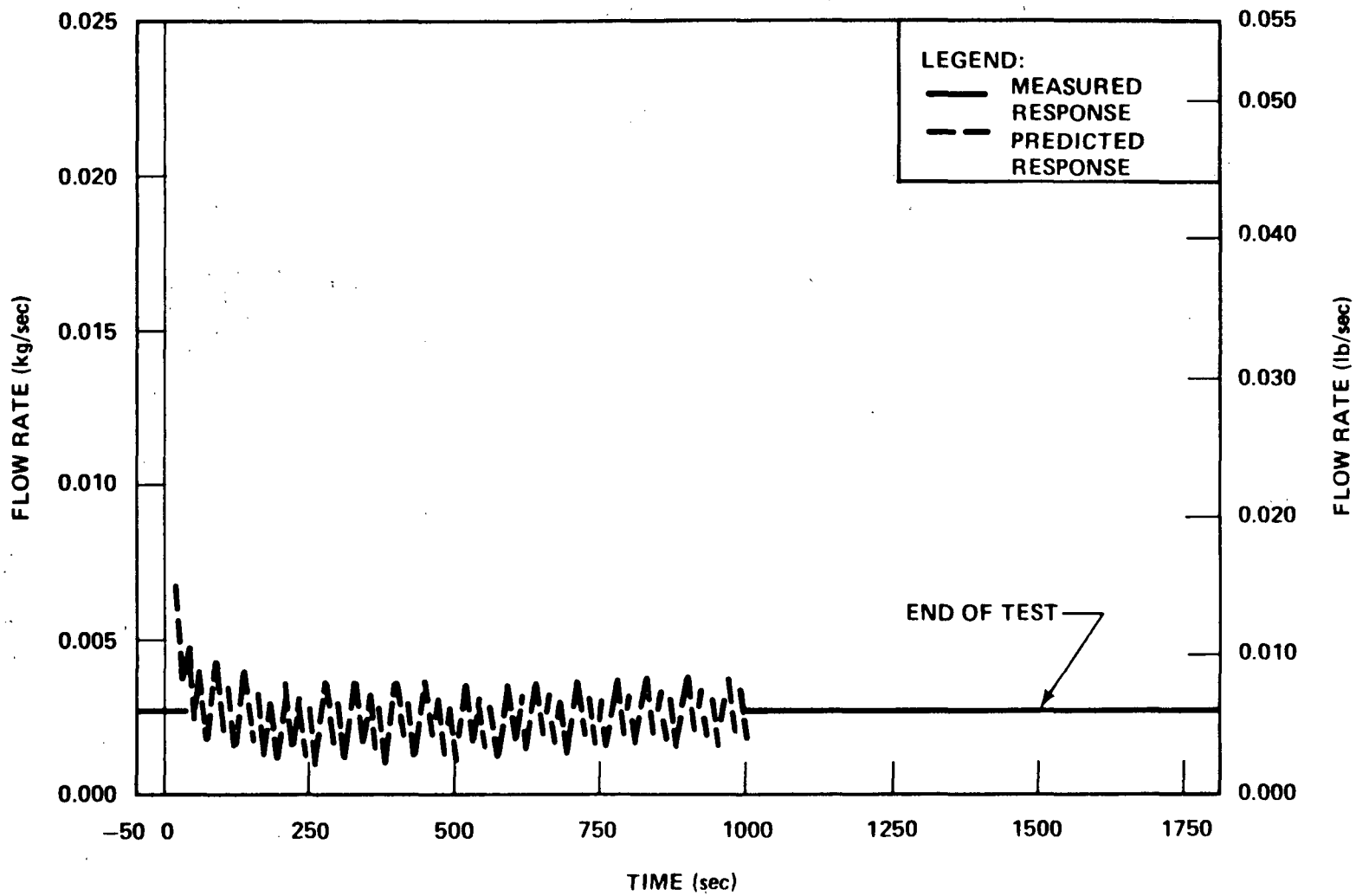


Figure 6-23. Pressure Sensitivity Run [0.14 MPa (20 psia)] Prediction Versus Data, Outlet Plenum Liquid Flow

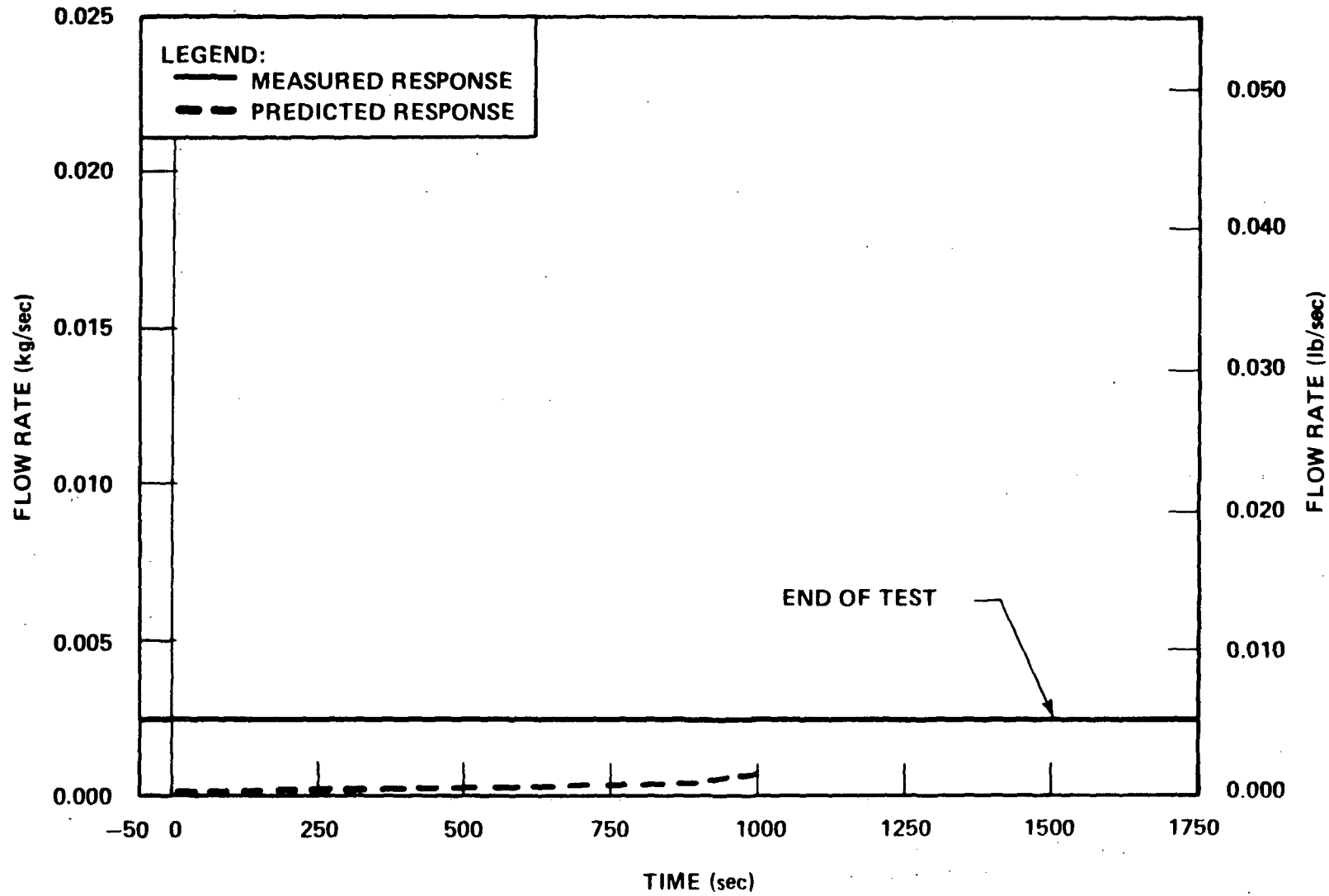


Figure 6-24. Pressure Sensitivity Run [0.41 MPa (60 psia)] Prediction Versus Data, Outlet Plenum Liquid Flow

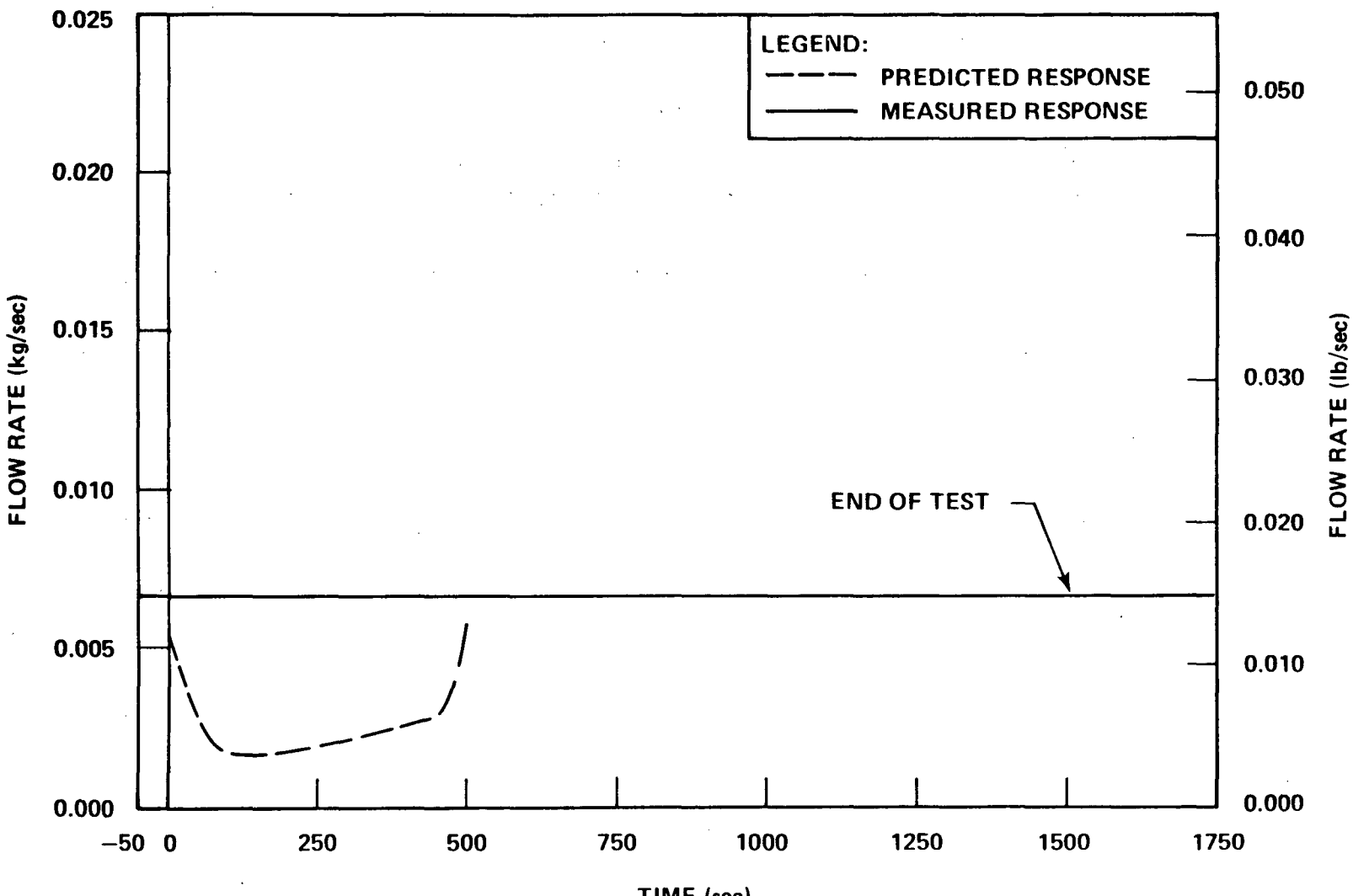


Figure 6-25. Quality Sensitivity Run (x=0.5) Prediction Versus Data, Outlet Plenum Liquid Flow

16817-80

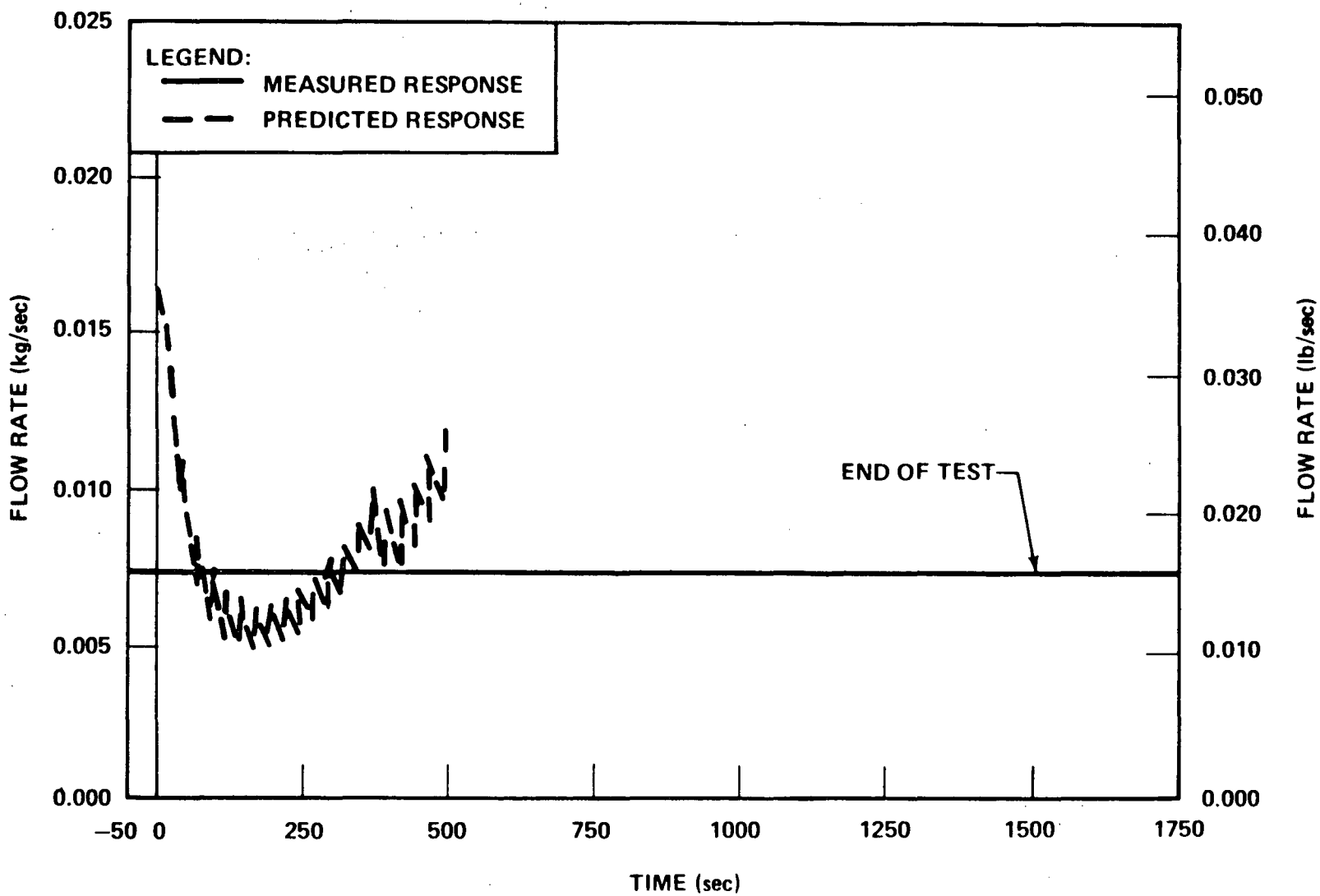


Figure 6-26. Quality Sensitivity Run (x=0.2) Prediction Versus Data, Outlet Plenum Liquid Flow

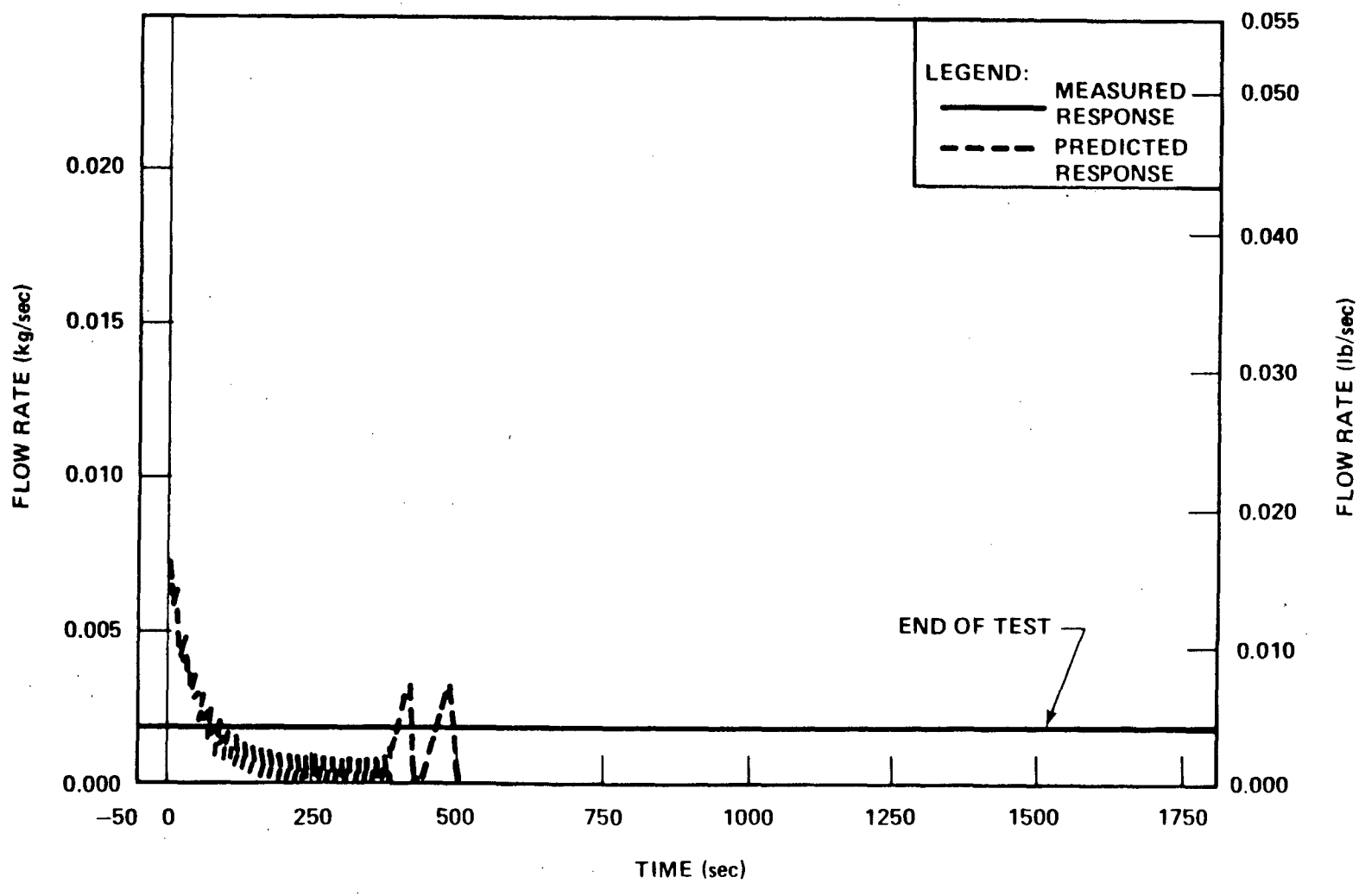


Figure 6-27. Secondary Temperature Sensitivity Run [204°C (400°F)] Prediction Versus Data, Outlet Plenum Liquid Flow

16817-82

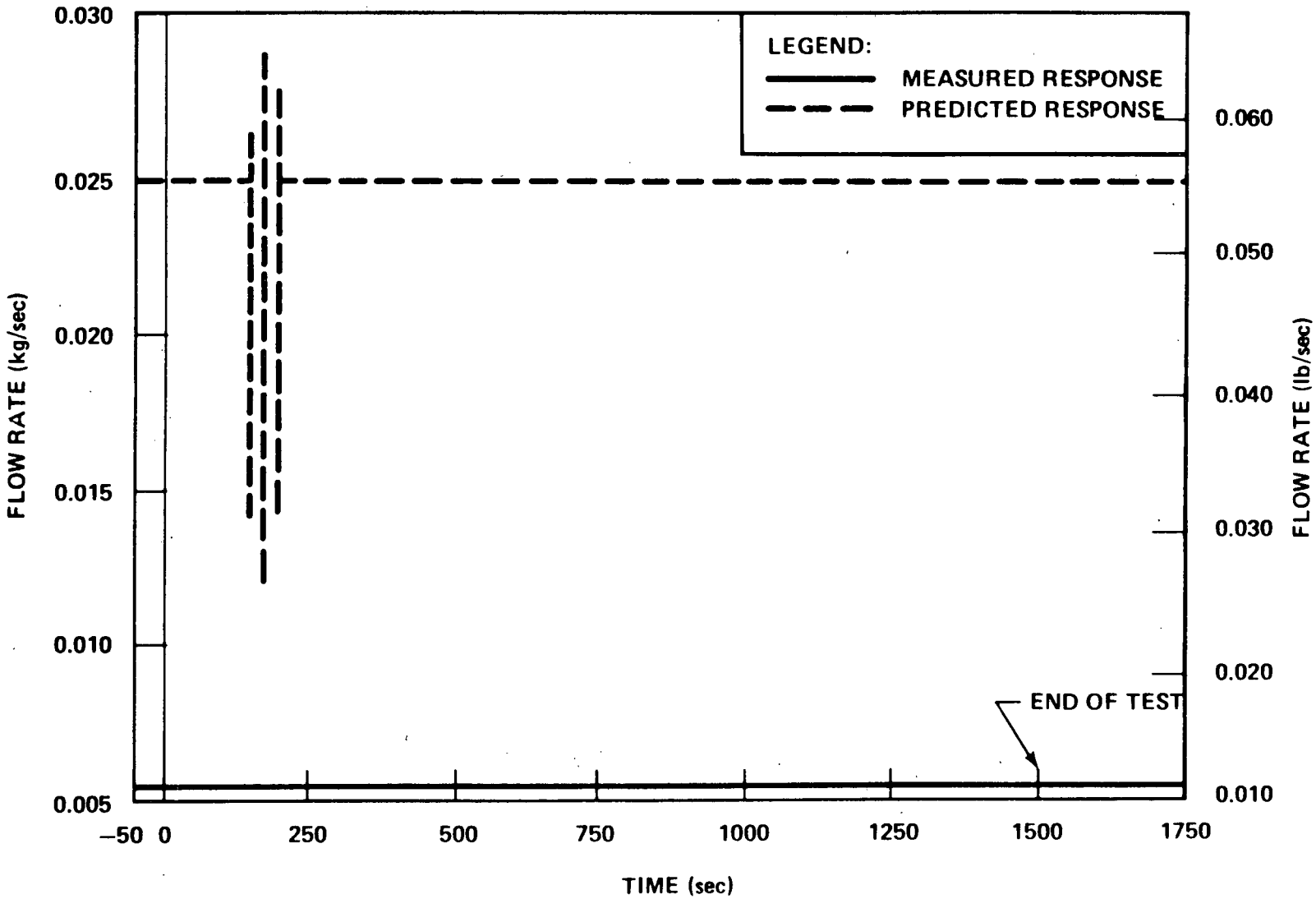


Figure 6-28. Postbundle Quench Run [x=0.10, Flow Rate = 0.45 kg/sec (1.0 lb/sec)] Prediction Versus Data, Outlet Plenum Liquid Flow

16817-83

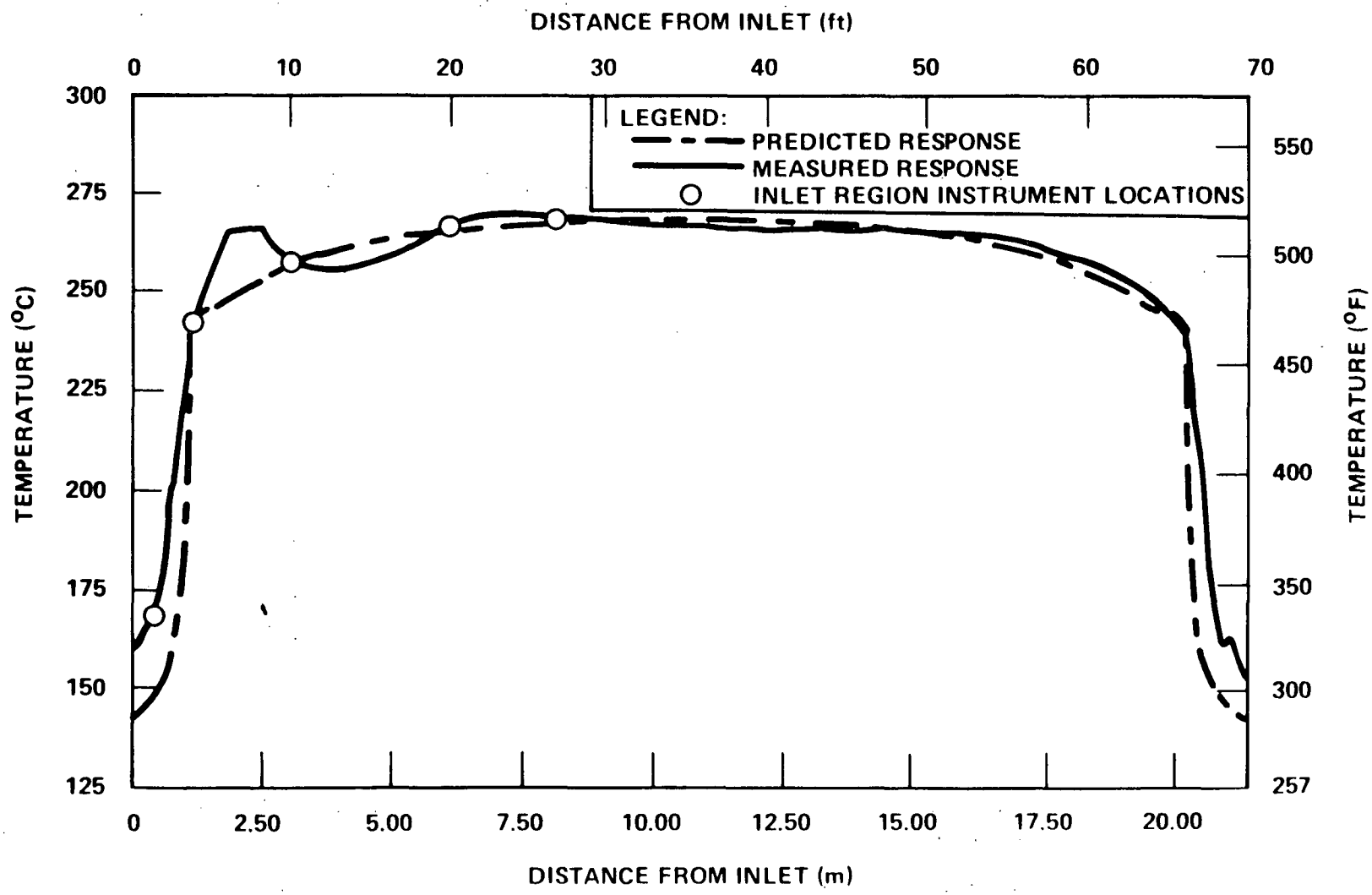


Figure 6-29. Flow Sensitivity Run Prediction Versus Data, Axial Temperature Variation of Secondary Fluid

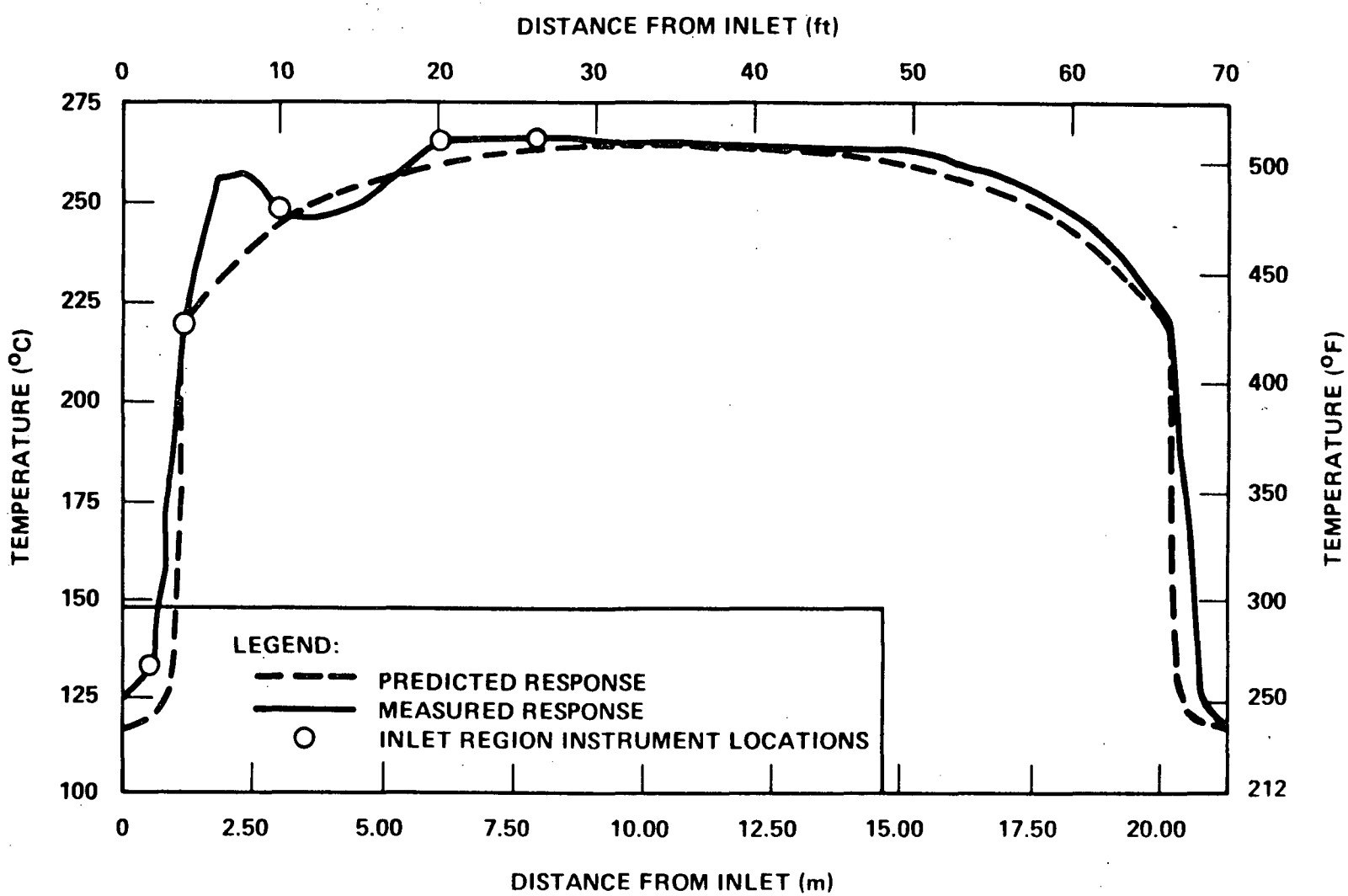


Figure 6-30. Pressure Sensitivity Run [0.14 MPa (20 psia)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid

16817-43

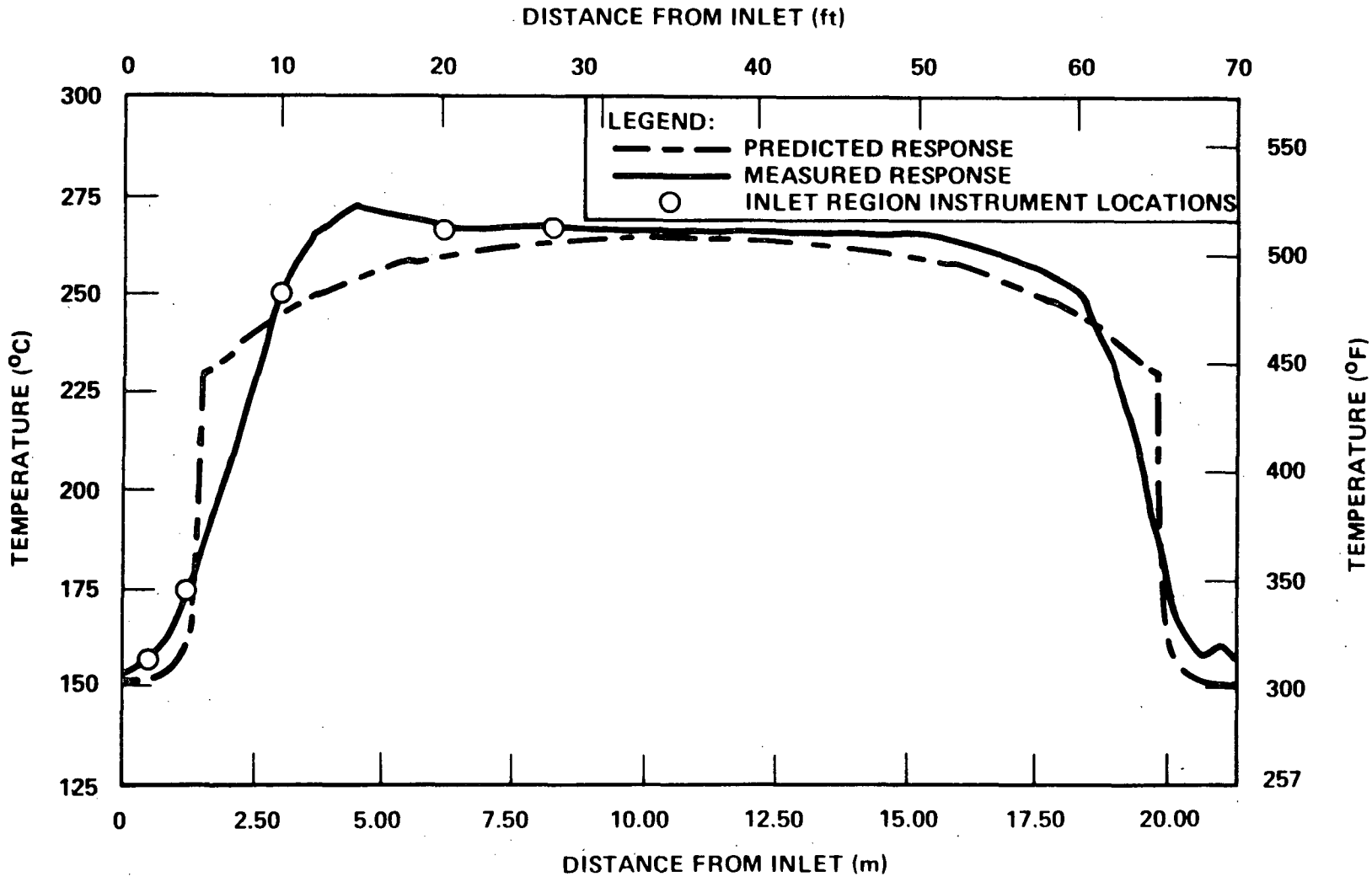


Figure 6-31. Pressure Sensitivity Run [0.41 MPa (60 psia)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid

16817-44

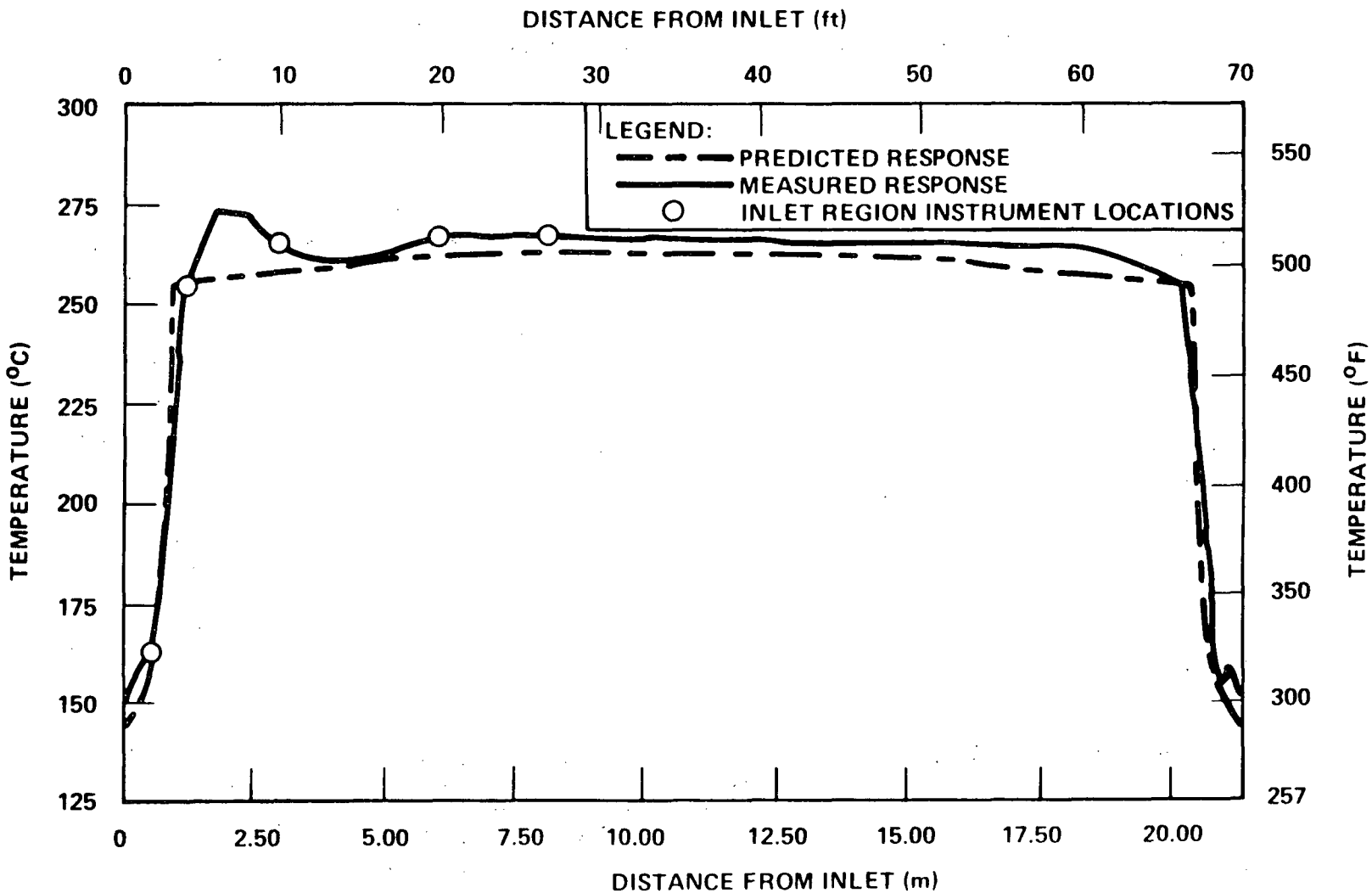


Figure 6-32. Quality Sensitivity Run (x=0.5) Prediction Versus Data, Axial Temperature Variation of Secondary Fluid

16817-45

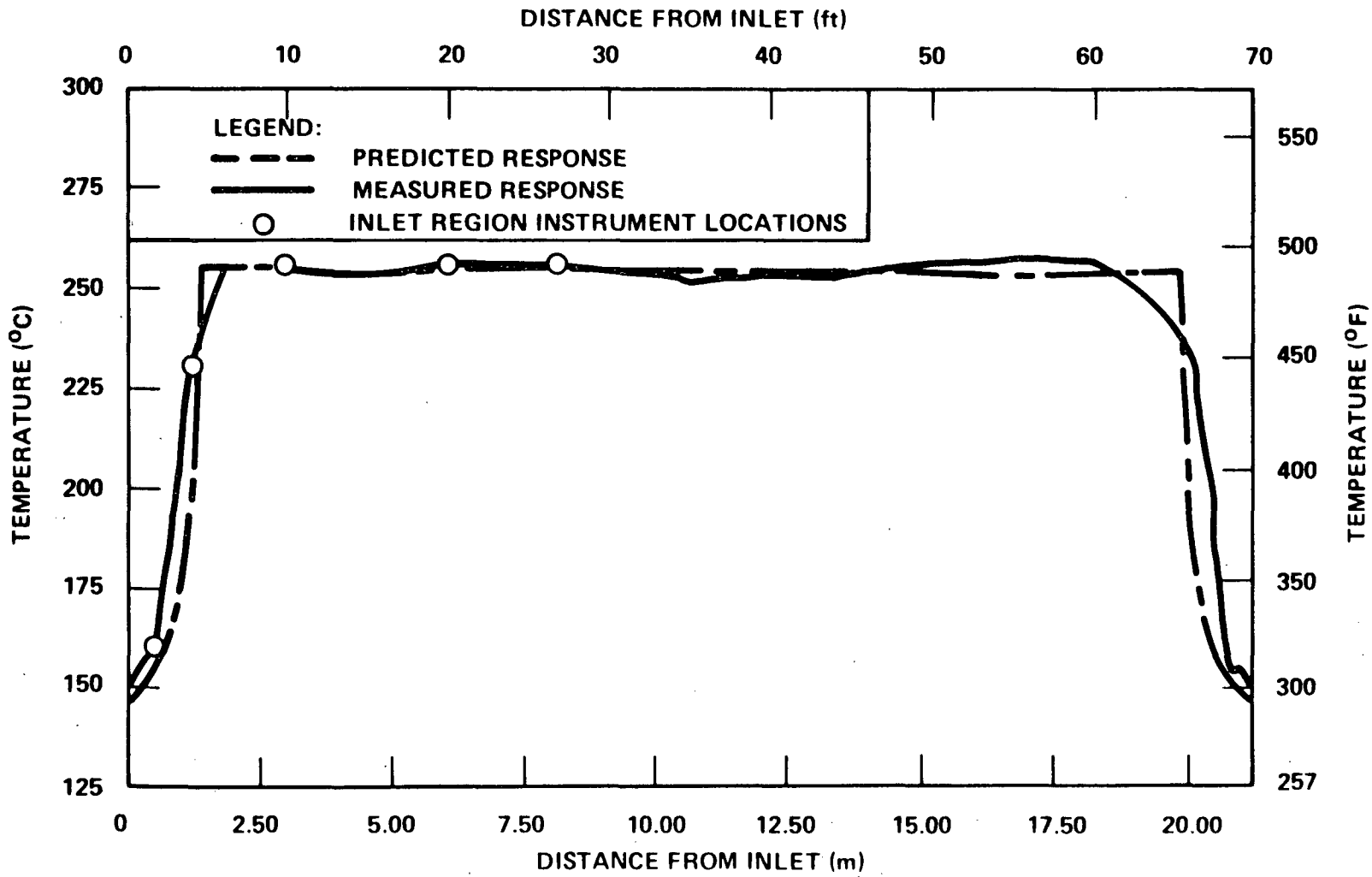


Figure 6-33. Quality Sensitivity Run (x=0.2) Prediction Versus Data, Axial Temperature Variation of Secondary Fluid

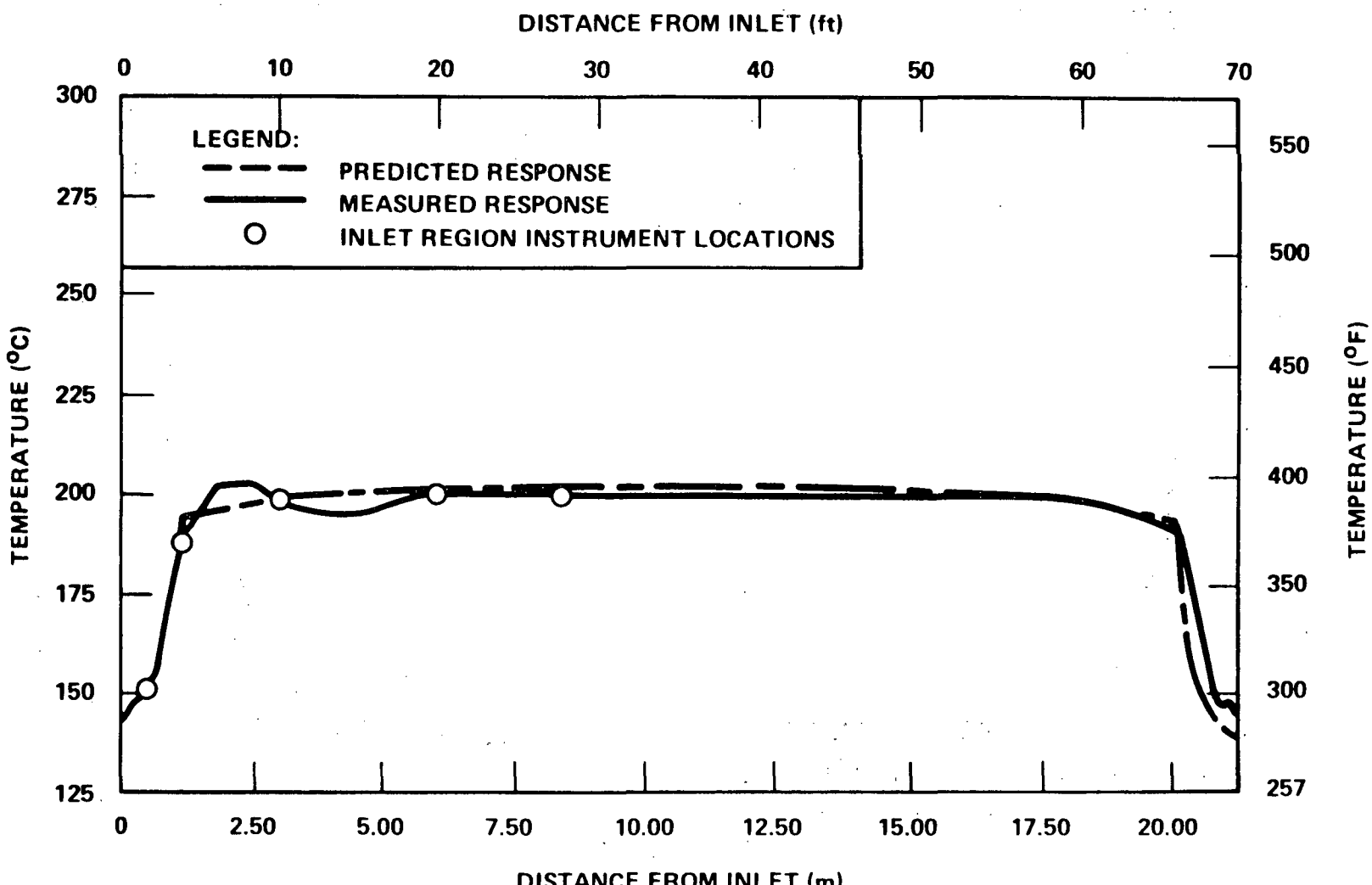


Figure 6-34. Secondary Temperature Sensitivity Run [204°C (400°F)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid

16817-47

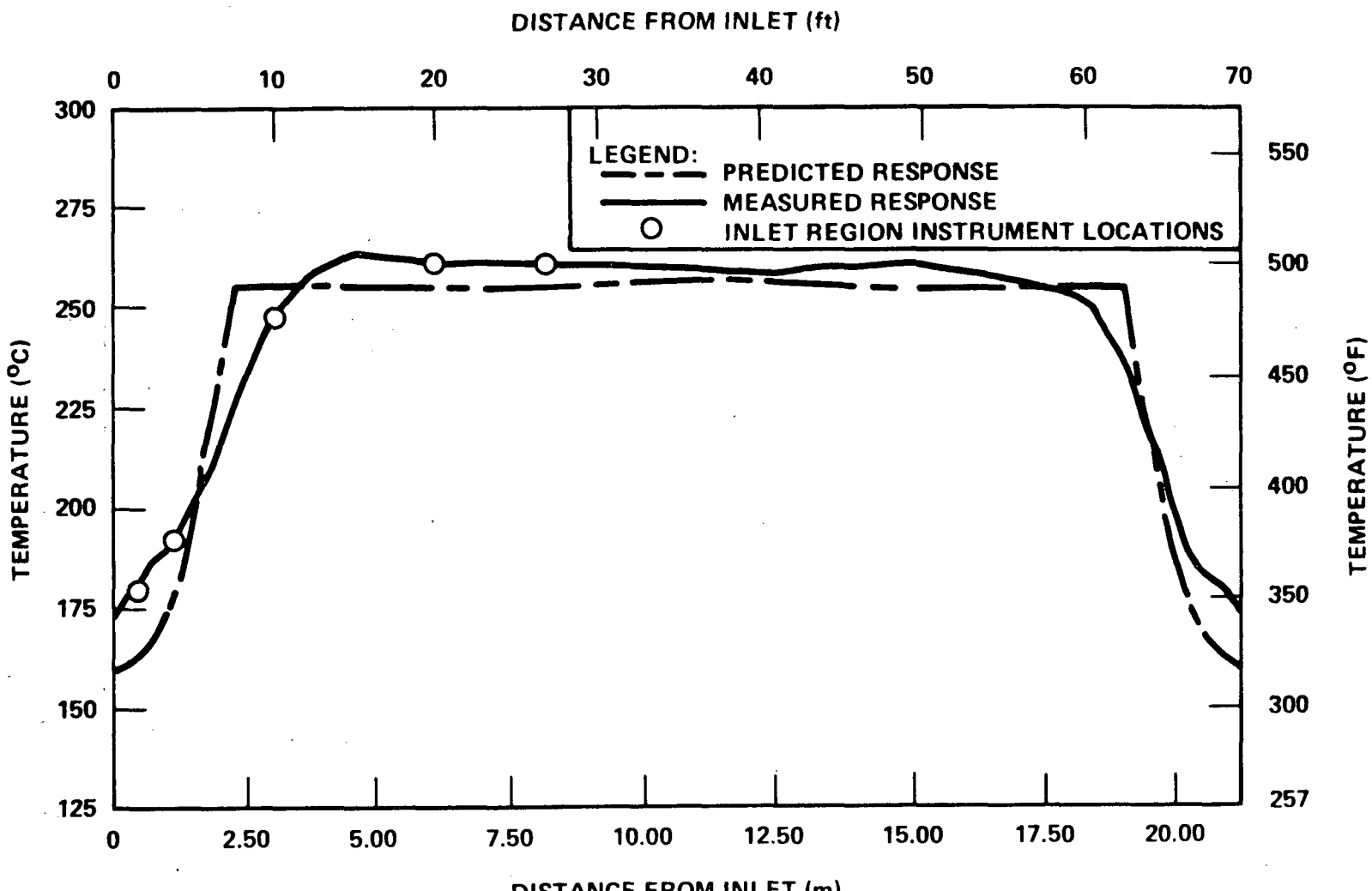


Figure 6-35. Postbundle Quench Run [x=0.10, Flow Rate = 0.45 kg/sec (1.0 lb/sec)] Prediction Versus Data, Axial Temperature Variation of Secondary Fluid

16817-48

SECTION 7
SUMMARY AND CONCLUSIONS

7-1. SUMMARY

The data from all the steam generator separate effects tests described in Report No. 4[1] have been evaluated. The data show that the tube bundle heat transfer response over the broad range of parameter variations in the test matrix is basically consistent. In the vertical upflow region of the bundle, the tube wall undergoes a rapid quench as a liquid film is established on the primary side of the tube wall. This quench front moves at a near constant velocity whose magnitude is a function of the primary loop flow parameters and the secondary bundle temperature.

A large axial temperature gradient develops in the secondary fluid as the quench front moves up the tube bundle. The colder secondary fluid that forms in the inlet region of the bundle readily migrates to the outlet region of the bundle. After the axial temperature gradient is established in the outlet region of the tube bundle, heat transfer from the hotter primary side steam to the cooler secondary fluid occurs.

Although all of the tests measured liquid accumulation rates in the outlet plenum, the outlet plenum quality is typically about 99 percent. This indicates that virtually all of the entrained liquid in the inlet plenum is evaporated in the tube bundle.

The total bundle heat transfer rate is at a maximum at time zero and decays to a constant rate which continues until the quench elevation reaches the top of the tubes. At this time the outlet plenum quality rapidly drops from a value close to 100 percent to a value close to the inlet plenum quality.

Variations in the radial distribution of the liquid phase at the tube bundle entrance have no detectable effect on the overall bundle response. From the local thermocouple data

---

1. Howard, R. C., et al., "PWR FLECHT SEASET Steam Generator Separate Effects Task Data Report," NRC/EPRI/Westinghouse-4, January 1980.

within the tube bundle, the local tube wall heat flux was calculated. Other local test data include a series of inlet plenum air/water tests which measured the air and water mass flow rates at the tube bundle entrance. The air/water test data were used to aid in the understanding of observed trends in the local tube wall heat flux data. In general, tubes with the highest liquid flow rates within a test also had the highest local heat flux.

The steam generator heat transfer response during the reflood phase of a large-break LOCA can be modeled using correlations from the open literature for single-phase and two-phase forced convection and turbulent free convection. To define the regions where these correlations apply, the location of the quench front must be known. An empirical correlation can be formulated from the test data to determine the quench front elevation. The heat release from the secondary fluid can be adequately modeled by assuming one common node of a given elevation which includes both inlet and outlet regions of the tube bundle. The secondary fluid nodal heat capacity can be modeled as a point with a lumped nodal heat capacity equal to the product of the total node secondary fluid mass and specific heat. The secondary fluid temperature is calculated from an energy balance on the secondary fluid node. Heat exchange between the secondary fluid node and the primary fluid consists of two terms. One term describes the heat transfer that occurs in the upflow inlet side of the U-tube, and the second term describes the heat transfer that occurs in the downflow outlet side of the U-tube. In both of these heat transfer calculations, the same secondary fluid temperature is used. The secondary fluid mass is assumed to be stationary, and axial heat conduction in the secondary fluid is neglected.

7-2. CONCLUSIONS

The objectives of the steam generator separate effects test were to develop a detailed understanding of the steam generator heat release and the secondary side fluid behavior during a large-break LOCA reflood transient. Also, the methods developed and verified in the separate effects test for calculating the bundle heat release from the secondary fluid and tube wall thermocouples were intended to be used in the systems effects reflood tests to determine the steam generator heat release. The final objective of the steam generator separate effects test was to develop a predictive model of the heat transfer process.

A mathematical model of the steam generator bundle heat transfer has been developed. This model will predict the overall bundle heat transfer over a wide range of primary flow parameters and secondary fluid temperatures. The model uses an empirical quench velocity correlation to determine the quench front change with time.

The local tube wall heat flux can be calculated from the temperatures recorded by the installed secondary fluid and tube wall temperatures. The data reduction software used in the separate effects test can also be used in the systems effects tests[1] to measure the steam generator heat transfer during these tests.

In summary, all the objectives of the steam generator separate effects task identified above were accomplished.

---

1. Hochreiter, L. E., et al., "PWR FLECHT SEASET 161-Rod Bundle Flow Blockage Task: Task Plan Report," NRC/EPRI/Westinghouse-6, July 1980.

APPENDIX A

STEAM GENERATOR SEPARATE EFFECTS TEST EVALUATION COMPUTER PROGRAM

This appendix contains a listing of the computer program inputs used to predict the heat transfer response of the steam generator.

An input list for the program is given in table A-1.

A sample program output is presented after the program listing. Notes on the output clarify the output quantities.

TABLE A-1

EVALUATION PROGRAM INPUT LIST

Input	Definition	Program Default Value[a]
WFTOT	Total inlet plenum liquid flow rate	0.10 lb/sec
WGTOT	Total inlet plenum steam flow flow rate	0.40 lb/sec
TSEC	Secondary bundle initial temperature	525°F
WFWT	Weighting factor for WFTOT	1.0
WGWT	Weighting factor for WGTOT	1.0
PPRIM	Primary system pressure	40.0 psia
DO	Tube OD	0.875 in.
DI	Tube ID	0.775 in.
DELZ1	Coarse axial mesh interval	1.0 ft
DELZ2	Fine axial mesh interval	0.1 ft
DELT	Time step	10.0 sec

a. Reference case parameters

TABLE A-1 (cont)

EVALUATION PROGRAM INPUT LIST

Input	Definition	Program Default Value[a]
NZ1	Total number of axial mesh	160
NZ2	Number of fine mesh at inlet or outlet region of tube bundle	50
NT	Number of time steps	80
PSEC	Secondary pressure	850 psia
ASEC	Secondary fluid area per tube, including equivalent metal	0.030 ft^2
RHOCPT	Heat capacity of tube bundle metal per unit volume	57.04 Btu/ft^3-^oF
ENTER	Not used	--
QSS	Not used	--
ISS	Transient calculation request	1
CPR	Not used	--

a. Reference case parameters

```
      PROGRAM SGEVAL(INPUT,OUTPUT,FILMPR,TAPE5=INPUT,TAPE6=FILMPR,TAPE1,000270
     *TAPE2,PLTOUT)                                                     000280
      REAL NUM                                                          000290
      DIMENSION QIN(300),TSECF(300),TSECI(300),TWALLI(300)              000300
      DIMENSION ZQTQ(200,2),TPOUTEL(300),TSECFEL(300),ELPLOT(300),      000310
     *TPOUTTM(200),ENTSMTM(200),TMPLOT(200),TITLEX(12),TITLEY(12),      000320
     *TITLE1(12),TITLE2(12),TITLE3(12),EL1PLOT(300),EMERTM(200)         000330
      DIMENSION QSECPLT(300),QSECTM(300)                                000340
      DIMENSION QSEC1(300),QSEC1T(300),QSEC2(300),QSEC2T(300),          000350
     *QSEC10(300),QSEC10T(300)                                          000360
      DIMENSION TITLDUM(12),TITALX1(12,3),TITALY1(12,5),TITALY2(12,5),  000370
     *TITALX(12,8),TITAL2(12,6),TITAL3(12,2)                            000380
      DIMENSION DDOUT(10),DDO(10),ALF(10)                               000390
      DIMENSION T(3),DT(3),E(21)                                        000400
      DIMENSION TPTM(300,6),TWTM(300,6),TSTM(300,6),CHOICEL(6)          000410
      COMMON/TITL/CPR,WETOT,WGTOT,TSEC,WEWT,WGWT,PPRIM,DO,DI,DELT,DELZ, 000420
     C  NT,PSEC,ASEC,RHOCPT,ENTER,QSS,ISS,NCAS,NPL,DELZ1,DELZ2,NZ1,NZ2 000430
      COMMON/DROPS/RHOL,TSATP,TPIN,WGIN,DD(10),NUM(10),                 000440
     *HPP,QOUTA,WGOUT,ENTSM                                             000450
      COMMON/QT/VISCGP,CONDVP,ZGR,QUEL,CONDLS,PE,ZQ,E1,E2               000460
      COMMON/CONTRL/NOWRITE,JTAPE,MANYLIN,LABSIZ,SSIZ,LWIDTH,SYMSIZ,    000470
     *XCONV,YCONV,TITLX2(12),TITLY2(12)                                 000480
      REAL LABSIZ                                                       000490
      NAMELIST/OPTION/WETOT,WGTOT,TSEC,WEWT,WGWT,PPRIM,DO,DI,DELZ1,     000500
     CDELZ2,DELT,TLEN,NZ2,NT,PSEC,ASEC,RHOCPT,ENTER,QSS,ISS,CPR,MTX,    000510
     *TUBES                                                             000520
      DATA CHOICEL/1.0,4.0,10.0,60.0,66.0,69.0/                         000530
      DATA WETOT,WGTOT,TSEC,WEWT,WGWT,PPRIM,DO,DI,DELZ1,DELZ2,DELT,MTX, 000540
     *CPR/0.10,0.4,525.0,1.0,1.0,40.0,0.875,0.775,1.0,0.1,10.0,1,1.0/   000550
      DATA TLEN,TUBES,NZ2,NT,PSEC,ASEC,RHOCPT,ENTER,QSS,ISS/70.0,32.,50,000560
     C80,850.0,0.039,57.04,0.0,10.0,0/                                  000570
      DATA TSECI,TWALLI/300*0.0,300*0.0/                                000580
      DATA PI,ALF/3.14159,5*0.0,5*0.2/                                  000590
      DATA DDO/.00375,.00225,.00150,.00117,.000917,.000708,.000542,     000600
     *.000417,.000292,.000125/                                          000610
      DATA N,I1,I2,E2,TSTART/3,2,1.0E-6,1.0E-4,0/                       000620
      DATA DDOUT/10*0/                                                  000630
      DATA NUM/10*0.0/                                                  000640
      DATA TITLX2/12*4H                                                 000650
      DATA TITLDUM/12*4H                                                000660
      DATA TITALX1/4HDISTAN,4HCE FRO,4HM INLE,4HT (FT),8*4H             000670
     *4HTIME (,4HSECOND,4HS)     ,8*4H      ,                           000680
     *4HQUENCH,4H TIME ,4H(SECON,4HDS)    ,8*4H                        00069
      DATA TITALY1/                                                     00070
```

```
      *6HTEMPER,6HATURE ,6H(DEGRE,6HE C)  ,8*6H       ,                  000710
      *6HFLOW R,6HATE (G,6HRAMS/S,6HECOND),8*6H       ,                  000720
      *6HQUENCH,6H ELEVA,6HTION (,6HMETERS,6H)      ,7*6H       ,         000730
      *6HTUBE W,6HALL HE,6HAT FLU,6HX (KW/,6HSQ MET,6HER)   ,            000740
      *6*6H       ,                                                      000750
      *6HTOTAL ,6HENERGY,6H TRANS,6HFER (K,6HW)     ,7*6H       /         000760
       DATA TITALY2/                                                     000770
      *6HTEMPER,6HATURE ,6H(DEGRE,6HE F)  ,8*6H       ,                  000780
      *6HFLOW R,6HATE (L,6HBS/SEC,6HOND)  ,8*6H       ,                  000790
      *6HQUENCH,6H ELEVA,6HTION (,6HFT)   ,8*6H       ,                  000800
      *6HTUBE W,6HALL HE,6HAT FLU,6HX (BTU,6H/SEC-S,6HQFT)  ,            000810
      *6*6H       ,                                                      000820
      *6HTOTAL ,6HENERGY,6H TRANS,6HFER (B,6HTU/SEC,6H)      ,            000830
      *6*6H       /                                                      000840
       DATA TITAL1/                                                      000850
      *6HPRIMAR,6HY SIDE,6H STEAM,6H PHASE,6H TEMP ,6HVS.   ,            000860
      *6*6H       ,                                                      000870
      *6HSECOND,6HARY FL,6HUID TE,6HMP VS.,8*6H       ,                  000880
      *6HOUTLET,6H PLENU,6HM STEA,6HM TEMP,6H VS. T,6HIME   ,            000890
      *6*6H       ,                                                      000900
      *6HOUTLET,6H PLENU,6HM LIQU,6HID FLO,6HW RATE,6H VS. T,            000910
      *6HIME    ,5*6H       ,                                            000920
      *6HQUENCH,6H ELEVA,6HTION V,6HS. QUE,6HNCH TI,6HME    ,            000930
      *6*6H       ,                                                      000940
      *6HTUBE W,6HALL HE,6HAT FLU,6HX VS. ,6HTIME  ,7*6H       ,         000950
      *6HTOTAL ,6HENERGY,6H TRANS,6HFER VS,6H. TIME,7*6H       ,         000960
      *6HLOCAL ,6HTEMPER,6HATURE ,6HVS. TI,6HME    ,7*6H       /         000970
       DATA TITAL2/                                                      000980
      *6HDISTAN,6HCE ALO,6HNG U-T,6HUBE AT,6H TIME=,6H      ,            000990
      *6HSEC    ,5*6H       ,                                            001000
      *6HFOR EL,6HEVATIO,6HN=3.95,6H FT   ,8*6H       ,                  001010
      *6H(1) ST,6HEAM PR,6HOBE  (,6H2) TUB,6HE WALL,6H  (3) ,            001020
      *6HSEC. F,6HLUID  ,4*6H       ,                                    001030
      *6HFOR EL,6HEVATIO,6HN=0.95,6H FT   ,8*6H       ,                  001040
      *6HFOR EL,6HEVATIO,6HN=1.95,6H FT   ,8*6H       ,                  001050
      *6HFOR EL,6HEVATIO,6HN=0.50,6H FT   ,8*6H       /                  001060
       DATA TITAL3/                                                      001070
      *6HMATRIX,6H RUN  ,10*6H       ,                                  001080
      *6HDIST. ,6HFROM [,6HNLET =,9*6H                                  001090
       CALL MOVEKA(330,0.0,QIN)                                          001100
       READ(1) WFTOT,WGTOT,TSEC,WFWT,WGWT,PPRIM,DO,DI,DELZ1,DELZ2,DELT,  001110
      *TLEN,NZ2,NT,PSEC,ASEC,RHOCPT,ENTER,QSS,ISS,CPP,TM,MTX,TUBES      001120
       IF(EOF(1)) 5,4                                                    001130
     4 ISTART=1                                                          001140
```

```
    9 READ(5,OPTION)                                                    001150
      IF(EOF(5))150,2                                                   001160
    2 CONTINUE                                                          001170
      XCONV=6.0                                                         001180
      YCONV=-2.0                                                        001190
      CALL MOVEAA(12,TITLDUM,TITLEX)                                    001200
      CALL MOVEAA(12,TITLDUM,TITLEY)                                    001210
      CALL MOVEAA(12,TITLDUM,TITLX2)                                    001220
      CALL MOVEAA(12,TITLDUM,TITLY2)                                    001230
      CALL MOVEAA(12,TITLDUM,TITLE1)                                    001240
      CALL MOVEAA(12,TITLDUM,TITLE2)                                    001250
      CALL MOVEAA(12,TITLDUM,TITLE3)                                    001260
      IF(TLEN.NE.70.0) WRITE(6,2005)                                    001270
      MP=1                                                              001280
      NSW=2                                                             001290
      NCAS=1                                                            001300
      NZ1=NZ2*2.0+(TLEN-DELZ2*2.0*NZ2)/DELZ1                            001310
      CONV=0.0                                                          001320
      IC=1                                                              001330
      DATA KT1,KT3,KT5,KT6,KT7,KT8,KT9/0,0,0,0,0,0,0/                   001340
      NOWRITE=1                                                         001350
      PANYLIN=1                                                         001360
      TM=DELT                                                           001370
      CALL HEADR                                                        001380
      TSATP=TSL(PPRIM)                                                  001390
      RHOL=1.0/VSL(TSATP)                                               001400
      H=HSV(PPRIM,TT,SS,VV)                                             001410
      HFG=HSV(PPRIM,X,Y,Z)-HSL(TSATP)                                   001420
      RHOG=1.0/VV                                                       001430
      VISCLP=VISL(PPRIM,TSATP)                                          001440
      VISCGP=VISV(PPRIM,TSATP)                                          001450
      CONDLS=CONDL(PSEC,TSATP)                                          001460
      CONDVP=CONDV(PPRIM,TSATP)                                         001470
      CONDLP=CONDL(PPRIM,TSATP)                                         001480
      IF(ISTART.NE.0) GO TO 6                                           001490
      DO 10 IZ=1,NZ1                                                    001500
      TSECI(IZ)=TSEC                                                    001510
   10 TWALLI(IZ)=TSEC-0.10                                              001520
      GO TO 7                                                           001530
    6 READ(1) (TSECI(ID),ID=1,300)                                      001540
      READ(1) (TWALLI(ID),ID=1,300)                                     001550
    7 IF(ISS.EQ.1) NT=1                                                 001560
      IF(ISS.EQ.2) NT=1                                                 00157
      NPL=1                                                             00158
```

```
      CALL MOVEAA(12,TITALX1(1,1),TITLEX)                               001590
      CALL MOVEAA(12,TITALY1(1,1),TITLEY)                               001600
      CALL MOVEAA(12,TITALY2(1,1),TITLY2)                               001610
      CALL MOVEAA(12,TITAL2,TITLE2)                                     001620
      CALL MOVEAA(12,TITAL3,TITLE3)                                     001630
      ENCODE(6,700,TITLE3(3)) MTX                                       001640
  700 FORMAT(I2,4X)                                                     001650
      XX=WGTOT/(WFTOT+WGTOT)                                            001660
      TQ4FT=(40.0/PPRIM)**0.25*(0.2/(1-XX))**0.84                       001670
     **(0.5/(WFTOT+WGTOT))**1.32*0.2154*(TSEC-267.0)**1.4803            001680
      QUEL=4.0/TQ4FT                                                    001690
      DO 110 K=IC,NT                                                    001700
      CALL MOVEAA(12,TITAL1(1,1),TITLE1)                                001710
      DELZ=0.0                                                          001720
      EL=0.0                                                            001730
      ELIPLOT(1)=EL1=0.0                                                001740
      KT2=0                                                             001750
      KT4=1                                                             001760
      KT6=KT6+1                                                         001770
      ZQ=QUEL*(TM-DELT)                                                 001780
      WGOUT=WGTOT*WGWT/TURES                                            001790
      WFOUT=WFTOT*WFWT/TURES*(1.-ENTFR)                                 001800
      TPOUTEL(1)=TPOUT=TSATP                                            001810
      ENTSM=0.0                                                         001820
      EIN=WFOUT*HSL(TSATP)+WGOUT*H                                      001830
      DO 100 I=1,NZ1                                                    001840
      EL=EL+0.5*DELZ                                                    001850
      DELZ=DELZ1                                                        001860
      IF(I.GT.NZ2.AND.I.LE.(NZ1-NZ2)) GO TO 16                          001870
      DELZ=DELZ2                                                        001880
   16 EL=EL+0.5*DELZ                                                    001890
      EL1=EL1+DELZ                                                      001900
      ENTR=0.0                                                          001910
      CHFR=CPR                                                          001920
      WGIN=WGOUT                                                        001930
      WFIN=WFOUT                                                        001940
      TPIN=TPOUT                                                        001950
      IF(WFIN.GT.0.0) GO TO 12                                          001960
      DO 11 J=1,10                                                      001970
   11 DD(J)=DDOUT(J)                                                    001980
   12 ZGP=5.63-EL                                                       001990
      IF(EL.GE. 5.83.AND.EL.LT.11.70) ZGR=11.70-EL                      002000
      IF(EL.GE.11.70.AND.EL.LT.17.56) ZGR=17.56-EL                      002010
      IF(EL.GE.17.56.AND.EL.LT.23.43) ZGR=23.43-EL                      002020
```

```
      IF(EL.GE.23.43.AND.EL.LT.33.57) ZGR=33.57-EL                      002030
      IF(EL.GE.33.57.AND.EL.LT.36.43) ZGR=ABS(35.00-EL)                 002040
      IF(EL.GE.36.43.AND.EL.LT.46.57) ZGR=46.57-EL                      002050
      IF(EL.GE.46.57.AND.EL.LT.52.44) ZGR=52.44-EL                      002060
      IF(EL.GE.52.44.AND.EL.LT.58.28) ZGR=58.28-EL                      002070
      IF(EL.GE.58.28.AND.EL.LT.64.15) ZGR=64.15-EL                      002080
      IF(EL.GE.64.15) ZGR=70.0-EL                                       002090
      IF(ISS.EQ.1) GO TO 34                                             002100
   19 XIN=WGIN/(WGIN+WFIN)                                              002110
      IF(WFIN.LE.0.0) GO TO 22                                          002120
      XTT=((1.-XIN)/XIN)**.9*(RHOG/RHOL)**.5*(VISCLP/VISCGP)**.1        002130
      REFO=(WFIN+WGIN)*4.*12./(DI*3.14159*VISCLP)                       002140
      PRLIOP=PRLIO(PPRIM,TPIN)                                          002150
      HFOP=.023*REFO**.8*PRLIOP**.4*12.*CONDLP/(DI*3600.)               002160
      HPP=HFOP*3.59*(1./XTT)**.5                                        002170
      QPRIM=HPP*(TWALLI(I)-TPIN)                                        002180
      GTOT=(WGIN+WFIN)/(3.1416*(DI**2))*1.44*0.36*4.                    002190
C   MACBETH LOW MASS VELOCITY CHF CORR.                                 002200
C     CHF=HFG/135.*(GTOT**.5)*(1.-XIN)                                  002210
C     QCHF=CHF*100./0.36*CHFR                                           002220
C   BIASI CHF CORR.  CGS UNITS REQD.                                    002230
      P=PPRIM*0.068947                                                  002240
      D=DI*2.54                                                         002250
      G=GTOT/.36*0.88824*100.                                           002260
      HP=-1.159+0.149*P*EXP(-0.019*P)                                   002270
      HP=HP+8.99*P/(10.0**2)                                            002280
      CHF=1780.*HP/(D**0.4*G**0.6)*(1.-XIN)                             002290
      QCHF=CHF/1.1369*CHFR                                              002300
      IF(EL.LT.20) GO TO 33                                             002310
      KT1=KT1+1                                                         002320
      ZQTO(KT1,1)=TM                                                    002330
      ZQTO(KT1,2)=EL                                                    002340
      ENTW=WFIN                                                         002350
      CALL QUENCHT(K,TSECT(I))                                          002360
      IF(WFIN.LE.0.0) GO TO 22                                          002370
      DO 28 J=1,10                                                      002380
      DDO(J)=DDO(J)                                                     002390
      VDO=PI*DDO(J)**3/6.0                                              002400
   28 NUM(J)=ALF(J)*(1.-XIN)/(RHOL*VDO)                                 002410
   22 REG=WGIN*4.*12./(DI*3.14159*VISCGP)                               002420
      PRGP=PRSTM(PPRIM,TSATP)                                           002430
      HPP=.023*REG**.9*PRGP**.4*CONDVP*12./(DI*3600.)                   002440
      NSW=0                                                             002450
      CALL DROPS(TWALLI(I),QPRIM,H   P,DDOUT,NSW)                       002460
```

```
   30 VISCLS=VISL(PSEC,TSECT(I))                                    002470
      V=VCL(PSEC,TSECT(I))                                          002480
      V1=VCL(PSEC,(TSECT(I)+10.))                                   002490
      V2=VCL(PSEC,(TSECT(I)-10.))                                   002500
      BETA=(1./V)*(V1-V2)/20.                                       002510
      DTGR=TSECT(I)-TWALLI(I)                                       002520
      DTGR=ABS(DTGR)                                                002530
      GR=(1./V)**2.*BETA*DTGR*ZGR**3.*32.174/VISCLS**2.             002540
      PRSEC=PRLIQ(PSEC,TSECT(I))                                    002550
      HSEC=0.0                                                      002560
      IF(ZGR.EQ.0.0) GO TO 20                                       002570
      HSEC=.021*(GR*PRSEC)**.4*CONDLS/(ZGR*3600.)                   002580
   20 QSEC=HSEC*(TSECT(I)-TWALLI(I))                                002590
      IF(EL.LE.0.9.OR.EL.GE.1.0) GO TO 135                          002600
      KT7=KT7+1                                                     002610
      QSEC1(KT7)=QSEC                                               002620
      QSEC1T(KT7)=TM                                                002630
      GO TO 180                                                     002640
  135 IF(EL.LE.1.9.OR.EL.GE.2.0) GO TO 136                          002650
      KT8=KT8+1                                                     002660
      QSEC2(KT8)=QSEC                                               002670
      QSEC2T(KT8)=TM                                                002680
      GO TO 180                                                     002690
  136 IF(EL.LE.3.9.OR.EL.GE.4.0) GO TO 137                          002700
      KT5=KT5+1                                                     002710
      QSECPLT(KT5)=QSEC                                             002720
      QSECTM(KT5)=TM                                                002730
      GO TO 180                                                     002740
  137 IF(EL.LE.9.0.OR.EL.GE.10.0) GO TO 180                         002750
      KT9=KT9+1                                                     002760
      QSEC10(KT9)=QSEC                                              002770
      QSEC10T(KT9)=TM                                               002780
C CALCULATE TURE WALL TEMP TRANS                                    002790
  180 Q1=QIN(I)=QSEC*3.14159*DO*DELZ/12.                            002800
      Q2=QOUT=QPRIM*3.14159*DI*DELZ/12.                             002810
      T(1)=TWALLI(I)                                                002820
      T(2)=TSECT(I)                                                 002830
      T(3)=0.0                                                      002840
      DTM=DELT                                                      002850
      TP=DELT                                                       002860
      L=4                                                           002870
      TN=0.0                                                        002880
      CPTW=3.14159/(4.*144.0)*(DO**2-DI**2)*DELZ*RHOCPT             002890
      CLP=CPL(PSEC,TSECT(I))                                        002900
```

```
      RHOLS=1./V                                                        002910
      Q3=QIN(NZ1-I+1)                                                   002920
      CPFL=RHOLS*CLP*ASEC*DELZ                                          002930
  190 CALL ICE(DTM,TN,TP,E1,E2,N,T,DT,F,L,INDEX,I1)                     002940
      GO TO (200,300,400,500),L                                         002950
  200 DDT=((T(2)-T(1))/(TSECT(I)-TWALLI(I)))                            002960
      Q1COR=(ABS(DDT))**1.4                                             002970
      Q1=QIN(I)*Q1COR*DDT/ABS(DDT)                                      002980
      Q2=QOUT*(T(1)-TPIN)/(TWALLI(I)-TPIN)                              002990
      DT(1)=(Q1-Q2)/CPTW                                                003000
      DT(2)=(-1.*(Q1+Q3)/CPFL)                                          003010
      IF(I.GT.(NZ1/2)) DT(2)=(TSECF(I)-TSECI(I))/DELT                   003020
      IF(ISS.EQ.2) DT(2)=0.0                                            003030
      DT(3)=T(1)                                                        003040
      GO TO 190                                                         003050
  300 IF(TN.GT.DTM) GO TO 600                                           003060
      GO TO 190                                                         003070
  400 TWALLF=T(1)                                                       003080
      TSECF(I)=T(2)                                                     003090
      TWA=T(3)/DELT                                                     003100
      QOUTA=QOUT*(TWA-TPIN)/(TWALLI(I)-TPIN)                            003110
      TP=TP+DTM                                                         003120
      GO TO 190                                                         003130
  500 WRITE(6,2003)                                                     003140
 2003 FORMAT(/17X,16H NON CONVERGENCE/)                                 003150
      STOP                                                              003160
  600 CONTINUE                                                          003170
      IF(ISS.EQ.2) CONV=ABS(DT(1))                                      003180
C CALCULATE TSEC COOLDOWN                                               003190
      IF(I.GT.(NZ1/2)) GO TO 37                                         003200
      TSECF(NZ1-I+1)=TSECF(I)                                           003210
      GO TO 37                                                          003220
   34 QOUTA=QSS*3.1416*DI/12.*DELZ                                      003230
      QPRIM=QSS                                                         003240
      XIN=WGIN/(WGIN+WFIN)                                              003250
      GTOT=(WGIN+WFIN)/(3.1416*DI**2)*1.44*0.36*4.                      003260
C   PACBETH LOW MASS VELOCITY CHF CORR.                                 003270
C     CHF=HFG/135.*(GTOT**.5)*(1.-XIN)                                  003280
C     QCHF=CHF*100./0.36*CHF                                            003290
C   BIASI CHF CORR.  CGS UNITS REQD.                                    003300
      P=PPRIM*0.048947                                                  003310
      D=DI*2.54                                                         003320
      G=GTOT/.36*3.48924*100.                                           003330
      HP=-1.159+0.149*P*EXP(-0.019*                                     003340
```

```
      HP=HP+R.99*P/(10.9*P**2)                                          003350
      CHF=1780.*HP/(D**0.4*G**0.6)*(1.-XIN)                             003360
      QCHF=CHF/1.1349*CHFR                                              003370
      IF(QCHF.LT.QPRIM) ENTR=WFIN                                       003380
   37 CONTINUE                                                          003390
C CALCULATE FILM FLOW LOSS                                              003400
      DELFM=ENTR*DDUTA/(HSV(PPRIM,X,Y,Z)-HSL(TSATP))                    003410
      IF(WFIN.EQ.0.) DELFM=0.0                                          003420
      IF(DELFM.GT.WFIN) DELFM=WFIN                                      003430
      WFOUT=WFIN-DELFM                                                  003440
      WGOUT=WGIN+DELFM-ENTR                                             003450
C CALCULATE TPOUT  AND  DDOUT                                           003460
      TPOUT=TSATP                                                       003470
      IF(NSW.EQ.0) GO TO 41                                             003480
      IF(WFIN.GT.0.0) GO TO 50                                          003490
   41 NSW=1                                                             003500
      CALL DROPS(TWA,XYZ,HOUTP,DDOUT,NSW)                               003510
      HINP=HSS(PPRIM,TPIN,DUM1,DUM2)                                    003520
      IF(HOUTP.GT.1500.)HOUTP=HINP                                      003530
      DUM1=SSSISS(PPRIM,HOUTP,TPOUT,DUM2,DUM3)                          003540
   50 IF(CONV.GT.0.10) GO TO 90                                         003550
      IF(K.EQ.(K/10)*10) GO TO 60                                       003560
      IF(ISS.EQ.1) GO TO 65                                             003570
      IF(ISS.EQ.2) GO TO 65                                             003580
      GO TO 90                                                          003590
   60 CONTINUE                                                          003600
      IF(NPL.GT.45)CALL HEADP                                           003610
      NPL=NPL+1                                                         003620
      IF(ISS.EQ.1)GO TO 65                                              003630
      IF(ISS.EQ.2) GO TO 65                                             003640
      WFOUTPP=WFOUT*TURES                                               003650
      WGOUTPP=WGOUT*TURES                                               003660
      ENTSMPP=ENTSM*TURES                                               003670
      WRITE(6,2003) TM,EL,QPRIM,WFOUTPP,WGOUTPP,TPOUT,TWALLF,TSECF(I)   003680
     *,ENTSMPP,QCHF,HPP,HSEC,DT(I)                                      003690
      KT2=KT2+1                                                         003700
      KT4=KT4+1                                                         003710
      TPOUTEL(KT4)=TPOUT                                                003720
      TSECFEL(KT2)=TSECF(I)                                             003730
      ELIPLOT(KT4)=EL1                                                  003740
      ELPLOT(KT2)=EL                                                    003750
      GO TO 70                                                          003760
   65 WRITE(6,2002)EL,QPRIM,WFOUT,WGOUT,TPOUT,TWALLF,TSECF(I),          003770
     C ENTSM,QCHF,HPP,HSEC,CONV                                         003780
```

```
   90 CONTINUE                                                          003790
      IF(ENTSM.NE.0.0) WRITE(6,2001) (DDOUT(J),J=1,10)                  003800
   90 TSECI(I)=TSECF(I)                                                 003810
      TWALLI(I)=TWALLF                                                  003820
      DO 210 II=1,6                                                     003830
      IF(ABS(EL-CHOICEL(II)).GT.DELZ/2.0) GO TO 210                     003840
      TPTM(KT6,II)=TPOUT                                                003850
      TWTM(KT6,II)=TWALLF                                               003860
      TSTM(KT6,II)=TSECF(I)                                             003870
  210 CONTINUE                                                          003880
      IF(CONV.GT. 0.10) GO TO 15                                        003890
  100 CONTINUE                                                          003900
      KT3=KT3+1                                                         003910
      TPOUTTM(KT3)=TPOUT                                                003920
      ENTSMTM(KT3)=ENTSM*TUBES                                          003930
      ENERTM(KT3)=(ENTSM*HSL(TSATP)+WGOUT*HOUTP-EIN)*TUBES              003940
      TMPLOT(KT3)=TM                                                    003950
      IF(KT2.LE.0) GO TO 105                                            003960
      ENCODE(6,800,TITLE2(6)) TM                                        003970
  800 FORMAT(F6.1)                                                      003980
      DO 102 JJ=1,KT2                                                   003990
      TPOUTEL(JJ)=5./9.*(TPOUTEL(JJ)-32.)                               004000
  102 TSECFEL(JJ)=5./9.*(TSECFEL(JJ)-32.)                               004010
      TPOUTEL(KT4)=5./9.*(TPOUTEL(KT4)-32.)                             004020
      CALL GRAFIT(0.0,TLEN,120.0,320.0,10.,7.,2,2,2H  ,0,MP,1H*,KT4,    004030
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,ELIPLOT,TPOUTEL)            004040
      CALL MOVEAA(12,TITAL1(1,2),TITLE1)                                004050
      CALL GRAFIT(0.0,TLEN,120.0,320.0,10.,7.,2,2,2H  ,0,MP,1H*,KT2,    004060
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,ELPLOT,TSECFEL)             004070
  105 TM=TM+DELT                                                        004080
  110 CONTINUE                                                          004090
      IF(KT3.LE.0) GO TO 115                                            004100
      DO 103 JJ=1,KT3                                                   004110
      ENERTM(JJ)=ENERTM(JJ)/0.94778                                     004120
      TPOUTTM(JJ)=5./9.*(TPOUTTM(JJ)-32.)                               004130
  103 ENTSMTM(JJ)=ENTSMTM(JJ)/0.00220459                                004140
      CALL MOVEAA(12,TITALX1(1,2),TITLEX)                               004150
      CALL MOVEAA(12,TITAL1(1,3),TITLE1)                                004160
      CALL MOVEAA(12,TITLDUM,TITLE2)                                    004170
      CALL GRAFIT(-50.0,1800.,125.0,275.0,10.,7.,2,2,2H  ,0,MP,1H*,KT3, 004180
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT,TPOUTTM)             004190
      YCONV=0.00220459                                                  004200
      CALL MOVEAA(12,TITALY1(1,2),TITLEY)                               004210
      CALL MOVEAA(12,TITALY2(1,2),TITLEY2)                              004220
```

```
      CALL MOVEAA(12,TITAL1(1,4),TITLE1)                                004230
      CALL GRAFIT(-80.0,1800.,0.0,25.0,10.,7.,2,2,2H  ,0,MP,1H*,KT3,    004240
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT,ENTSMTM)             004250
400   YCONV=0.94778                                                     004260
      CALL MOVEAA(12,TITALY1(1,5),TITLEY)                               004270
      CALL MOVEAA(12,TITALY2(1,5),TITLY2)                               004280
      CALL MOVEAA(12,TITAL1(1,7),TITLE1)                                004290
      CALL GRAFIT(-50.0,1800.,0.0,315.0,10.,7.,2,2,2H  ,0,MP,1H*,KT3,   004300
405  *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT,ENERTM)              004310
  110 IF(KT1.LE.0) GO TO 141                                            004320
      DO 104 JJ=1,KT1                                                   004330
  104 ZOTO(JJ,2)=ZOTO(JJ,2)/3.2808                                      004340
      YCONV=3.2808                                                      004350
410   CALL MOVEAA(12,TITALX1(1,3),TITLEX)                               004360
      CALL MOVEAA(12,TITALY1(1,3),TITLEY)                               004370
      CALL MOVEAA(12,TITALY2(1,3),TITLY2)                               004380
      CALL MOVEAA(12,TITAL1(1,5),TITLE1)                                004390
      CALL GRAFIT(0.0,1000.60.0,1.5,10.,7.,2,2,2H  ,0,MP,1H*,KT1,       004400
415  *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,ZOTO(1,1),ZOTO(1,2))        004410
  141 YCONV=0.088457                                                    004420
      CALL MOVEAA(12,TITALX1(1,2),TITLEX)                               004430
      CALL MOVEAA(12,TITALY1(1,4),TITLEY)                               004440
      CALL MOVEAA(12,TITALY2(1,4),TITLY2)                               004450
420   CALL MOVEAA(12,TITAL1(1,6),TITLE1)                                004460
      IF(KT7.LE.0) GO TO 142                                            004470
      DO 143 JJ=1,KT7                                                   004480
  143 QSEC1(JJ)=QSEC1(JJ)/YCONV                                         004490
      CALL MOVEAA(12,TITAL2(1,4),TITLE2)                                004500
425   CALL GRAFIT(0.0,1583.60.0,350.0,10.,7.,2,2,2H  ,0,MP,1H*,KT7,     004510
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,QSEC1T,QSEC1)               004520
  142 IF(KT8.LE.0) GO TO 125                                            004530
      DO 144 JJ=1,KT8                                                   004540
  144 QSEC2(JJ)=QSEC2(JJ)/YCONV                                         004550
430   CALL MOVEAA(12,TITAL2(1,5),TITLE2)                                004560
      CALL GRAFIT(0.0,1583.60.0,350.0,10.,7.,2,2,2H  ,0,MP,1H*,KT8,     004570
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,QSEC2T,QSEC2)               004580
  125 IF(KT5.LE.0) GO TO 145                                            004590
      DO 130 JJ=1,KT5                                                   004600
435 130 QSECPLT(JJ)=QSECPLT(JJ)/YCONV                                   004610
      CALL MOVEAA(12,TITAL2(1,2),TITLE2)                                004620
      CALL GRAFIT(0.0,1583.60.0,350.0,10.,7.,2,2,2H  ,0,MP,1H*,KT5,     004630
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,QSECTM,QSECPLT)             004640
  145 IF(KT9.LE.0) GO TO 120                                            004650
440   DO 146 JJ=1,KT9                                                   004660
```

```
  146 QSEC10(JJ)=QSEC10(JJ)/YCONV                                   004670
      CALL MOVEAA(12,TITAL2(1,6),TITLE2)                            004680
      CALL GRAFIT(0.0,1583.60.0,350.0,10.,7.,2,2,2H  ,0,MP,1H*,KT9, 004690
     *-1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,QSEC10T,QSEC10)         004700
  120 IF(KT6.LE.0) GO TO 122                                        004710
      YCONV=-2.0                                                    004720
      CALL MOVEAA(12,TITALY1(1,1),TITLEY)                           004730
      CALL MOVEAA(12,TITALY2(1,1),TITLY2)                           004740
      CALL MOVEAA(12,TITAL1(1,8),TITLE1)                            004750
      CALL MOVEAA(12,TITAL2(1,3),TITLE2)                            004760
      CALL MOVEAA(3,TITAL3(1,2),TITLE3)                             004770
      DO 133 II=1,6                                                 004780
      MP=0                                                          004790
      DO 124 JJ=1,KT6                                               004800
      TPTM(JJ,II)=5./9.*(TPTM(JJ,II)-32.)                           004810
      TWTM(JJ,II)=5./9.*(TWTM(JJ,II)-32.)                           004820
  124 TSTM(JJ,II)=5./9.*(TSTM(JJ,II)-32.)                           004830
      ENCODE(6,140,TITLE3(4)) CHOICEL(II)                           004840
  140 FORMAT(F6.1)                                                  004850
      CALL GRAFIT(-67.,1811.,120.,320.,10.,7.,2,2,2H  ,0,MP,1H ,KT6, 004860
     *0,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT,TPTM(1,II))       004870
      MP=3                                                          004880
      CALL GRAFIT(-67.,1811.,120.,320.,10.,7.,2,2,2H  ,0,MP,1H1,1,   004890
     *1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT(KT6),TPTM(KT6,II)) 004900
      CALL GRAFIT(-67.,1811.,120.,320.,10.,7.,2,2,2H  ,0,MP,1H ,KT6, 004910
     *0,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT,TWTM(1,II))       004920
      CALL GRAFIT(-67.,1811.,120.,320.,10.,7.,2,2,2H  ,0,MP,1H2,1,   004930
     *1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT(KT6),TWTM(KT6,II)) 004940
      CALL GRAFIT(-67.,1811.,120.,320.,10.,7.,2,2,2H  ,0,MP,1H3,1,   004950
     *1,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT(KT6),TSTM(KT6,II)) 004960
      MP=2                                                          004970
  133 CALL GRAFIT(-67.,1811.,120.,320.,10.,7.,2,2,2H  ,0,MP,1H ,KT6, 004980
     *0,TITLEX,TITLEY,TITLE1,TITLE2,TITLE3,TMPLOT,TSTM(1,II))       004990
  122 WRITE(2) WETOT,WGTOT,TSEC,WEWT,WGWT,PPRIM,DO,DI,DELZ1,DELZ2,   005000
     *DELT,TLEN,N72,NT,PSEC,ASEC,RHOCPT,ENTFR,QSS,ISS,CPR,TM,MTX,TURES 005010
      WRITE(2) (TSECT(ID),ID=1,300)                                 005020
      WRITE(2) (TWALLT(ID),ID=1,300)                                005030
 2000 FORMAT(1X,F4.1,F8.2,F9.2,2F8.4,2F8.1,F7.1,5E12.3)             005040
 2001 FORMAT(1X,12F10.3F)                                           005050
 2002 FORMAT(6H S-STATE,F7.1,F9.2,2F8.4,2F8.1,F7.1,5E12.3)          005060
 2004 FORMAT(1H ,I10)                                               005070
 2005 FORMAT(1H1,*ALL ZGR BASED ON 70 FT TUBE IN FLECHT S.G.*//)    005080
      NCAS=NCAS+1                                                   005090
      GO TO 5                                                       005100
```

```
485          190 CALL PLTEND                                          005110
                 STOP                                                 005120
                 END                                                  005130
```

SYMBOLIC REFERENCE MAP (R=3)

ENTRY POINTS		DEF LINE	REFERENCES
152	SGEVAL	1	

VARIABLES	SN	TYPE		RELOCATION							
20407	ALF	REAL	ARRAY		REFS	13	215	DEFINED	33		
15	ASEC	REAL		TITL	REFS	16	24	267	474		
3675	BETA	REAL			DEFINED	30	85				
3663	CHF	REAL			REFS	228	DEFINED	229			
3645	CHFP	REAL			REFS	204	311	DEFINED	203	310	
33104	CHOICEL	REAL	ARRAY		REFS	204	311	DEFINED	166		
					REFS	15	358	458			
3713	CLP	REAL			DEFINED	27					
3626	CONDLP	REAL			REFS	267	DEFINED	264			
4	CONDLS	REAL		DT	REFS	190	DEFINED	122			
1	CONDVP	REAL		DT	REFS	20	232	DEFINED	120		
3612	CONV	REAL			REFS	20	218	DEFINED	121		
					REFS	329	351	363			
3716	CPFL	REAL			DEFINED	106	292				
0	CPR	REAL		TITL	REFS	275	DEFINED	267			
					REFS	16	24	166	474		
3712	CPTW	REAL			DEFINED	28	85				
3660	D	REAL			REFS	274	DEFINED	263			
4	DD	REAL	ARRAY	DROPS	REFS	203	310	DEFINED	199	306	
20375	DDO	REAL	ARRAY		REFS	18	DEFINED	172	213		
					REFS	13	213	214			
20363	DDOUT	REAL	ARRAY		DEFINED	34					
					REFS	13	172	220	325	354	
3720	DDT	REAL			DEFINED	37					
3724	DELFM	REAL			REFS	271	2*272	DEFINED	270		
					REFS	317	318	319			
11	DELT	REAL		TITL	DEFINED	315	316	317			
					REFS	16	24	111	192	259	
					[illegible]	276	284	382	474		
					DEFI[illegible]	28	85				

VARIABLES	SN	TYPE		RELOCATION						
12	DELZ	REAL		TITL	REFS	16	159	163	164	294
					255	263	267	297	358	
					DEFINED	146	160	162		
24	DELZ1	REAL		TITL	REFS	16	24	105	160	474
					DEFINED	28	85			
25	DELZ2	REAL		TITL	REFS	16	24	105	162	474
					DEFINED	28	85			
10	DI	REAL		TITL	REFS	16	24	188	190	193
					199	216	218	255	263	297
					300	306	474	DEFINED	28	85
7	DO	REAL		TITL	REFS	16	24	254	263	474
					DEFINED	28	85			
20424	DT	REAL	ARRAY		REFS	14	268	292	342	
					DEFINED	274	275	276	277	278
3676	DTGR	REAL			REFS	227	228	DEFINED	226	227
3706	DTM	REAL			REFS	268	280	286		
					DEFINED	259				
3727	DUM1	REAL			REFS	326	DEFINED	328		
3730	DUM2	REAL			REFS	326	328			
3731	DUM3	REAL			REFS	328				
3642	EIN	REAL			REFS	368	DEFINED	157		
3634	EL	REAL			REFS	159	163	173	3*174	3*175
					3*176	3*177	3*178	3*179	3*180	3*181
					3*182	2*183	205	208	2*234	2*239
					2*244	2*249	342	349	351	358
					DEFINED	147	159	163		
10167	ELPLOT	REAL	ARRAY		REFS	5	380	DEFINED	349	
3635	EL1	REAL			REFS	164	348	DEFINED	148	164
12067	EL1PLOT	REAL	ARRAY		REFS	5	377	DEFINED	148	348
12543	ENERTM	REAL	ARRAY		REFS	5	386	404		
					DEFINED	368	386			
17	ENTER	REAL		TITL	REFS	16	24	154	474	
					DEFINED	30	85			
3644	ENTP	REAL			REFS	315	319	DEFINED	165	209
					312					
33	ENTSM	REAL		DRTPS	REFS	18	341	351	354	367
					368	DEFINED	156			
3734	ENTSMPR	REAL			REFS	342	DEFINED	341		
11153	ENTSMTM	REAL	ARRAY		REFS	5	388	398		
					DEFINED	367	388			
7	E1	REAL		OT	REFS	20	268	DEFINED	36	
10	E2	REAL		OT	REFS	20	268	DEFINED	36	
20427	F	REAL	ARRAY		RE[illegible]	14	268			
3661	G	REAL			R[illegible]	203	310	DEFINED	200	307

```
      SUBROUTINE DROPS(TWALL,QPRIM,HOUTP,DDOUT,NSW)                     005140
      REAL NUM                                                          005150
      DIMENSION DDOUT(10),HD(10)                                        005160
      COMMON/TITL/CPR,WETOT,WGTOT,TSEC,WFWT,WGWT,PPRIM,DO,DI,DELT,DELZ, 005170
     C  NT,PSEC,ASEC,RHOCPT,ENTER,OSS,ISS,NCAS,NPL,DELZ1,DELZ2,NZ1,NZ2  005180
      COMMON/DROPS/RHOL,TSATP,TPIN,WGIN,DD(10),NUM(10),                 005190
     *HPP,QOUTA,WGOUT,ENTSM                                             005200
C  COMPUTE TOTAL WALL TO DROP RADIATION                                 005210
      XTOT=0.0                                                          005220
      QRWT=0.0                                                          005230
      DO 10 I=1,10                                                      005240
      X=RHOL*NUM(I)*3.14159*DD(I)**3/6.0                                005250
   10 XTOT=XTOT+X                                                       005260
      XTOT=1.-XTOT                                                      005270
      QRD=0.495*(((TWALL+460.)/1000.)**4-((TSATP+460.)/1000.)**4)       005280
      VL=1./RHOL                                                        005290
      H=HSS(PPRIM,TPIN,S,V)                                             005300
      VBAR=VL+XTOT*(V-VL)                                               005310
      DO 12 I=1,10                                                      005320
      QRW=QRD*3.14159*(DD(I)**2)*NUM(I)                                 005330
   12 QRWT=QRWT+QRW*3.14159*((DI/12)**2)*DELZ/VBAR/4.                   005340
      QPRIM=HPP*(TWALL-TPIN)+QRWT                                       005350
      IF(NSW.EQ.0) GO TO 17                                             005360
C COMPUTE VAPOR TO DROP FILM COEFFICIENT                                005370
      VG=VISV(PPRIM,TPIN)                                               005380
      RHG=1./V                                                          005390
      QUD=0.0                                                           005400
      DO 14 I=1,10                                                      005410
      RED1=(0.292*DD(I)/VG*(32.174*RHG*(RHOL-RHG)*DD(I))**0.5)**        005420
     *1.725                                                             005430
      RED2=4.*32.174*(RHOL-RHG)*DD(I)/(3.*RHG*0.5)                      005440
      RED2=RED2**0.5*RHG*DD(I)/VG                                       005450
      RED=AMIN1(RED1,RED2)                                              005460
      IF(RED.NE.0.0) GO TO 13                                           005470
      HD(I)=0.0                                                         005480
      GO TO 14                                                          005490
   13 CONV=CONDV(PPRIM,TPIN)                                            005500
      PR=PRSTM(PPRIM,TPIN)                                              005510
      HD(I)=CONV/(3600.*DD(I))*(2.+0.55*RED**0.5*PR**0.33)              005520
   14 QUD=QUD+HD(I)*(TPIN-TSATP)*3.14159*DD(I)**2*NUM(I)                005530
      QUDT=QUD*3.14159/4.*((DI/12.)**2)*DELZ/VBAR                       005540
      CK1=HD(10)                                                        005550
      CK2=DD(10)                                                        005560
C COMPUTE DROPLET EVAPORATION                                           005570
```

```
      HG=HSV(PPRIM,TT,SS,VV)                                            005580
C CALCULATE NEW DROP DIAMETERS                                          005590
      VSTM=VBAR*WGIN/(3.14159*DI**2)*4.*144./XTOT                       005600
      ENTSM=0.0                                                         005610
      DO 16 I=1,19                                                      005620
      DELDD=(-2.)/(RHOL*(HG-HSL(TSATP))*VSTM)*(HD(I)*(TPIN-             005630
     *TSATP)+QRD)*DELT                                                  005640
      DDOUT(I)=DD(I)+DELDD                                              005650
      IF(DDOUT(I).LT.0.0) DDOUT(I)=0.                                   005660
      ENTSM=3.14159**2*DDOUT(I)**3/6*RHOL*VSTM*NUM(I)                   005670
     C*DI**2/(4*144*VBAR)+ENTSM                                         005680
   16 CONTINUE                                                          005690
C CALCULATE HOUTP                                                       005700
      WGOUT=WGIN/XTOT-ENTSM                                             005710
      WEVAP=WGOUT-WGIN                                                  005720
      HOUTP=(WGIN*H+(QOUTA-QUDT)+WEVAP*(HG))/WGOUT                      005730
      CK3=DELDD                                                         005740
  100 FORMAT(1H ,10E12.5)                                               005750
   17 RETURN                                                            005760
      END                                                               005770
```

SYMBOLIC REFERENCE MAP (R=3)

ENTRY POINTS		DEF LINE	REFERENCES
3	DROPS	1	63

VARIABLES		SN	TYPE		RELOCATION							
15	ASEC		REAL		TITL	REFS	4					
367	CK1	*	REAL			DEFINED	42					
370	CK2	*	REAL			DEFINED	43					
400	CK3	*	REAL			DEFINED	61					
364	CONV		REAL			REFS	39	DEFINED	37			
0	CPR		REAL		TITL	REFS	4					
4	DD		REAL	ARRAY	DROPS	REFS	6	12	20	2*29	31	
						32	39	40	43	52		
0	DDOUT		REAL	ARRAY	F.P.	REFS	3	53	54			
						DEFINED	1	52	53			
376	DELDD		REAL			REFS	52	61	DEFINED	50		
11	DELT		REAL		TITL	REFS	4					
12	DEL		REAL		TITL	RE	4	21	41	50		

```
      SUBROUTINE HEADR                                                  005780
      COMMON/TITL/CPR,WFTOT,WGTOT,TSEC,WFWT,WGWT,PPRIM,DO,DI,DELT,DELZ, 005790
     C  NT,PSEC,ASEC,RHOCPT,ENTFR,QSS,ISS,NCAS,NPL,DELZ1,DELZ2,NZ1,NZ2  005800
      NPL=1                                                             005810
      WRITE(6,100)WFTOT,WGTOT,TSEC,WFWT,WGWT,PPRIM,DO,DI,DELZ1,DELZ2    005820
  100 FORMAT(1H1,54WFTOT=,F6.4,7H WGTOT=,F6.4,6H TSEC=,                 005830
     C F5.1,6H WFWT=,F4.2,6H WGWT=,F4.2,7H PPRIM=,F4.1,4H DO=,          005840
     C F5.3,4H DI=,F5.3,7H DEL71=,F4.2,7H DELZ2=,F4.2)                  005850
      WRITE(6,110)DELT,NZ1,NZ2,NT,PSEC,ASEC,RHOCPT,ENTFR,QSS,ISS,CPR    005860
  110 FORMAT(6H DELT=,F4.1,5H NZ1=,I3,5H NZ2=,I3,4H NT=,I3,6H PSEC=,    005870
     C F5.1,6H ASEC=,F5.3,8H RHOCPT=,F6.3,7H ENTFR=,                    005880
     C F5.3,5H QSS=,F5.2,5H ISS=,I1,5H CPR=,F5.2/)                      005890
      WRITE(6,120)NCAS                                                  005900
  120 FORMAT(* THIS IS CASE NUMBER =,I2/)                               005910
      WRITE(6,130)                                                      005920
  130 FORMAT(2X,4HTIME,2X,9HELEVATION,2X,5HOPRIM,3X,5HWFOUT,            005930
     C 3X,5HWGOUT,3X,5HTPOUT,2X,6HTWALLF,2X,5HTSECF,                    005940
     C5X,5HENTSM,7X,4HOCHF,8X,4HHTPP,7X,4HHSEC,8X,7HDTW DTM/)           005950
      RETURN                                                            005960
      END                                                               005970
```

SYMBOLIC REFERENCE MAP (R=3)

ENTRY POINTS		DEF LINE	REFERENCES
1	HEADR	1	19

VARIABLES		SN	TYPE	RELOCATION			
15	ASEC		REAL	TITL	REFS	2	9
0	CPR		REAL	TITL	REFS	2	9
11	DELT		REAL	TITL	REFS	2	9
12	DELZ		REAL	TITL	REFS	2	
24	DELZ1		REAL	TITL	REFS	2	5
25	DELZ2		REAL	TITL	REFS	2	5
10	DI		REAL	TITL	REFS	2	5
7	DO		REAL	TITL	REFS	2	5
17	ENTFR		REAL	TITL	REFS	2	9
21	ISS		INTEGER	TITL	REFS	2	9
22	NCAS		INTEGER	TITL	REFS	2	13
23	NPL		INTEGER	TITL	REFS	2	DEFINED
13	NT		INTEGER	TITL	RE	2	9

```
      SUBROUTINE QUENCHT(KK,TISEC)                                      005980
      COMMON/TITL/CPP,WFTOT,WGTOT,TSEC,WFWT,WGWT,PPRIM,DO,DI,DELT,DELZ, 005990
     C  NT,PSEC,ASEC,RHOCPT,ENTER,QSS,ISS,NCAS,NPL,DELZ1,DELZZ,NZ1,NZ2  006000
      COMMON/DROPS/RHOL,TSATP,TPIN,WGIN,DD(10),NUM(10),                 006010
     *HPP,QOUTA,WGOUT,ENTSS                                             006020
      COMMON/QT/VISCGP,CONDVP,ZGR,QUEL,CONDLS,PI,ZO,E1,E2               006030
      DIMENSION T(2),DT(2),F(14),TW(10),DELG(10)                        006040
      VISCLS=VISL(PSEC,TISEC)                                           006050
      V=VCL(PSEC,TISEC)                                                 006060
      BETA=2.85E-5                                                      006070
      TP=TPIN                                                           006080
      TF=TISEC                                                          006090
      KK=0                                                              006100
      AT=1.0/4.0*(DO**2-DI**2)/12.0/DO                                  006110
      AKT=10.1/3600.                                                    006120
C  CALCULATE CONVECTIVE FILM COEFF ABOVE ZO                             006130
      REG=WGIN*4.0*12.0/(DI*PI*VISCGP)                                  006140
      PRGP=PRSTM(PPRIM,TSATP)                                           006150
      HCONV=0.023*REG**0.8*PRGP**0.4*CONDVP*12.0/(DI*3600.)             006160
      PRSEC=PRLIQ(PSEC,TISEC)                                           006170
      TWO=(TF+TP)/2.0                                                   006180
   10 TWO1=TWO                                                          006190
   14 DTGR=TF-TWO1                                                      006200
      GR=(1.0/V)**2*BETA*DTGR*ZGR**3*32.174/VISCLS**2                   006210
      HSEC=0.021*(GR*PRSEC)**0.4*CONDLS/(ZGR*3600.)                     006220
      C1=(HSEC+HPP)/(AKT*AT)                                            006230
      D=((HSEC*TF)+(HPP*TP))/(AKT*AT)                                   006240
      TSS=D/C1                                                          006250
      TCOR=ABS(TSS-TWO1)                                                006260
      IF(TCOR/DTGR.LT.0.10) GO TO 12                                    006270
      TWO1=TSS                                                          006280
      GO TO 14                                                          006290
   12 CONTINUE                                                          006300
      TSS1=TSS                                                          006310
   50 Z=0.0                                                             006320
      KK=KK+1                                                           006330
      T(1)=TWO                                                          006340
      R=RHOCPT*QUEL/AKT                                                 006350
      TDEL=TWO-TSS1                                                     006360
      ROOT2=(SQRT(R**2+4*C1)+R)/(-2.0)                                  006370
      RT21=ROOT2                                                        006380
      T(2)=ROOT2*TDEL                                                   006390
      ZMAX=0.019                                                        006400
      ZM=0.001                                                          006410
```

```
      ZZM=0.0                                                           006420
      N=2                                                               006430
      I=2                                                               006440
      L=4                                                               006450
      K=0                                                               006460
      IF(KM/10*10.EQ.KM.AND.KK.EQ.2)WRITE(6,2005)                       006470
  100 CALL ICE(ZM,Z,ZZM,E1,E2,N,T,DT,F,L,INDEX,I)                       006480
      GO TO(200,300,400,500),L                                          006490
  200 DT(1)=T(2)                                                        006500
      Q1=HSEC*(TF-T(1))                                                 006510
      Q2=HPP*(T(1)-TP)                                                  006520
      DT(2)=(Q2-Q1-RHOCPT*AT*QUEL*T(2))/(AKT*AT)                        006530
      IF(DT(2).GT.0.0) GO TO 250                                        006540
      DT(1)=0.0                                                         006550
      DT(2)=0.0                                                         006560
  250 CONTINUE                                                          006570
      GO TO 100                                                         006580
  300 K=K+1                                                             006590
      IF(K.EQ.1) GRAD1=DT(1)*(-1.0)                                     006600
      IF(Z.GE.ZMAX) GO TO 600                                           006610
      GO TO 100                                                         006620
  400 IF(KM/10*10.EQ.KM.AND.KK.EQ.2) WRITE(6,2004) Z,T(1),T(2),DT(2)    006630
      ZZM=ZZM+ZM                                                        006640
      GO TO 100                                                         006650
 2005 FORMAT(6H AXIAL,12H  CONDUCTION,7H  BELOW,8H  QUENCH,7H  FRONT,   006660
     *//,13H DISTANCE(FT),9H  TEMP(F),14H  DT/DZ(F/FT),                 006670
     *18H  D2T/DZ2(F/FT**2),/)                                          006680
 2004 FORMAT(1H ,10F12.5)                                               006690
 2006 FORMAT(6H AXIAL,12H  CONDUCTION,7H  ABOVE,8H  QUENCH,7H  FRONT,   006700
     *//,13H DISTANCE(FT),9H  TEMP(F),14H  DT/DZ(F/FT),                 006710
     *18H  D2T/DZ2(F/FT**2),/)                                          006720
  500 WRITE(6,2000)                                                     006730
 2000 FORMAT(1X,/1H NON CONVERGENCE 1/)                                 006740
      STOP                                                              006750
  600 CONTINUE                                                          006760
      ZZM=0.0                                                           006770
      K=0                                                               006780
      L=4                                                               006790
      Z=0.0                                                             006800
      TW01=TWO                                                          006810
   11 DTGR=TF-TW01                                                      006820
      GR=(1.0/V)**2*BETA*DTGR*ZGR**3*32.174/VISCLS**2                   006830
      HSEC=0.021*(GR*PRSEC)**0.4*COND  S/(ZGR*3600.)                    006840
      C=(HCONV+HSEC)/(AKT*AT)                                           006850
```

```
      D=((HSEC*TF)+(HCONV*TP))/(AKT*AT)                                 006860
      TSS=D/C                                                           006870
      TCOR=ABS(TSS-TW01)                                                006880
      IF(TCOR/DTGR.LT.0.10) GO TO 13                                    006890
      TW01=TSS                                                          006900
      GO TO 11                                                          006910
   13 TDEL=TSS-TW0                                                      006920
      TSS2=TSS                                                          006930
      T(1)=TW0                                                          006940
      ROOT2=(SQRT(B**2+4*C)+B)/2.0                                      006950
      RT22=ROOT2                                                        006960
      T(2)=ROOT2*TDEL                                                   006970
      IF(KM/10*10.EQ.KM.AND.KK.EQ.2)WRITE(6,2006)                       006980
  101 CALL ICE(ZM,Z,ZZM,E1,E2,N,T,DT,F,L,INDEX,I)                       006990
      GO TO (201,301,401,501),L                                         007000
  201 DT(1)=T(2)                                                        007010
      Q1=HSEC*(TF-T(1))                                                 007020
      Q2=HCONV*(T(1)-TP)                                                007030
      DT(2)=(Q2-Q1-RHOCPT*AT*QUEL*T(2))/(AKT*AT)                        007040
      GO TO 101                                                         007050
  301 K=K+1                                                             007060
      IF(K.EQ.1) GRAD2=DT(1)                                            007070
      IF(Z.GT.ZMAX) GO TO 601                                           007080
      GO TO 101                                                         007090
  401 IF(KM/10*10.EQ.KM.AND.KK.EQ.2) WRITE(6,2004) Z,T(1),T(2),DT(2)    007100
      ZZM=ZZM+ZM                                                        007110
      GO TO 101                                                         007120
  501 WRITE(6,2001)                                                     007130
 2001 FORMAT(1X,/18H NON CONVERGENCE 2/)                                007140
      STOP                                                              007150
  601 CONTINUE                                                          007160
      DELG(KK)=GRAD1-GRAD2                                              007170
      TW(KK)=TW0                                                        007180
      CONV=ABS(DELG(KK)/GRAD1)                                          007190
      IF(CONV.LT.).01.OR.KK.EQ.10) GO TO 699                            007200
      IF(KK.GT.1) GO TO 699                                             007210
      TW0=(TSS1-TSS2*(RT22/RT21))/(1.-(RT22/RT21))                      007220
      GO TO 10                                                          007230
  699 CONTINUE                                                          007240
      RETURN                                                            007250
      END                                                               007260
```

(INPUT PARAMETERS)

```
WFTOT= .1     WGTOT= .4000 TSEC=400.0 WFWT=1.00 WGWT    .0 PPRIM=40.0 DO= .875 DI= .775 DELZ1=1.    DELZ2= .10
DELT= 5.0 ..1=160 NZ2= 50 NT=100 PSEC=950.0 ASEC= .0.. RHOCPT=57.040 ENTFR=0.000 QSS=10.00 ISS=0 CPR= 1.00

THIS IS CASE NUMBER  1
```

TIME SEC	ELEVATION FT	QPRIM BTU-FT²	WFOUT LB/S	WGOUT LB/S	TPOUT °F	TWALLF °F	TSECF °F	ENTSM LB/S	QCHF BTU-FT²	HTPP BTU-FT²-°F	HSEC BTU-FT²-°F
50.0	.05	8.68	.0943	.4057	267.2	280.9	334.4	0.	.921E+02	.581E+00	.133E+00
50.0	.15	10.46	.0874	.4126	267.2	283.0	343.1	0.	.868E+02	.601E+00	.142E+00
50.0	.25	11.54	.0797	.4203	267.2	283.9	347.9	0.	.804E+02	.627E+00	.147E+00
50.0	.35	14.44	.0702	.4298	267.2	286.9	359.9	0.	.734E+02	.658E+00	.161E+00
50.0	.45	16.37	.0595	.4405	267.2	288.1	366.9	0.	.647E+02	.704E+00	.169E+00
50.0	.55	92.28	.0428	.4572	267.2	292.4	385.2	0.	.548E+02	.767E+00	.718E-01

AXIAL CONDUCTION BELOW QUENCH FRONT

DISTANCE(FT)	TEMP(F)	DT/DZ(F/FT),	D2T/DZ2(F/FT**2)
0.	.31188E+03	-.17136E+05	.79973E+07
.10000E-02	.29814E+03	-.10814E+05	.49776E+07
.20000E-02	.28947E+03	-.68247E+04	.31613E+07
.30000E-02	.28430E+03	-.43070E+04	.19825E+07
.40000E-02	.28055E+03	-.27181E+04	.12511E+07
.50000E-02	.27837E+03	-.17154E+04	.78957E+06
.60000E-02	.27730E+03	-.10826E+04	.49829E+06
.70000E-02	.27613E+03	-.68320E+03	.31447E+06
.80000E-02	.27558E+03	-.43116E+03	.19846E+06
.90000E-02	.27524E+03	-.27210E+03	.12525E+06
.10000E-01	.27502E+03	-.17172E+03	.79042E+05
.11000E-01	.27488E+03	-.10837E+03	.49893E+05
.12000E-01	.27480E+03	-.68393E+02	.31480E+05
.13000E-01	.27474E+03	-.43162E+02	.19867E+05
.14000E-01	.27471E+03	-.27239E+02	.12539E+05
.15000E-01	.27468E+03	-.17191E+02	.79126E+04
.16000E-01	.27467E+03	-.10849E+02	.49936E+04
.17000E-01	.27466E+03	-.68466E+01	.31514E+04
.18000E-01	.27466E+03	-.43208E+01	.19888E+04
.19000E-01	.27465E+03	-.27268E+01	.12591E+04

AXIAL CONDUCTION ABOVE QUENCH FRONT

DISTANCE(FT)	TEMP(F)	DT/DZ(F/FT),	D2T/DZ2(F/FT**2)
0.	.31188E+03	.17166E+05	-.49249E+07
.10000E-02	.32678E+03	.12902E+05	-.34391E+07
.20000E-02	.33802E+03	.97307E+04	-.27447E+07
.30000E-02	.34450E+03	.73391E+04	-.22701E+07
.40000E-02	.35230E+03	.55353E+04	-.15813E+07
.50000E-0	.35772E+03	.41749E+04	-.11776E+07

TIME = TRANS TIME

ELEV = NODAL MID POINT EL.

QPRIM = TUBE WALL HEAT FLUX

WFOUT = LIQ. MASS FLOW OUT OF NODE

WGOUT = STEAM " " " " "

TPOUT = STEAM TEMP. LEAVING NODE

TWALLF = End-of Time Step Tube Wall Temp

TSECF = " " " " Sec. Fluid Temp.

ENTSM = MASS FLOW OF ENTRAINED DROPLETS

QCHF = CHF HEAT FLUX (BTU/...)

HTPP = PRIMARY WALL FILM COEFF

HSEC = SEC WALL FILM COEFF

→ Axial Conduction Temps At Zg

```
.60000E      .36136E+03  .31488E+04 -.89816E+06
.70000E-02   .36410E+03  .23749E+04 -.66987E+06
.80000E-02   .36617E+03  .17912E+04 -.53523E+06
.90000E-02   .36773E+03  .13510E+04 -.39106E+06
.10000E-01   .36891E+03  .10189E+04 -.29740E+06
.11000E-01   .36980E+03  .76850E+03 -.21677E+06
.12000E-01   .37047E+03  .57962E+03 -.16349E+06
.13000E-01   .37097E+03  .43716E+03 -.12331E+06
.14000E-01   .37135E+03  .32972E+03 -.93002E+05
.15000E-01   .37164E+03  .24866E+03 -.70144E+05
.16000E-01   .37186E+03  .18756E+03 -.52904E+05
.17000E-01   .37202E+03  .14146E+03 -.39902E+05
.18000E-01   .37214E+03  .10669E+03 -.30095E+05
.19000E-01   .37224E+03  .80472E+02 -.22698E+05
```

1st line, same as Edit above Axial Conduction Edit

2nd line, pelp diameter, in group i, i = 1,10, [Fb]

```
50.0     .65      .77  0.0000   .4572   269.8   387.0  396.1    .428E-01    .394E+02    .636E-02    .713E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0     .75      .75  0.0000   .4573   271.4   387.1  396.1    .427E-01    .394E+02    .636E-02    .708E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0     .85      .74  0.0000   .4573   273.4   387.3  396.2    .427E-01    .394E+02    .636E-02    .703E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0     .95      .73  0.0000   .4573   275.3   387.4  396.3    .427E-01    .394E+02    .636E-02    .697E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0    1.05      .72  0.0000   .4573   277.3   387.5  396.3    .427E-01    .394E+02    .636E-02    .692E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0    1.15      .71  0.0000   .4573   279.1   387.7  396.4    .427E-01    .394E+02    .636E-02    .687E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0    1.25      .70  0.0000   .4574   280.9   387.8  396.4    .426E-01    .394E+02    .636E-02    .682E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0    1.35      .69  0.0000   .4574   282.7   387.9  396.5    .426E-01    .394E+02    .636E-02    .677E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .125E-03
50.0    1.45      .67  0.0000   .4574   284.4   388.0  396.5    .426E-01    .394E+02    .636E-02    .672E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .124E-03
50.0    1.55      .66  0.0000   .4575   286.1   388.1  396.5    .425E-01    .394E+02    .636E-02    .667E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .292E-03  .124E-03
50.0    1.65      .65  0.0000   .4575   287.8   388.2  396.6    .425E-01    .394E+02    .636E-02    .662E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .417E-03  .291E-03  .124E-03
50.0    1.75      .64  0.0000   .4576   289.4   388.3  396.6    .424E-01    .394E+02    .636E-02    .657E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .708E-03  .542E-03  .416E-03  .291E-03  .124E-03
50.0    1.85      .63  0.0000   .4576   290.9   388.4  396.7    .424E-01    .394E+02    .636E-02    .652E-01
.375E-02  .225E-02  .150E-02  .117E-02  .917E-03  .707E-03  .541E-03  .416E-03  .291E-03  .124E-03
50.0    1.95      .62  0.0000   .4577   292.5   388.5  396.7    .423E-01    .394E+02    .637E-02    .647E-01
.375E-02  .225E-02  .150E-02  .117E-02  .916E-03  .707E-03  .541E-03  .416E-03  .291E-03  .124E-03
50.0    2.05      .62  0.0000   .4577   293.9   388.6  396.8    .423E-01    .394E+02    .637E-02    .642E-01
.375E-02  .225E-02  .150E-02  .117E-02  .916E-03  .707E-03  .541E-03  .416E-03  .291E-03  .124E-03
50.0    2.15      .61  0.0000   .4578   295.4   388.7  396.8    .422E-01    .394E+02    .637E-02    .637E-01
.375E-02  .225E-02  .150E-02  .117E-02  .916E-03  .707E-03  .541E-03  .416E-03  .291E-03  .123E-03
50.0    2.        .60  0.0000   .4578   296.8   388.8  396.8    .422E-01    .394E+02    .637E-02    .632E-01
```

.375E-[illegible]	.225E-02	.150E-02	.117E-02	.916E-03	[illegible]E-03	.541E-03	.416E-03	.291E-03	[illegible]	[illegible]03			
50.0	[illegible].35	.59	0.0000	.4579	298.[illegible]	3[illegible]	396.9	.421E-01	.394E+02	.637[illegible]02	.628E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.916E-03	.707E-03	.541E-03	.416E-03	.291E-03	.123E-03				
50.0	2.45	.58	0.0000	.4580	299.16	389.0	396.9	.420E-01	.394E+02	.637E-02	.623E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.916E-03	.707E-03	.541E-03	.416E-03	.291E-03	.123E-03				
50.0	2.55	.57	0.0000	.4580	300.[illegible]	389.1	396.9	.420E-01	.394E+02	.637E-02	.618E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.916E-03	.707E-03	.541E-03	.416E-03	.291E-03	.122E-03				
50.0	2.65	.57	0.0000	.4581	302.2	389.1	397.0	.419E-01	.394E+02	.637E-02	.613E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.916E-03	.707E-03	.541E-03	.416E-03	.290E-03	.122E-03				
50.0	2.75	.56	0.0000	.4582	303.[illegible]	389.2	397.0	.418E-01	.394E+02	.637E-02	.608E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.916E-03	.707E-03	.541E-03	.416E-03	.290E-03	.122E-03				
50.0	2.85	.55	0.0000	.4583	304.17	389.3	397.0	.417E-01	.394E+02	.637E-02	.603E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.707E-03	.541E-03	.415E-03	.290E-03	.122E-03				
50.0	2.95	.54	0.0000	.4584	305.[illegible]	389.3	397.1	.416E-01	.394E+02	.637E-02	.598E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.916E-03	.706E-03	.540E-03	.415E-03	.290E-03	.121E-03				
50.0	3.05	.54	0.0000	.4584	307.0	389.4	397.1	.416E-01	.394E+02	.637E-02	.593E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.540E-03	.415E-03	.290E-03	.121E-03				
50.0	3.15	.53	0.0000	.4585	308.2	389.5	397.1	.415E-01	.394E+02	.637E-02	.588E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.540E-03	.415E-03	.290E-03	.121E-03				
50.0	3.25	.52	0.0000	.4586	309.3	389.5	397.1	.414E-01	.394E+02	.638E-02	.582E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.540E-03	.415E-03	.290E-03	.121E-03				
50.0	3.35	.51	0.0000	.4587	310.4	389.6	397.2	.413E-01	.394E+02	.638E-02	.577E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.540E-03	.415E-03	.289E-03	.120E-03				
50.0	3.45	.51	0.0000	.4588	311.4	389.6	397.2	.412E-01	.394E+02	.638E-02	.572E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.540E-03	.415E-03	.289E-03	.120E-03				
50.0	3.55	.50	0.0000	.4589	312.4	389.7	397.2	.411E-01	.394E+02	.638E-02	.567E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.540E-03	.414E-03	.289E-03	.120E-03				
50.0	3.65	.50	0.0000	.4590	313.5	389.7	397.2	.410E-01	.394E+02	.638E-02	.561E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.540E-03	.414E-03	.289E-03	.119E-03				
50.0	3.75	.49	0.0000	.4591	314.4	389.8	397.3	.409E-01	.394E+02	.638E-02	.556E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.706E-03	.539E-03	.414E-03	.289E-03	.119E-03				
50.0	3.85	.48	0.0000	.4592	315.4	389.8	397.3	.408E-01	.394E+02	.638E-02	.550E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.915E-03	.705E-03	.539E-03	.414E-03	.288E-03	.119E-03				
50.0	3.95	.48	0.0000	.4593	316.3	389.8	397.3	.407E-01	.394E+02	.638E-02	.544E-01		
.375E-02	.225E-02	.150E-02	.117E-02	.914E-03	.705E-03	.539E-03	.414E-03	.288E-03	.118E-03				

```
WFTOT= .1    WGTOT= .4000 TSEC=400.0 WFWT=1.00 WGWT    0 PPRIM=40.0 DD= .875 DI= .775 DELZ1=1.    DELZ2= .10
DELT= 5.0 ..1=160 NZ2= 50 NT=100 PSEC=450.0 ASEC= .6    R40CPT=57.040 ENTFR=0.000 QSS=10.00 ISS=. CPR= 1.00

THIS IS CASE NUMBER  1

 TIME  ELEVATION  QPRIM   WFOUT   WGOUT   TPOUT  TWALLF  TSECF     ENTSM       QCHF        HTPP        HSEC

 50.0     4.05     .47  0.0000   .4594   317.2   389.9   397.3    .406E-01    .394E+02    .638E-02    .539E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .914E-03  .705E-03  .539E-03  .414E-03  .288E-03  .118E-03
 50.0     4.15     .47  0.0000   .4595   318.1   389.9   397.4    .405E-01    .394E+02    .638E-02    .533E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .914E-03  .705E-03  .539E-03  .414E-03  .288E-03  .118E-03
 50.0     4.25     .46  0.0000   .4596   319.0   389.9   397.4    .404E-01    .394E+02    .639E-02    .526E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .914E-03  .705E-03  .539E-03  .413E-03  .288E-03  .117E-03
 50.0     4.35     .45  0.0000   .4597   319.9   389.9   397.4    .403E-01    .394E+02    .639E-02    .520E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .914E-03  .705E-03  .539E-03  .413E-03  .288E-03  .117E-03
 50.0     4.45     .45  0.0000   .4598   320.7   389.9   397.4    .402E-01    .394E+02    .639E-02    .513E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .914E-03  .705E-03  .538E-03  .413E-03  .287E-03  .117E-03
 50.0     4.55     .44  0.0000   .4599   321.5   389.9   397.4    .401E-01    .394E+02    .639E-02    .506E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .914E-03  .704E-03  .538E-03  .413E-03  .287E-03  .116E-03
 50.0     4.65     .44  0.0000   .4600   322.3   389.9   397.5    .400E-01    .394E+02    .639E-02    .499E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .913E-03  .704E-03  .538E-03  .413E-03  .287E-03  .116E-03
 50.0     4.75     .43  0.0000   .4601   323.0   389.9   397.5    .399E-01    .394E+02    .639E-02    .491E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .913E-03  .704E-03  .538E-03  .413E-03  .287E-03  .115E-03
 50.0     4.85     .43  0.0000   .4602   323.8   389.9   397.5    .398E-01    .394E+02    .639E-02    .483E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .913E-03  .704E-03  .538E-03  .412E-03  .286E-03  .115E-03
 50.0     4.95     .42  0.0000   .4603   324.5   389.9   397.5    .397E-01    .394E+02    .639E-02    .474E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .913E-03  .704E-03  .538E-03  .412E-03  .286E-03  .115E-03
 50.0     5.50     .41  0.0000   .4614   331.5   388.9   397.6    .386E-01    .394E+02    .640E-02    .410E-01
 .375E-02  .229E-02  .150E-02  .117E-02  .912E-03  .702E-03  .536E-03  .410E-03  .284E-03  .111E-03
 50.0     6.50     .39  0.0000   .4626   337.4   392.0   397.6    .374E-01    .394E+02    .641E-02    .600E-01
 .375E-02  .229E-02  .149E-02  .116E-02  .910E-03  .701E-03  .534E-03  .408E-03  .282E-03  .106E-03
 50.0     7.50     .35  0.0000   .4639   342.1   392.3   397.7    .361E-01    .394E+02    .642E-02    .569E-01
 .374E-02  .224E-02  .149E-02  .116E-02  .908E-03  .699E-03  .532E-03  .406E-03  .279E-03  .100E-03
 50.0     8.50     .33  0.0000   .4652   345.8   392.5   397.8    .348E-01    .394E+02    .644E-02    .537E-01
 .374E-02  .224E-02  .149E-02  .116E-02  .906E-03  .697E-03  .530E-03  .404E-03  .276E-03  .944E-04
 50.0     9.50     .30  0.0000   .4664   348.8   392.6   397.9    .336E-01    .394E+02    .645E-02    .501E-01
 .374E-02  .224E-02  .149E-02  .116E-02  .904E-03  .695E-03  .528E-03  .401E-03  .273E-03  .878E-04
 50.0    10.50     .28  0.0000   .4676   351.5   392.4   398.0    .324E-01    .394E+02    .646E-02    .452E-01
 .374E-02  .224E-02  .149E-02  .116E-02  .902E-03  .693E-03  .526E-03  .399E-03  .270E-03  .806E-04
 50.0    11.50     .26  0.0000   .4688   353.6   391.3   398.1    .312E-01    .394E+02    .648E-02    .342E-01
 .374E-02  .224E-02  .149E-02  .115E-02  .900E-03  .691E-03  .523E-03  .396E-03  .267E-03  .725E-04
 50.0    12.50     .26  0.0000   .4699   355.0   393.7   398.0    .301E-01    .394E+02    .649E-02    .546E-01
 .374E-02  .224E-02  .148E-02  .115E-02  .899E-03  .688E-03  .521E-03  .394E-03  .264E-03  .634E-04
 50.0    13.50     .25  0.0000   .4710   358.2   393.8   398.1    .290E-01    .394E+02    .650E-02    .521E-01
 .374E-02  .224E-02  .148E-02  .115E-02  .896E-03  .686E-03  .519E-03  .391E-03  .260E-03  .530E-04
 50.0    14.[illegible]     .23  0.0000   .4719   360.4   393.[illegible]   398.1    .281E-01    .394E+02    .651E-0[illegible]    .494E-01
 .374E-02  [illegible]23E-02  .148E-02  .115E-02  .894E-03  .6[illegible]-03  .516E-03  .388E-03  .257E-03  .403E-4
```

```
50.0        0       .22  0.0000   .4727   367.6   3       398.2    .273E-01    .394E+02    .65?        .460E-01
.374E-02  .223E-02  .148E-02  .115E-02  .892E-03    .02E-03  .514E-03  .385E-03  .253E-03  .2. -04
50.0   16.50       .20  0.0000   .4733   365.0   393.7  398.2    .267E-01    .394E+02    .653E-02    .410E-01
.373E-02  .223E-02  .148E-02  .115E-02  .890E-03  .679E-03  .511E-03  .382E-03  .250E-03 0.
50.0   17.50       .18  0.0000   .4739   367.5   392.1  398.4    .261E-01    .394E+02    .654E-02    .263E-01
.373E-02  .223E-02  .148E-02  .114E-02  .887E-03  .677E-03  .508E-03  .379E-03  .246E-03 0.
50.0   18.50       .18  0.0000   .4745   370.1   395.0  398.3    .255E-01    .394E+02    .655E-02    .495E-01
.373E-02  .223E-02  .147E-02  .114E-02  .885E-03  .674E-03  .506E-03  .376E-03  .242E-03 0.
50.0   19.50       .16  0.0000   .4751   372.2   395.2  398.4    .249E-01    .394E+02    .655E-02    .468E-01
.373E-02  .223E-02  .147E-02  .114E-02  .883E-03  .672E-03  .503E-03  .373E-03  .238E-03 0.
50.0   20.50       .15  0.0000   .4757   373.9   395.3  398.5    .243E-01    .394E+02    .656E-02    .438E-01
.373E-02  .222E-02  .147E-02  .114E-02  .880E-03  .669E-03  .500E-03  .370E-03  .234E-03 0.
50.0   21.50       .14  0.0000   .4763   375.4   395.4  398.6    .237E-01    .394E+02    .657E-02    .404E-01
.373E-02  .222E-02  .147E-02  .113E-02  .878E-03  .667E-03  .497E-03  .367E-03  .229E-03 0.
50.0   22.50       .13  0.0000   .4769   376.9   395.2  398.6    .231E-01    .394E+02    .657E-02    .356E-01
.373E-02  .222E-02  .147E-02  .113E-02  .875E-03  .664E-03  .494E-03  .363E-03  .225E-03 0.
50.0   23.50       .13  0.0000   .4775   377.7   396.3  398.7    .225E-01    .394E+02    .658E-02    .502E-01
.372E-02  .222E-02  .146E-02  .113E-02  .873E-03  .661E-03  .491E-03  .360E-03  .221E-03 0.
50.0   24.50       .12  0.0000   .4780   378.7   396.4  398.6    .220E-01    .394E+02    .659E-02    .486E-01
.372E-02  .222E-02  .146E-02  .113E-02  .870E-03  .659E-03  .488E-03  .357E-03  .216E-03 0.
50.0   25.50       .12  0.0000   .4786   379.5   396.4  398.7    .214E-01    .394E+02    .659E-02    .472E-01
.372E-02  .222E-02  .146E-02  .112E-02  .868E-03  .656E-03  .485E-03  .353E-03  .211E-03 0.
50.0   26.50       .11  0.0000   .4792   380.2   396.5  398.7    .208E-01    .394E+02    .660E-02    .457E-01
.372E-02  .221E-02  .146E-02  .112E-02  .865E-03  .653E-03  .482E-03  .350E-03  .206E-03 0.
50.0   27.50       .11  0.0000   .4797   380.9   396.5  398.7    .203E-01    .394E+02    .660E-02    .442E-01
.372E-02  .221E-02  .146E-02  .112E-02  .863E-03  .651E-03  .479E-03  .346E-03  .202E-03 0.
50.0   28.50       .10  0.0000   .4803   381.4   396.5  398.7    .197E-01    .394E+02    .661E-02    .426E-01
.372E-02  .221E-02  .145E-02  .112E-02  .860E-03  .648E-03  .476E-03  .343E-03  .197E-03 0.
50.0   29.50       .10  0.0000   .4808   381.9   396.5  398.7    .192E-01    .394E+02    .662E-02    .409E-01
.372E-02  .221E-02  .145E-02  .112E-02  .857E-03  .645E-03  .473E-03  .339E-03  .191E-03 0.
50.0   30.50       .10  0.0000   .4814   382.3   396.4  398.7    .186E-01    .394E+02    .662E-02    .389E-01
.371E-02  .221E-02  .145E-02  .111E-02  .855E-03  .642E-03  .470E-03  .335E-03  .186E-03 0.
50.0   31.50       .09  0.0000   .4819   382.7   396.4  398.7    .181E-01    .394E+02    .663E-02    .364E-01
.371E-02  .220E-02  .145E-02  .111E-02  .852E-03  .640E-03  .467E-03  .332E-03  .181E-03 0.
50.0   32.50       .09  0.0000   .4824   383.0   396.2  398.7    .176E-01    .394E+02    .663E-02    .328E-01
.371E-02  .220E-02  .144E-02  .111E-02  .850E-03  .637E-03  .464E-03  .328E-03  .175E-03 0.
50.0   33.50       .08  0.0000   .4829   383.2   395.2  398.8    .171E-01    .394E+02    .664E-02    .217E-01
.371E-02  .220E-02  .144E-02  .111E-02  .847E-03  .634E-03  .461E-03  .324E-03  .170E-03 0.
50.0   34.50       .09  0.0000   .4834   383.5   396.1  398.8    .166E-01    .394E+02    .665E-02    .291E-01
.371E-02  .220E-02  .144E-02  .110E-02  .844E-03  .631E-03  .458E-03  .321E-03  .164E-03 0.
```

```
WFTOT= .1    WGTOT= .400U TSEC=400.0 WFWT=1.00 WGWT    0 PPRIM=40.0 DO= .875 DI= .775 DELZ1=1.    DELZ2= .10
DELT= 5.0 NZ1=150 NZ2= 50 NT=100 PSEC=850.0 ASEC= .6    RHOCPT=57.040 ENTFR=0.000 OSS=10.00 ISS=    CPR= 1.00

THIS IS CASE NUMBER  1

 TIME  ELEVATION  QPRIM'  WFOUT   WGOUT   TPOUT  TWALLF  TSECF     ENTSM       QCHF        HTPP        HSEC

 50.0   35.50      .08  0.0000   .4939   383.8   396.1  398.8    .161E-01    .394E+02    .665E-02    .289E-01
 .371E-02  .220E-02  .144E-02  .110E-02  .842E-03  .628E-03  .455E-03  .317E-03  .158E-03 0.
 50.0   36.50      .09  0.0000   .4943   384.2   397.0  398.8    .157E-01    .394E+02    .666E-02    .450E-01
 .370E-02  .220E-02  .144E-02  .110E-02  .839E-03  .626E-03  .451E-03  .313E-03  .152E-03 0.
 50.0   37.50      .08  0.0000   .4948   384.6   397.0  398.7    .152E-01    .394E+02    .666E-02    .439E-01
 .370E-02  .219E-02  .143E-02  .110E-02  .837E-03  .623E-03  .448E-03  .309E-03  .146E-03 0.
 50.0   38.50      .08  0.0000   .4952   385.0   397.0  398.7    .148E-01    .394E+02    .667E-02    .428E-01
 .370E-02  .219E-02  .143E-02  .109E-02  .834E-03  .620E-03  .445E-03  .305E-03  .139E-03 0.
 50.0   39.50      .08  0.0000   .4957   385.4   397.0  398.7    .143E-01    .394E+02    .667E-02    .416E-01
 .370E-02  .219E-02  .143E-02  .109E-02  .831E-03  .617E-03  .442E-03  .301E-03  .132E-03 0.
 50.0   40.50      .08  0.0000   .4961   385.7   397.0  398.7    .139E-01    .394E+02    .668E-02    .403E-01
 .370E-02  .219E-02  .143E-02  .109E-02  .829E-03  .614E-03  .439E-03  .298E-03  .125E-03 0.
 50.0   41.50      .07  0.0000   .4965   386.0   396.9  398.7    .135E-01    .394E+02    .668E-02    .390E-01
 .370E-02  .219E-02  .142E-02  .109E-02  .826E-03  .611E-03  .435E-03  .294E-03  .118E-03 0.
 50.0   42.50      .07  0.0000   .4969   386.3   396.9  398.7    .131E-01    .394E+02    .668E-02    .374E-01
 .370E-02  .218E-02  .142E-02  .108E-02  .823E-03  .608E-03  .432E-03  .290E-03  .110E-03 0.
 50.0   43.50      .07  0.0000   .4973   386.6   396.9  398.7    .127E-01    .394E+02    .669E-02    .356E-01
 .369E-02  .218E-02  .142E-02  .108E-02  .821E-03  .606E-03  .429E-03  .285E-03  .102E-03 0.
 50.0   44.50      .07  0.0000   .4977   386.8   396.8  398.7    .123E-01    .394E+02    .669E-02    .333E-01
 .369E-02  .218E-02  .142E-02  .108E-02  .819E-03  .603E-03  .425E-03  .281E-03  .927E-04 0.
 50.0   45.50      .07  0.0000   .4981   387.1   396.6  398.6    .119E-01    .394E+02    .670E-02    .300E-01
 .369E-02  .218E-02  .142E-02  .108E-02  .815E-03  .600E-03  .422E-03  .277E-03  .830E-04 0.
 50.0   46.50      .06  0.0000   .4984   387.2   395.8  398.7    .116E-01    .394E+02    .670E-02    .198E-01
 .369E-02  .218E-02  .141E-02  .107E-02  .813E-03  .597E-03  .419E-03  .273E-03  .723E-04 0.
 50.0   47.50      .07  0.0000   .4987   387.6   397.0  398.6    .113E-01    .394E+02    .671E-02    .372E-01
 .369E-02  .218E-02  .141E-02  .107E-02  .810E-03  .594E-03  .415E-03  .269E-03  .601E-04 0.
 50.0   48.50      .06  0.0000   .4991   388.0   397.0  398.6    .109E-01    .394E+02    .671E-02    .356E-01
 .369E-02  .217E-02  .141E-02  .107E-02  .807E-03  .591E-03  .412E-03  .265E-03  .457E-04 0.
 50.0   49.50      .06  0.0000   .4993   388.3   396.9  398.5    .107E-01    .394E+02    .671E-02    .336E-01
 .368E-02  .217E-02  .141E-02  .107E-02  .804E-03  .588E-03  .409E-03  .260E-03  .270E-04 0.
 50.0   50.50      .06  0.0000   .4996   388.7   396.8  398.4    .104E-01    .394E+02    .672E-02    .312E-01
 .368E-02  .217E-02  .140E-02  .106E-02  .802E-03  .585E-03  .405E-03  .256E-03 0.        0.
 50.0   51.50      .05  0.0000   .4999   389.0   396.6  398.3    .101E-01    .394E+02    .672E-02    .276E-01
 .368E-02  .217E-02  .140E-02  .106E-02  .799E-03  .582E-03  .402E-03  .251E-03 0.        0.
 50.0   52.50      .05  0.0000   .5001   389.4   397.1  398.4    .985E-02    .394E+02    .672E-02    .359E-01
 .368E-02  .217E-02  .140E-02  .106E-02  .796E-03  .579E-03  .398E-03  .247E-03 0.        0.
 50.0   53.50      .05  0.0000   .5004   389.8   397.0  398.2    .960E-02    .394E+02    .672E-02    .341E-01
 .368E-02  .215E-02  .140E-02  .106E-02  .794E-03  .576E-03  .395E-03  .242E-03 0.        0.
 50.0   54.[illegible]      .05  0.0000   .5007   390.0   396.[illegible]  398.2    .935E-02    .394E+02    .673E-0[illegible]    .324E-01
 .368E-02  .216E-02  .140E-02  .105E-02  .791E-03  .5[illegible]E-03  .391E-03  .238E-03 0.        0.
```

```
50.0        -0        .05  0.0000    .4909   390.3   3        398.1    .910E-02    .394E+02    .67          .304E-01
.368E-02  .216E-02  .139E-02  .105E-02  .7[illegible]8E-03  [illegible]0E-03  .388E-03  .233E-03 0.        0.
50.0   56.50       .04  0.0000    .4911   390.4   396.8   398.1    .885E-02    .394E+02    .673E-02    .261E-01
.367E-02  .216E-02  .139E-02  .105E-02  .785E-03  .567E-03  .384E-03  .228E-03 0.        0.
50.0   57.50       .04  0.0000    .4914   390.6   396.6   398.0    .861E-02    .394E+02    .674E-02    .245E-01
.367E-02  .216E-02  .139E-02  .105E-02  .783E-03  .564E-03  .381E-03  .223E-03 0.        0.
50.0   58.50       .04  0.0000    .4916   390.8   397.0   398.1    .837E-02    .394E+02    .674E-02    .329E-01
.367E-02  .215E-02  .139E-02  .104E-02  .780E-03  .561E-03  .377E-03  .218E-03 0.        0.
50.0   59.50       .04  0.0000    .4919   391.0   396.9   398.0    .814E-02    .394E+02    .674E-02    .314E-01
.367E-02  .215E-02  .138E-02  .104E-02  .777E-03  .558E-03  .374E-03  .213E-03 0.        0.
50.0   60.50       .04  0.0000    .4921   391.1   396.8   397.9    .791E-02    .394E+02    .674E-02    .298E-01
.367E-02  .215E-02  .138E-02  .104E-02  .774E-03  .555E-03  .370E-03  .208E-03 0.        0.
50.0   61.50       .04  0.0000    .4923   391.2   396.8   397.8    .769E-02    .394E+02    .675E-02    .280E-01
.367E-02  .215E-02  .138E-02  .103E-02  .772E-03  .552E-03  .366E-03  .203E-03 0.        0.
50.0   62.50       .04  0.0000    .4925   391.3   396.6   397.7    .747E-02    .394E+02    .675E-02    .257E-01
.366E-02  .215E-02  .138E-02  .103E-02  .769E-03  .549E-03  .363E-03  .198E-03 0.        0.
50.0   63.50       .04  0.0000    .4927   391.4   396.4   397.6    .725E-02    .394E+02    .675E-02    .221E-01
.366E-02  .214E-02  .138E-02  .103E-02  .766E-03  .546E-03  .359E-03  .192E-03 0.        0.
50.0   64.50       .04  0.0000    .4930   391.5   396.7   397.6    .704E-02    .394E+02    .675E-02    .301E-01
.366E-02  .214E-02  .137E-02  .103E-02  .763E-03  .543E-03  .355E-03  .187E-03 0.        0.
50.0   65.05       .04  0.0000    .4930   391.5   396.7   397.5    .702E-02    .394E+02    .676E-02    .292E-01
.366E-02  .214E-02  .137E-02  .103E-02  .763E-03  .543E-03  .355E-03  .186E-03 0.        0.
50.0   65.15       .04  0.0000    .4930   391.5   396.7   397.5    .700E-02    .394E+02    .676E-02    .290E-01
.366E-02  .214E-02  .137E-02  .103E-02  .763E-03  .542E-03  .355E-03  .186E-03 0.        0.
50.0   65.25       .04  0.0000    .4930   391.5   396.7   397.5    .698E-02    .394E+02    .676E-02    .289E-01
.366E-02  .214E-02  .137E-02  .103E-02  .762E-03  .542E-03  .354E-03  .185E-03 0.        0.
50.0   65.35       .04  0.0000    .4930   391.5   396.6   397.5    .696E-02    .394E+02    .676E-02    .287E-01
.366E-02  .214E-02  .137E-02  .103E-02  .762E-03  .542E-03  .354E-03  .185E-03 0.        0.
50.0   65.45       .04  0.0000    .4931   391.5   396.6   397.4    .694E-02    .394E+02    .676E-02    .285E-01
.366E-02  .214E-02  .137E-02  .103E-02  .762E-03  .541E-03  .354E-03  .184E-03 0.        0.
50.0   65.55       .04  0.0000    .4931   391.6   396.6   397.4    .691E-02    .394E+02    .676E-02    .284E-01
.366E-02  .214E-02  .137E-02  .103E-02  .762E-03  .541E-03  .353E-03  .184E-03 0.        0.
50.0   65.65       .04  0.0000    .4931   391.6   396.6   397.4    .689E-02    .394E+02    .676E-02    .282E-01
.366E-02  .214E-02  .137E-02  .102E-02  .761E-03  .541E-03  .353E-03  .183E-03 0.        0.
50.0   65.75       .03  0.0000    .4931   391.6   396.6   397.4    .687E-02    .394E+02    .676E-02    .280E-01
.366E-02  .214E-02  .137E-02  .102E-02  .761E-03  .541E-03  .352E-03  .182E-03 0.        0.
50.0   65.85       .03  0.0000    .4931   391.6   396.6   397.4    .685E-02    .394E+02    .676E-02    .278E-01
.366E-02  .214E-02  .137E-02  .102E-02  .761E-03  .540E-03  .352E-03  .182E-03 0.        0.
50.0   65.9[illegible]       .03  0.0000    .4932   391.6   396.5   397.3    .683E-02    .394E+02    .676E-02    .277E-01
.366E-02  .214E-02  .137E-02  .102E-02  .760E-03  .540E-03  .352E-03  .181E-03 0.        0.
```

WFTOT= . WGTOT= .4000 TSEC=400.0 WFWT=1.03 WGWT 0 PPRIM=40.0 DO= .875 DI= .775 DELZ1=1 DELZ2= .10
DELT= 5.0 NZ1=150 NZ2= 50 NT=130 PSEC=993.0 ASEC= . RHOCPT=57.040 ENTER=0.000 OSS=10.00 ISS CPR= 1.00

THIS IS CASE NUMBER 1

TIME	ELEVATION	QPRIM	WFOUT	WGTOT	TPOUT	TWALLF	TSECF	ENTSM	QCHF	HTPP	HSEC
50.0	66.05	.03	0.0000	.4932	391.6	396.5	397.3	.681E-02	.394E+02	.676E-02	.275E-01
.366E-02	.214E-02	.137E-02	.102E-02	.760E-03	.540E-03	.351E-03	.181E-03	0.	0.		
50.0	66.15	.03	0.0000	.4932	391.6	396.5	397.3	.679E-02	.394E+02	.676E-02	.273E-01
.366E-02	.214E-02	.137E-02	.102E-02	.760E-03	.539E-03	.351E-03	.180E-03	0.	0.		
50.0	66.25	.03	0.0000	.4932	391.6	396.5	397.3	.677E-02	.394E+02	.676E-02	.271E-01
.366E-02	.214E-02	.137E-02	.102E-02	.760E-03	.539E-03	.351E-03	.180E-03	0.	0.		
50.0	66.35	.03	0.0000	.4933	391.6	396.5	397.2	.675E-02	.394E+02	.676E-02	.269E-01
.366E-02	.214E-02	.137E-02	.102E-02	.759E-03	.539E-03	.350E-03	.179E-03	0.	0.		
50.0	66.45	.03	0.0000	.4933	391.6	396.4	397.2	.673E-02	.394E+02	.676E-02	.267E-01
.366E-02	.214E-02	.137E-02	.102E-02	.759E-03	.538E-03	.350E-03	.178E-03	0.	0.		
50.0	66.55	.03	0.0000	.4933	391.6	396.4	397.2	.671E-02	.394E+02	.676E-02	.265E-01
.366E-02	.214E-02	.137E-02	.102E-02	.759E-03	.538E-03	.349E-03	.178E-03	0.	0.		
50.0	66.65	.03	0.0000	.4933	391.6	396.4	397.2	.669E-02	.394E+02	.676E-02	.263E-01
.366E-02	.214E-02	.137E-02	.102E-02	.759E-03	.538E-03	.349E-03	.177E-03	0.	0.		
50.0	66.75	.03	0.0000	.4933	391.7	396.4	397.1	.667E-02	.394E+02	.676E-02	.261E-01
.366E-02	.214E-02	.137E-02	.102E-02	.758E-03	.537E-03	.349E-03	.177E-03	0.	0.		
50.0	66.85	.03	0.0000	.4934	391.7	396.4	397.1	.665E-02	.394E+02	.676E-02	.259E-01
.366E-02	.214E-02	.137E-02	.102E-02	.758E-03	.537E-03	.348E-03	.176E-03	0.	0.		
50.0	66.95	.03	0.0000	.4934	391.7	396.3	397.1	.663E-02	.394E+02	.676E-02	.257E-01
.366E-02	.214E-02	.137E-02	.102E-02	.758E-03	.537E-03	.348E-03	.176E-03	0.	0.		
50.0	67.05	.03	0.0000	.4934	391.7	396.3	397.1	.661E-02	.394E+02	.676E-02	.254E-01
.366E-02	.214E-02	.137E-02	.102E-02	.757E-03	.537E-03	.348E-03	.175E-03	0.	0.		
50.0	67.15	.03	0.0000	.4934	391.7	396.3	397.0	.659E-02	.394E+02	.676E-02	.252E-01
.366E-02	.214E-02	.137E-02	.102E-02	.757E-03	.536E-03	.347E-03	.174E-03	0.	0.		
50.0	67.25	.03	0.0000	.4934	391.7	396.3	397.0	.657E-02	.394E+02	.676E-02	.250E-01
.366E-02	.214E-02	.137E-02	.102E-02	.757E-03	.536E-03	.347E-03	.174E-03	0.	0.		
50.0	67.35	.03	0.0000	.4935	391.7	396.2	397.0	.655E-02	.394E+02	.676E-02	.248E-01
.366E-02	.214E-02	.137E-02	.102E-02	.757E-03	.536E-03	.346E-03	.173E-03	0.	0.		
50.0	67.45	.03	0.0000	.4935	391.7	396.2	396.9	.653E-02	.394E+02	.676E-02	.245E-01
.366E-02	.214E-02	.137E-02	.102E-02	.756E-03	.535E-03	.346E-03	.173E-03	0.	0.		
50.0	67.55	.03	0.0000	.4935	391.7	396.2	396.9	.651E-02	.394E+02	.676E-02	.243E-01
.366E-02	.214E-02	.137E-02	.102E-02	.756E-03	.535E-03	.346E-03	.172E-03	0.	0.		
50.0	67.65	.03	0.0000	.4935	391.7	396.1	396.9	.649E-02	.394E+02	.676E-02	.240E-01
.366E-02	.214E-02	.137E-02	.102E-02	.756E-03	.535E-03	.345E-03	.171E-03	0.	0.		
50.0	67.75	.03	0.0000	.4935	391.7	396.1	396.8	.647E-02	.394E+02	.676E-02	.237E-01
.366E-02	.214E-02	.137E-02	.102E-02	.755E-03	.534E-03	.345E-03	.171E-03	0.	0.		
50.0	67.85	.03	0.0000	.4936	391.7	396.1	396.8	.645E-02	.394E+02	.676E-02	.235E-01
.366E-02	.214E-02	.137E-02	.102E-02	.755E-03	.534E-03	.345E-03	.170E-03	0.	0.		
50.0	67.[illegible]	.03	0.0000	.4936	391.7	396.[illegible]	396.8	.643E-02	.394E+02	.676E-0[illegible]	.232E-01
.366E-02	[illegible]14E-02	.137E-02	.102E-02	.755E-03	.5[illegible]E-03	.344E-03	.170E-03	0.	0.		

```
50.0                .03  0.0000   .4936   391.17   3[illegible]   396.7    .641E-02    .394E+02    .676[illegible]    .229E-01
.366E-02  .214E-02  .137E-02  .102E-02  .755E-03   [illegible]3E-03  .344E-03  .169E-03 0.          0.
50.0   68.15        .03  0.0000   .4936   391.17   396.0  396.7    .639E-02    .394E+02    .676E-02    .226E-01
.366E-02  .214E-02  .137E-02  .102E-02  .754E-03  .533E-03  .343E-03  .168E-03 0.          0.
50.0   68.25        .03  0.0000   .4936   391.17   396.0  396.6    .637E-02    .394E+02    .676E-02    .223E-01
.366E-02  .214E-02  .137E-02  .102E-02  .754E-03  .533E-03  .343E-03  .168E-03 0.          0.
50.0   68.35        .03  0.0000   .4936   391.17   395.9  396.6    .635E-02    .394E+02    .676E-02    .220E-01
.366E-02  .214E-02  .137E-02  .102E-02  .754E-03  .533E-03  .343E-03  .167E-03 0.          0.
50.0   68.45        .03  0.0000   .4937   391.17   395.9  396.5    .633E-02    .394E+02    .676E-02    .217E-01
.366E-02  .214E-02  .136E-02  .102E-02  .753E-03  .532E-03  .342E-03  .167E-03 0.          0.
50.0   68.55        .03  0.0000   .4937   391.17   395.8  396.5    .631E-02    .394E+02    .676E-02    .213E-01
.366E-02  .214E-02  .136E-02  .102E-02  .753E-03  .532E-03  .342E-03  .166E-03 0.          0.
50.0   68.65        .03  0.0000   .4937   391.17   395.8  396.5    .629E-02    .394E+02    .676E-02    .210E-01
.366E-02  .214E-02  .136E-02  .102E-02  .753E-03  .532E-03  .342E-03  .165E-03 0.          0.
50.0   68.75        .03  0.0000   .4937   391.17   395.8  396.4    .627E-02    .394E+02    .676E-02    .206E-01
.366E-02  .214E-02  .136E-02  .102E-02  .753E-03  .531E-03  .341E-03  .165E-03 0.          0.
50.0   68.85        .03  0.0000   .4937   391.17   395.7  396.4    .625E-02    .394E+02    .676E-02    .202E-01
.366E-02  .214E-02  .136E-02  .102E-02  .752E-03  .531E-03  .341E-03  .164E-03 0.          0.
50.0   68.95        .03  0.0000   .4938   391.17   395.7  396.3    .623E-02    .394E+02    .676E-02    .198E-01
.366E-02  .214E-02  .136E-02  .102E-02  .752E-03  .531E-03  .340E-03  .163E-03 0.          0.
50.0   69.05        .03  0.0000   .4938   391.17   395.6  396.3    .621E-02    .394E+02    .676E-02    .193E-01
.366E-02  .214E-02  .136E-02  .102E-02  .752E-03  .530E-03  .340E-03  .163E-03 0.          0.
50.0   69.15        .03  0.0000   .4938   391.17   395.6  396.2    .620E-02    .394E+02    .676E-02    .189E-01
.365E-02  .213E-02  .136E-02  .102E-02  .752E-03  .530E-03  .340E-03  .162E-03 0.          0.
50.0   69.25        .03  0.0000   .4938   391.17   395.5  396.1    .618E-02    .394E+02    .676E-02    .184E-01
.365E-02  .213E-02  .136E-02  .102E-02  .751E-03  .530E-03  .339E-03  .162E-03 0.          0.
50.0   69.35        .03  0.0000   .4938   391.17   395.5  396.1    .616E-02    .394E+02    .677E-02    .179E-01
.365E-02  .213E-02  .136E-02  .102E-02  .751E-03  .529E-03  .339E-03  .161E-03 0.          0.
50.0   69.45        .03  0.0000   .4939   391.17   392.3  385.2    .614E-02    .394E+02    .677E-02    .173E-01
.365E-02  .213E-02  .136E-02  .101E-02  .751E-03  .529E-03  .338E-03  .160E-03 0.          0.
50.0   69.55       -.04  0.0000   .4939   391.14   377.1  366.9    .612E-02    .394E+02    .677E-02    .429E-01
.365E-02  .213E-02  .136E-02  .101E-02  .750E-03  .529E-03  .338E-03  .160E-03 0.          0.
50.0   69.65       -.09  0.0000   .4939   391.0    370.6  359.9    .610E-02    .394E+02    .677E-02    .412E-01
.365E-02  .213E-02  .136E-02  .101E-02  .750E-03  .528E-03  .338E-03  .159E-03 0.          0.
50.0   69.75       -.18  0.0000   .4939   390.14   359.3  347.9    .608E-02    .394E+02    .677E-02    .384E-01
.365E-02  .213E-02  .136E-02  .101E-02  .750E-03  .528E-03  .337E-03  .158E-03 0.          0.
50.0   69.85       -.20  0.0000   .4939   389.17   355.3  343.1    .606E-02    .394E+02    .677E-02    .352E-01
.365E-02  .213E-02  .136E-02  .101E-02  .750E-03  .528E-03  .337E-03  .158E-03 0.          0.
50.0   69.95       -.25  0.0000   .4940   389.0    348.8  334.4    .604E-02    .394E+02    .677E-02    .295E-01
.365E-02  .213E-02  .136E-02  .101E-02  .749E-03  .528E-03  .337E-03  .157E-03 0.          0.
```

NRC FORM 335 (7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER (Assigned by DDC)
NUREG/CR-1534
NP-1461
WCAP-9724

4. TITLE AND SUBTITLE (Add Volume No., if appropriate)
PWR FLECHT-SEASET Steam Generator Separate Effects Task Data Analysis and Evaluation Report
NRC/EPRI/Westinghouse Report No. 9

2. (Leave blank)

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
R. C. Howard, L. E. Hochreiter

5. DATE REPORT COMPLETED

MONTH	YEAR
June	1981

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Westinghouse Electric Corporation
Nuclear Energy Systems
P. O. Box 355
Pittsburgh, PA 15230

DATE REPORT ISSUED

MONTH	YEAR
February	1982

6. (Leave blank)

8. (Leave blank)

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Office of Nuclear Regulatory Research
Division of Accident Evaluation
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.
NRC-04-77-127
FIN B6204

13. TYPE OF REPORT
Topical

PERIOD COVERED (Inclusive dates)

15. SUPPLEMENTARY NOTES

14. (Leave blank)

16. ABSTRACT (200 words or less)

This report presents the evaluation of the data from the Steam Generator Separate Effects Task of the Full-Length Emergency Cooling Heat Transfer Separate Effects and Systems Effects Test Program (FLECHT SEASET). In this task a series of heat transfer tests were run on a model steam generator operating under simulated loss-of-coolant conditions. The model steam generator was made up of 32 full-length U-tubes instrumented with thermocouples to measure secondary fluid, tube wall, and primary steam temperatures. The separate effects tests measured steam generator bundle heat transfer with known boundary conditions to provide better understanding of the steam generator behavior in the systems effects tests. The test results are presented in NRC/EPRI/Westinghouse Report No. 4. This report described the analysis of the data and an analytical model that adequately predicts the test data.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS (This report)
Unclassified

20. SECURITY CLASS (This page)
Unclassified

21. NO. OF PAGES

22. PRICE
$

NRC FORM 335 (7-77)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
U.S. NUCLEAR REGULATORY
COMMISSION

U.S. MAIL