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LOFT TECHNICAL REPORT

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TITLE EXPERIMENTAL DATA REPORT FOR HEATER ROD TEST SERIES B-TC		REPORT NO. LTR 20-69
AUTHOR D. J. Barnum, C. W. Solbrig, H. S. Selcho	GWA NO.	ACCOUNT NO.
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ABSTRACT

Tests were performed on low-power, zircaloy clad, electrically heated rods at the Blowdown facility located at the LOFT Test Support Facility, (LTSF). Testing consisted of two parts, steady state and blowdown-reflood testing. Initial test conditions were as close to Loss-Of-Fluid-Test (LOFT) as practical.

Test objectives were to: (a) develop and evaluate techniques for embedding thermocouples into zircaloy sheaths of nuclear fuel and electrical heater rods, (b) gain operating experience with the Blowdown facility, and (c) evaluate the performance of LOFT cladding surface thermocouples during simulated Loss-Of-Coolant-Accident (LOCA) conditions.

DISPOSITION OF RECOMMENDATIONS

No disposition required.

CONTENTS

TABLES

FIGURES

1.0 INTRODUCTION

The test series on the low-power zircaloy clad heater rods has been completed at the Blowdown facility. This test series, designated as test series B-TC, was the first of several to obtain test measurements for evaluation of the performance of LOFT fuel cladding thermocouples. In particular, it is desirable to know whether the protrusion of the cladding thermocouples into the surrounding coolant causes significant measurement errors.

Testing was performed on two separate test heater rods, LH-5 and LH-7, and consisted of two parts, steady state and blowdown-reflood (LOCA) testing. The objectives of the tests were to: (a) develop and evaluate techniques for embedding thermocouples into zircaloy sheaths of nuclear fuel and electrical heater rods, (b) gain operating experience with the recently reassembled Blowdown facility, and (c) to evaluate the performance of LOFT cladding surface thermocouples during simulated loss-of-coolant accident (LOCA) conditions.

Representative results from the test series are presented. The complete set of data is not presented because of the total number of plots. However, all test data have been examined and are available on magnetic tape. Cursory analysis of the data is made to evaluate the meeting of test objectives and to establish the Blowdown facility as a valid instrumentation testing apparatus.

2.0 LOFT BLOWDOWN FACILITY DESCRIPTION

The Blowdown facility is a comprehensive test apparatus located at the Idaho National Engineering Laboratory. It is designed to simulate transient thermal-hydraulic conditions expected during a loss-of-coolant accident. The facility is used to test advanced instrumentation techniques and provide original research in support of the LOFT program. The test facility is depicted in Figure 1.

2.1 Facility Description

An isometric of the facility is given in Figure 2. Major components consist of a pressure vessel, a circulation pump, two electrical heater rod housings (one for power and one for test), a quick-opening blowdown valve, and a coolant injection system.

Piping of various sizes connects the components. Flow control valves allow flexibility in flow path selection and flow rates. Additional piping provides a blowdown path for venting the fluid to the atmosphere. Test components in the blowdown line include a drag-disc turbine transducer for flow measurements and a test section supplied by Atomic Energy of Canada, Ltd (AECL).

Through appropriate selection of flow paths, two different test loops may be established. These test loops, identified as the small and the large test loops, will provide blowdowns of varying duration for a test. Both loops simulate a hot leg break. The small test loop is depicted in Figure 3. The large test is shown in Figure 4. The small test loop was used in this test. System flow rate during the blowdown was controlled utilizing a 1/4-in. orifice preceeding the blowdown valve.

2.2 Description Of Heater Rods

The heater rods tested were internally heated low-power test rods with zircaloy-4 cladding. The two rods, designated as Rods LH-7 and LH-5, were originally purchased for qualification testing of LOFT cladding thermocouple welds. Rod LH-7 had experienced four blowdown-reflood tests and some dynamic response scoping tests prior to this testing which are described in Reference 2. Rod LH-5 did not appear to have experienced any prior testing. Applicable data for Rods LH-7 and LH-5 follow:

(1) Power: the heater rods are capable of producing 9.48 kW ± 5% at 93 volts dc

(2) Heating element resistance: approximately 0.9 ohm

(3) Outside diameter: 0.422 ± 0.002 in.

(4) Rod length: LH-7 - 88 in.; LH-5 - 86 in.

(5) Rod heated length: 66 in.

(6) Upper electrode extension length: LH-7 - 14 in.; LH-5 - 13 in.

(7) Cladding material: zircaloy-4

(8) Upper electrode material: nickel-clad copper

(9) Insulation: boron nitride.

The heater rods were instrumented with three varieties of thermocouples. Titanium sheathed (0.046-in. diameter) type K thermocouples were installed in the LOFT cladding thermocouple geometry complete with dummy pieces. In addition, titanium type K thermocouples were embedded within the heater rod cladding for lengths of approximately 1 in. as described in Reference 3. The embedded thermocouple cables have a 0.046-in. diameter and are laser welded to the cladding. Stainless steel sheathed (0.025-in. diameter) type K thermocouples were installed on the rods to measure the bulk coolant temperature at the same axial locations as the embedded and LOFT geometry thermocouples. These coolant thermocouples were strapped to the rods. The coolant thermocouples were removed following the calibration test prior to the LOCA tests to avoid forming a stainless steel-zirconium eutectic at high temperatures.

3.0 TEST DESCRIPTION

Testing on the test heater rods in LOFT Blowdown facility consisted of steady state testing to determine the embedded thermocouple installation factors and LOCA tests including reflood. The steady state tests used constant power conditions.

3.1 Initial Conditions

The system was filled with treated demineralized water (N_2H_4 for O_2 scavenging, and LiOH for pH control). Periodic instrument checking took place during heatup. The system was brought to initial temperature by the heater rods and to initial pressure of 1400 psi. The system coolant was circulated by the pump until steady state conditions were obtained. A water sample was taken at 200°F to check the water chemistry to ensure chemical concentrations were within acceptable bounds. The specifications were as close to the LOFT system as possible. The requirements were:

(1) pH 9.0 - 10.5

(2) Conductivity 1 - 40 umho/cm

(3) Oxygen 0.1 ppm maximum

(4) Chloride 0.15 ppm maximum

(5) Hydrazine 1.0 ppm minimum.

3.2 Test Conditions

Test conditions were intended to simulate conditions in the LOFT system. The installation of the AECL test section necessitated lowering pressure to 1400 from 2250 psia. The test conditions and results for each run are discussed in Appendix A.

3.2.1 Steady State Tests. The test runs used to establish installation factors for the embedded thermocouples required subcooled steady state coolant conditions. Each test run was preceded by a 5-min time interval to verify that stable conditions had been established. During this time period, the following parameters did not vary by more than the maximum amount specified:

(1) Test heater rod housing inlet temperature	2°F
(2) Test heater rod power	0.1 kW
(3) Test heater rod housing flow	1% of maximum flow
(4) Test heater rod housing inlet pressure	20 psi.

Following the 5-min stabilization period, data were recorded for a 10-sec period. The mean values of measured parameters for this period were then used for the data analysis. All steady state tests proceeded as planned with no equipment failures except embedded thermocouple LZE4 on Rod LH-5 developed an open circuit prior to start of testing on that rod.

3.2.2 LOCA Tests. All LOCA tests were conducted using similar scenarios. First, stable conditions were established as described above with the heater rod power at 9 kW. The blowdown was initiated by opening the quick-opening valve at the end of the blowdown line. At the same time at which the blowdown was commenced, the coolant pump was stopped and the heater rod housings were isolated from the pressure vessel, permitting blowdown of the heater rod housings without the pressure vessel. The blowdown controlling orifice was sized such that the heater rod housing inlet pressure dropped to 100 psi approximately 20 to 40 sec after blowdown started dependent upon the amount of subcooling of system fluid in the blowdown line.

For the first two tests, the heater rod power level was lowered to a specified value at a time 2 sec after blowdown commenced. The power level then remained at that level until reflood and quench of the rod was completed. After the first two tests, the level of power was lowered at the time of the blowdown initiation.

Reflood of the heater rod housings began when the rod cladding temperature as read on thermocouple LZE1 or LZE2 for Rod LH-7 (LZE3 for Rod LH-5) reached the specified value. Water was injected into the heater rod housing at a rate of approximately 5 in. per sec. Reflood continued until the whole heated length of the rod was quenched. If the rod cladding temperature measured by the embedded thermocouples reached a specified maximum cutoff value the power to the test rod was immediately interrupted.

The heater rod power levels and temperature at which reflood commenced were selected to duplicate the thermal-hydraulic conditions expected in the first LOFT nuclear test series.

Rod LH-7 was the first to be tested. Test runs 1 and 2 (test conditions are outlined in Appendix A) were performed as planned. However, during test run 3 the heater rod resistance began to change erratically. During test run 4 the rod heating element failed open circuit. This failure was later traced to a flaw in the heater rod and was not due to testing techniques or thermocouple installation.

Test runs 1, 2, 3, 4, 6, 8, and 10 were performed for Rod LH-5. These tests were all completed as planned without equipment failure. The remaining tests were originally omitted due to other testing priorities. Rescheduling of the tests was not done due to a later failure of embedded thermocouple LZE3.

3.3 Test Measurements

Test objectives stipulated that several instrument measurements were to be recorded during testing. All data were recorded on analog tapes and then digitized on the LOFT DAVDS. The instruments recorded during each test varied due to test requirements and recording capability.

Instruments in the Blowdown facility consist of two parts, permanent facility and test component instrumentation. Instrumentation consists of pressure, differential pressure, temperature, density, and flow (turbine and drag-disc) transducers. The instrument list is given in Table I. Additional description of the test heater rod thermocouples are presented in Table II.

TABLE I

BLOWDOWN FACILITY INSTRUMENTATION

MEASUREMENT ID	LOCATION	RANGE
Flow Meters		
FT-H1	Inlet to north heater vessel	5 - 50 gpm
FT-H2	Inlet to south heater vessel	5 - 50 gpm
FT-PVBP	Pump bypass line	40 - 650 gpm
FT-BPW	Nozzle warmup bypass	0.75 - 7.5 gpm
FT-ACC	Accumulator line	0.25 - 2.5 gpm
FT-Nozzle	Blowdown line	0 - 2000 gpm
FD-Nozzle	Blowdown line	
Pressure Transducer		
PE1	Heater rod housing inlet	0 - 3000 psig
P-H2-0	South heater rod housing outlet	0 - 3000 psig
P-Vessel	Pressure vessel	0 - 3000 psig
P-Nozzle	Blowdown line	0 - 3000 psig

TABLE I (Continued)

MEASUREMENT ID	LOCATION	RANGE
Density		
DE1	Blowdown line	0 - 64 lb/ft^3
DE2	Blowdown line	0 - 64 lb/ft^3
DE3	Blowdown line	0 - 64 lb/ft^3
Heater Rod Temperature		
TH-35-A5	Bypass heater rod	150 - 1800°F
TH-59-C7	Bypass heater rod	150 - 1800°F
TH-49-B6	Bypass heater rod	150 - 1800°F
TH-H1	Bypass heater rod	150 - 1800°F
Differential Pressure		
DP-Pump	Pump suction to discharge	0 - 100 psid
DP-DTT	Blowdown line	0 - 1 psid
DP-4-7	Heater rod inlet to outlet	0 - 50 psid
LOFT Test Rod Thermocouples (ROD LH-7)		
LOFT Type		
LZL1		150 - 1800°F
Embedded		
LZE1		150 - 1800°F
LZE2		150 - 1800°F
Coolant		
LZC1		150 - 1800°F
LZC2		150 - 1800°F
LOFT Test Rod Thermocouples (Rod LH-5)		
LOFT Type		
LZL3		150 - 1800°F
LZL4		150 - 1800°F

TABLE I (Continued)

MEASUREMENT ID	LOCATION	RANGE
LZL5		150 - 1800°F
LZL6		150 - 1800°F
Embedded		
LZE3		150 - 1800°F
LZE4		150 - 1800°F
Coolant		
LZC3		150 - 1800°F
LZC4		150 - 1800°F
Vessel Metal Temperature		
TMV2-41	41 in. above center of heater vessel	150 - 1800°F
TMV2-25	25 in. below center of heater vessel	150 - 1800°F
Thermocouple Measurement		
Fluid Temperature		
TF-H1-I	North heater vessel inlet	150 - 1250°F
TF-H1-O	North heater vessel outlet	150 - 1250°F
TF-H2-I	South heater vessel inlet	150 - 1250°F
TF-H2-O	South heater vessel outlet	150 - 1250°F
TF-Vessel	Pressure vessel	150 - 1250°F
TF-Nozzle	Blowdown nozzle	150 - 1250°F
AECL Section		
DE-AECL-1	Density	
DE-AECL-2	Density	
DE-AECL-3	Density	
PE-AECL-1	Pressure	0 - 1400 kp

TABLE I (Continued)

MEASUREMENT ID	LOCATION	RANGE
PE-AECL-2	Pressure	0 - 14 mp
TE-AECL-1	Thermocouple	0 - 350°C
FE-AECL-1	Turbine	0 - 15 sec^2
Drag-Disc Turbine Transducer (DTT)		
DTT-FD-1	Drag disc	
DTT-Turbine	Turbine	
DTT-TF	Thermocouple	
DTT-FD-2	Drag disc	
Rod Power		
H1 V	North rod V	0 - 200 V
H2 V	South rod V	C - 100 V
HBP V	Bypass rod V	0 - 200 V
H1 amps	North rod amps	0 - 400 amps
H2 amps	South rod amps	0 - 100 amps
HBP amps	Bypass rod amps	0 - 400 amps
Measurement Identification Symbols		
FT Flow turbine		
FD Drag-Disc		
TF, Tm, TH Thermocouple		
DE Gamma densitometer		
P Pressure		
DP Differential pressure		

TABLE II

HEATER ROD INSTRUMENTATION

Rod	TC Type	TC Designation	Axial Position (in.)	Azimuth Position (degree)
LH-7	LOFT	LZL1	29-3/8	0
LH-7	Embedded	LZE1	29-3/8	90
LH-7	Embedded	LZE2	29-3/8	270
LH-7	Coolant	LZC1	29-3/8	120
LH-7	Coolant	LZC2	29-3/8	240
LH-5	LOFT	LZL3	10-5/8	0
LH-5	LOFT	LZL4	28-5/8	90
LH-5	LOFT	LZL5	43-5/8	180
LH-5	LOFT	LZL6	60-5/8	270
LH-5	Embedded	LZE3	28-5/8	60
LH-5	Embedded	LZE4	43-5/8	150
LH-5	Coolant	LZC3	28-5/8	30
LH-5	Coolant	LZC4	43-5/8	210

Only required measurements were recorded during testing due to recording capability limits. Instrument measurements recorded for each test are described in Appendix A, along with measured thermocouple response for the steady state, constant power tests.

4.0 TEST DATA ANALYSIS

The objectives of the tests were to gain experience in the operation of the Blowdown facility as a test facility, evaluate techniques for embedding thermocouples into zircaloy cladding, and evaluate the performance of LOFT cladding surface thermocouples during simulated LOCA conditions. The steady state, constant power tests were used to develop an installation factor for the embedded thermocouple. The LOCA tests were used to evaluate the LOFT cladding thermocouple relative to the performance of the embedded thermocouple.

4.1 Steady State Tests

The purpose of the steady state testing was to obtain installation factors for each of the thermocouples embedded within the sheaths of the heater rods. This installation factor will allow calculation of the heater rod surface temperature from the temperature measured by the embedded thermocouple.

The relationship between the embedded thermocouple value and the actual surface temperature is given by Equation (1).

$$T_s = T_E - CP \qquad (1)$$

where

T_s = surface temperature
T_E = embedded thermocouple reading
P = rod power
C = installation factor.

By using the steady state heat conduction equation, the installation factor can be related to the heater rod properties by:

$$C = \frac{\Delta X}{k} \quad (2)$$

where

ΔX = distance thermocouple is embedded

K = thermal conductivity.

By considering heat flow to the fluid, the following relationship, independent of the unknown surface temperature, may be used

$$\frac{\Delta T}{Q} = \frac{1}{h} + \frac{\Delta X}{k} \quad (3)$$

where

$\Delta T = T_E - T_C$

T_C = coolant temperature

Q = heater rod heat flux

h = coolant heat transfer coefficient.

By plotting $\Delta T/Q$ versus 1/h from the data, the installation factor may be found.

For each test the rod surface heat transfer coefficient was varied by adjusting the flow through the test heater vessel between 3.5×10^5 and 3.5×10^6 lbm/ft^2 hr. For each steady state condition the flow, rod power, embedded thermocouple temperature, coolant temperature, and coolant pressure were determined such that each data point could be plotted on a $\Delta T/Q$ versus 1/h plot per Equation (3). In addition to changing the flow, data points were collected with the heater rod power both at 5 and 9 kW and with the heater vessel coolant inlet temperature at approximately 350 and 550°F.

Appendix B contains the theoretical background and model development for the technique which was used for these tests. The parameters used for analysis of the steady state test data are also included in Appendix B.

The data for each embedded thermocouple, coolant thermocouple pair for Rods LH-5 and LH-7 are presented in Figures 5 to 7. The data are categorized by coolant temperature and rod power. The plots also contain the regression line for each set of data for a thermocouple pair as well as the regression line for all data from a thermocouple. The regression line for the 550°F, 9-kW data for Rod LH-7 is not shown since the embedded thermocouple failed during the test.

The slope for all data of each thermocouple pair agrees well with the model given in Equation (3). In addition the installation factors (Y-intercept) computed for each thermocouple pair agree quite well (within 30%) with one another.

However, further evaluation of the figures indicates that sets of data points where the coolant inlet temperature and heater rod power were kept constant exhibit a more linear characteristic than do all sets of data combined. This is evidenced in Appendix B where the correlation coefficient is higher for conditions when the coolant temperature and rod power are held constant than when all data are combined. This effect is most pronounced in Figure 7.

Since the individual data sets exhibit good linearity, then the spread in the total data cannot be attributed to statistical variation or noise of the measurements. Instead it suggests that one of the parameter measurements was influenced by the heater rod power level.

It is suspected that either the embedded thermocouples or thermocouples measuring the coolant temperature may have been slightly influenced to various degrees by the heater rod power. Induced errors of less than 1% could cause the data spreads but remain unnoticed throughout the testing. Two of the LOFT geometry thermocouples exhibited a dependence upon the heater rod power of a large enough magnitude (10%) to be identified during the testing. This is thought to possibly be due to a point of low insulation resistance between one of the thermoelements and the thermocouple sheath at a location other than the grounded junction. A similar condition of a much smaller magnitude may have existed in the embedded or coolant thermocouples. As a result, all rods to be used in the future will be tested to determine if such an influence exists.

The magnitudes of $\Delta X/k$ result in embedded thermocouple installation factors (C) on the order of 2.5×10^{-3} °F/W. For the low power levels used to simulate decay heat during a LOCE, the difference between the calculated surface temperature and the temperature measured by the embedded thermocouple is approximately 5°F. This is small enough to be neglected when compared to the magnitude of the noise on the embedded thermocouple signals of up to 20°F. In later tests of high power rods, the temperature difference may be large enough to be significant due to the stored energy within the rod at the time of blowdown.

Figure 8 gives a representative comparison between a LOFT cladding thermocouple and an embedded thermocouple. This thermocouple pair (LZL4 and LZE3) shows that typical differences are less than 10%, on the order of 40°F.

4.2 LOCA Testing

All LOCA tests were run with the same scenario as described in Section 3.2.2. Figure 9 shows a typical plot of heater rod vessel outlet pressure versus time, and Figure 10 shows a plot of an embedded thermocouple measured temperature (LZE3) versus time. These data are taken from run 4 of Rod LH-5.

Following blowdown the cladding temperature begins to drop off. This is due to the small amount of stored energy available in the low power rods at the time of blowdown and increased mass flow due to the hot leg break simulation. The heater rods used for this testing were only capable of producing approximately 15% of the peak power generation rate expected in the LOFT reactor. Thus critical heat flux (CHF) is not experienced shortly after blowdown as it has been in Semiscale testing. The high power capability of future rods to be tested along with a change to the heater rod power versus time should result in cladding temperature conditions more representative of those expected on the LOFT fuel rods.

After approximately 20 to 30 sec, the cladding temperature begins to rise due to residual stored energy and decreased heat transfer between the rod surface and the high quality two-phase coolant mixture during the low power generation. This temperature rise continues until the reflood temperature is reached. In most cases the time required to reach reflood temperature was several minutes long. The heater rod power was reduced to simulate LOFT decay heat (5% of LOFT power) during the blowdown. However, the Blowdown facility geometry produces different coolant conditions surrounding the single heater rod than would be experienced by a LOFT nuclear fuel bundle. Thus, the relatively long time required to reach reflood temperature is due to these differences in experimental conditions, not the least of which is the amount of radiation heat transfer.

The several minutes exposure at high temperatures in a steam environment caused severe corrosion to the rod thermocouple welds and sheaths. Therefore, in future testing the heater rod power should be left high enough to reach reflood temperature quickly, minimizing the damage to the heater rod and attached thermocouples.

The LOCA testing of both rods was consistent with general Semiscale results and with FLOOD-4 computer code prediction of the order of thermocouple quench during reflood. Figure 11 is a plot of the LOFT geometry thermocouple temperatures for run 1 of Rod LH-5. The thermocouple nearest the bottom of the rod (LZL3) was the first to quench. It is followed by the thermocouple nearest the top of the rod (LZL6). The thermocouples nearest the center of the rods (LZE4 and LZL5) reach the highest temperature and are the last to quench.

One of the major test objectives was to compare the measurements of LOFT geometry cladding thermocouples to the embedded thermocouples. The only functional LOFT geometry thermocouple on Rod LH-7 (LZL1) was discovered to be partially defective in that its temperature reading was influenced by the heater rod power level. This prevented a quantitative comparison of temperature measurements for the LOCA tests of Rod LH-7. The dependence of LZL1 on heater rod power is suspected to be due to a point of low resistance between a thermoelement and the thermocouple sheath at a point other than the grounded junction.

In Figure 8, the embedded thermocouple LZE3 on Rod LH-5 was compared to the LOFT geometry thermocouple LZL4, which was at the same axial location on the rod, for run 4. The temperatures measured by these two thermocouples agreed within 20°F during the blowdown portions of all LOCA tests. However, in Figure 12 it can be seen that during reflood prior to quench, temperature differences of up to 100°F developed with the embedded thermocouple measurement higher than the LOFT geometry thermocouple. These large temperature differences appeared on approximately 50% of the LOCA tests.

The presence of this temperature difference agrees with the results of Reference 3. This is, errors in measurement of the surface temperature by the LOFT cladding thermocouples may exist when the thermocouple can create a thermal bridge from the rod across a steam blanket to a heat sink of coolant. However, small errors will exist due to the fin effect of the thermocouple when the rod and thermocouple are surrounded by a homogeneous coolant as would be the case during blowdown prior to initiation of reflood.

Although the data from Rod LH-5 indicate that cladding surface temperature measurement errors of up to 100°F may be made during reflood, this is not necessarily the case for LOFT nuclear fuel rods. The data reflect only the results of one pair of thermocouples on one heater rod. However, the potential for error which has been exposed is justification to continue the cladding thermocouple characterization testing program as presently outlined. Similar LOCA tests will be performed using heater rods of higher power capability.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The Blowdown facility heater rod test series B-TC has been successfully completed in accomplishing the established test objectives.

Three of the four developmental embedded thermocouples installed on the heater rods operated satisfactorily throughout all tests performed. Steady state tests were performed to determine installation factors for these thermocouples. The installation factors calculated indicate that the thermocouple embedding process is consistently repeatable.

Comparison of the temperature as measured by LOFT cladding surface thermocouples to the embedded thermocouples reveals that a measurement error may be made by the LOFT cladding thermocouple. This error will be largest during times when the thermocouple can act as a thermal bridge rather than only as a fin, particularly during reflood.

Valuable experience was obtained in both the general operation of the Blowdown facility and in the use of electrical heater rods to simulate LOFT blowdown rods. Several improvements to the test procedure have been identified which will improve the quality of the test data and reduce the probability of heater rod and thermocouple failures.

It is recommended that the cladding thermocouple characterization test series be continued. Future tests will include heater rods of higher power capability. It is also recommended that the Blowdown facility be used for other testing of instruments in a two-phase flow environment where LOCA transient conditions are required.

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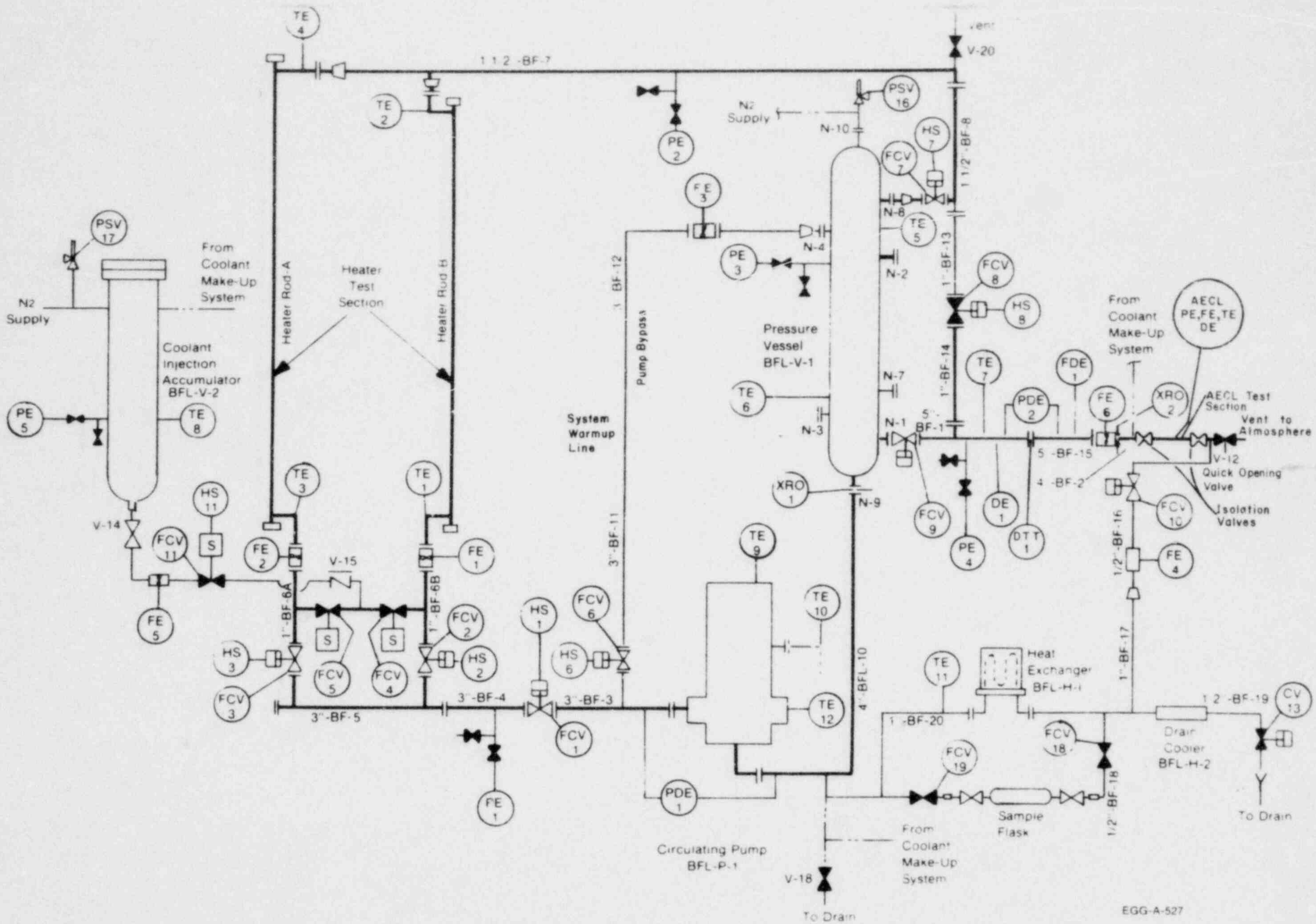

Figure 1. Blowdown Facility Test Assembly

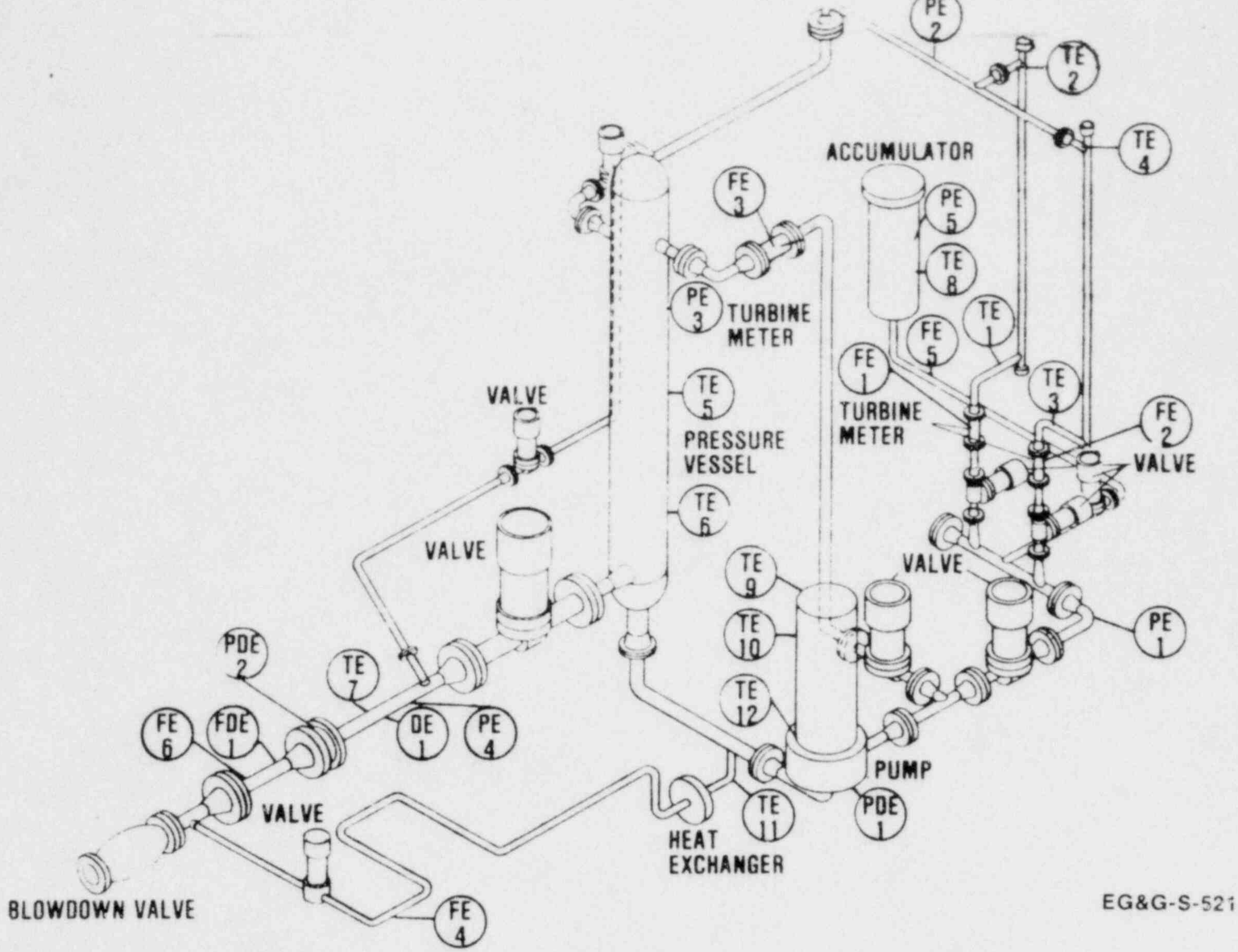

Figure 2. Blowdown Facility Instrumentation Isometric

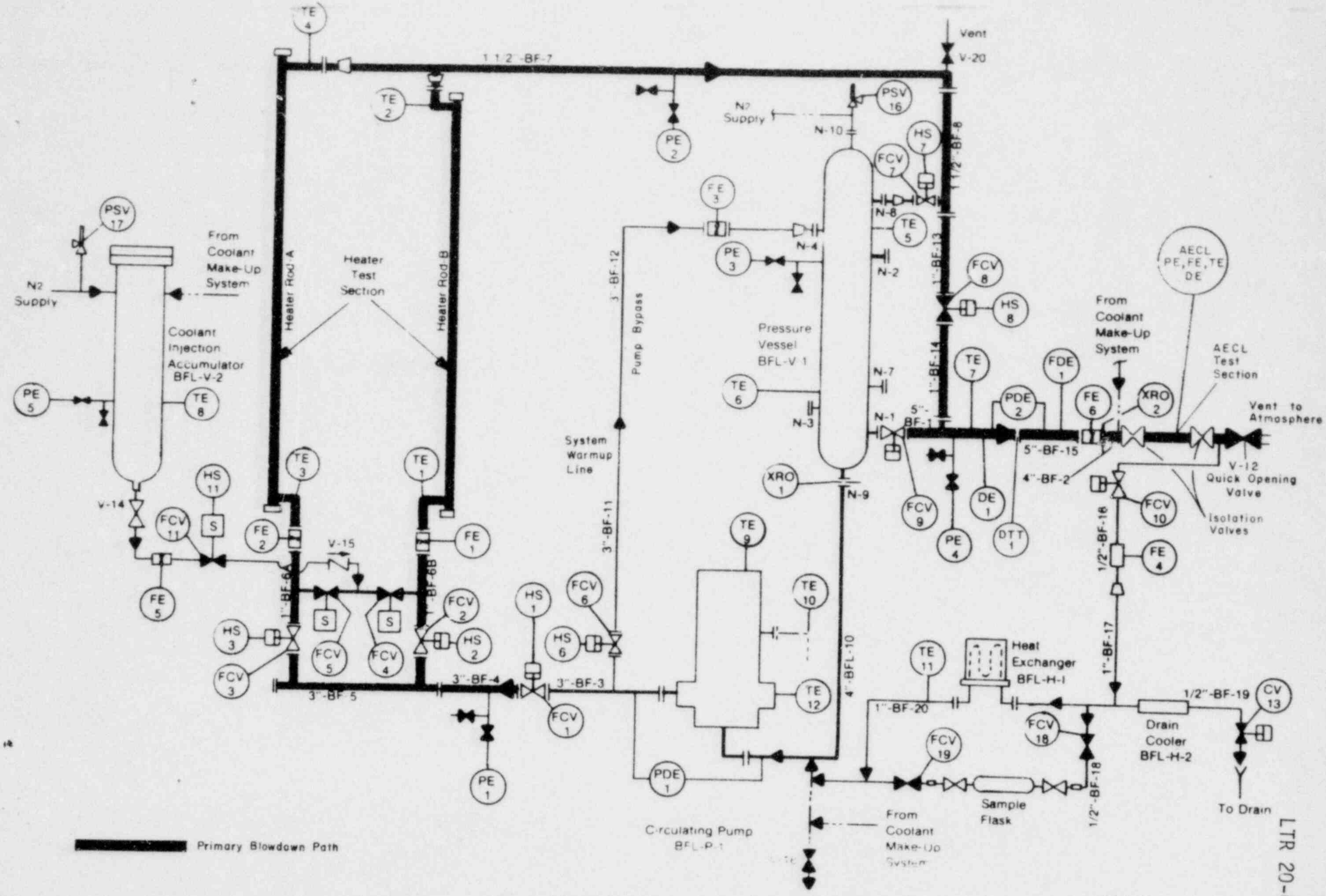

Figure 3. Small Blowdown Loop

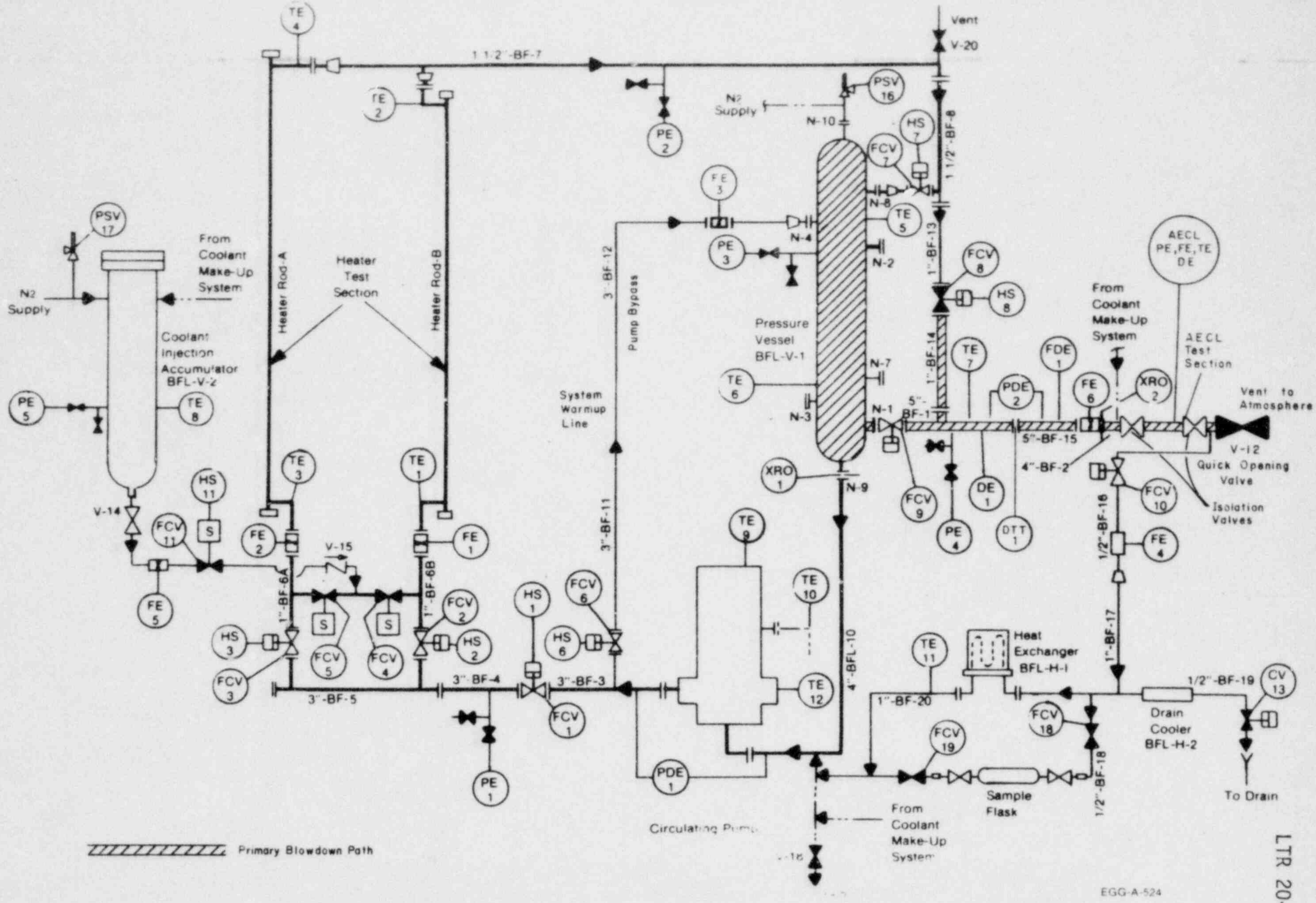

Figure 4. Large Blowdown Loop

LTR 20-C9

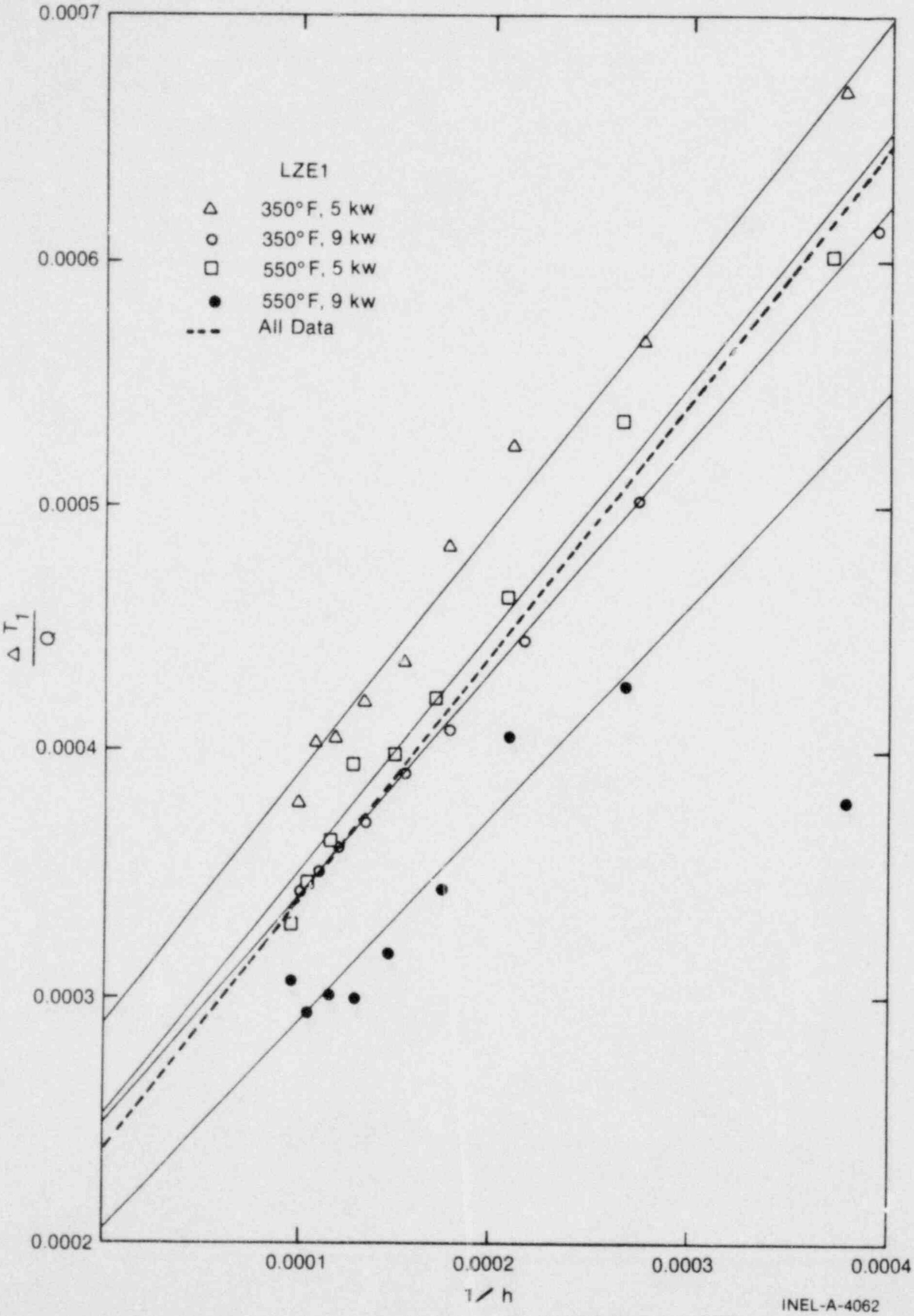

Figure 5. Test Data For Thermocouple LZE1

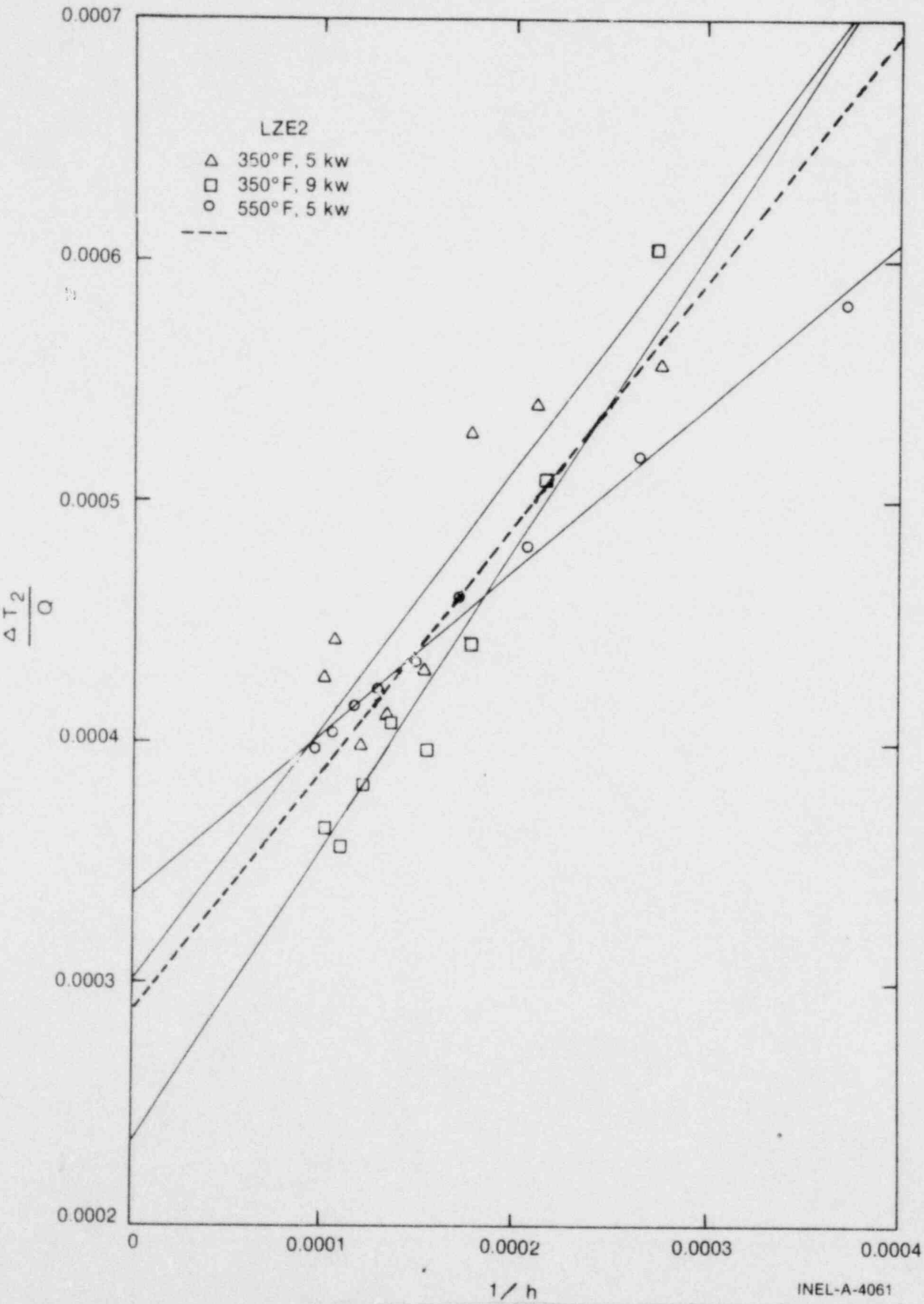

Figure 6. Test Data For Thermocouple LZE2

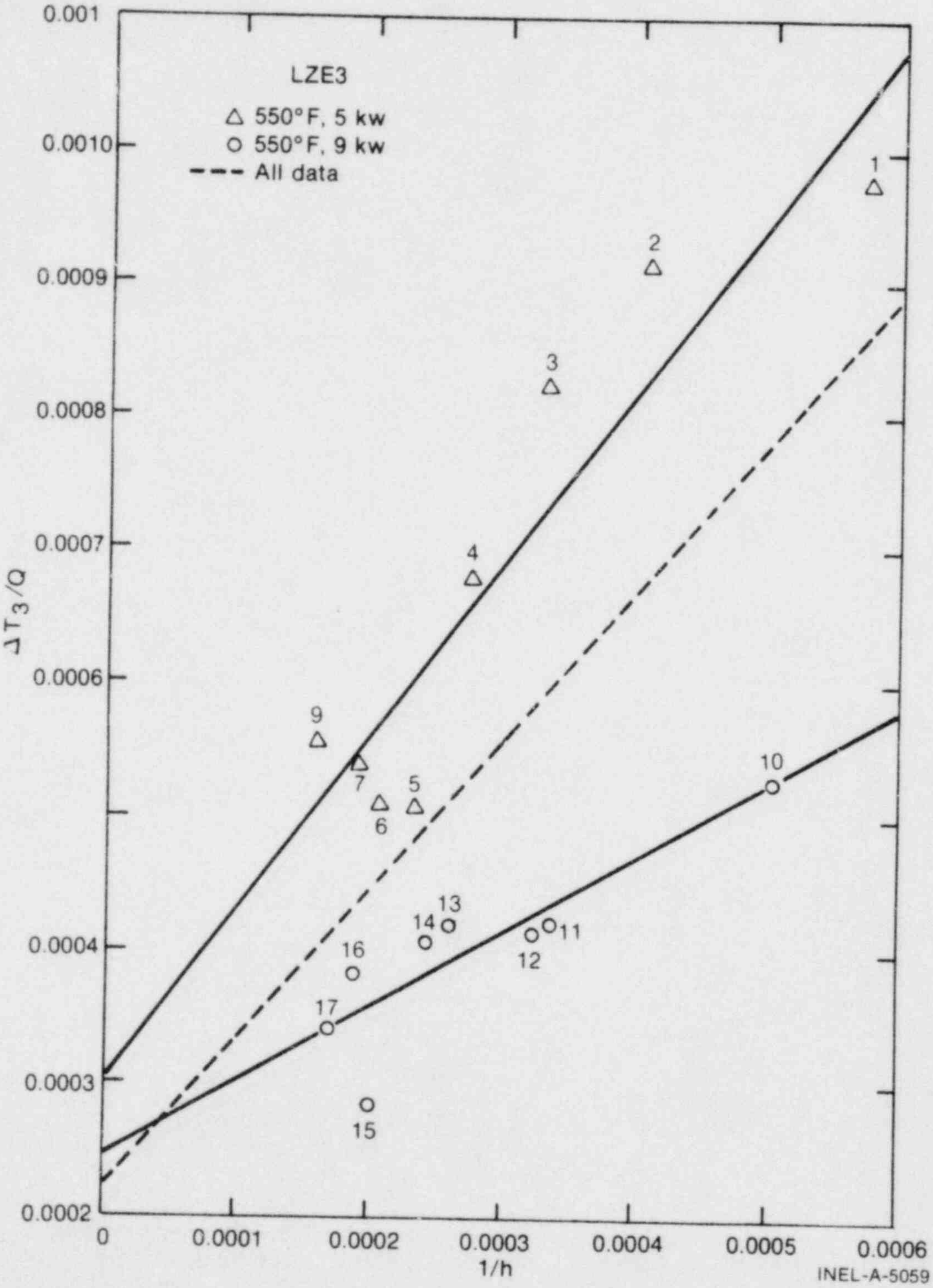

Figure 7. Test Data For Thermocouple LZE3

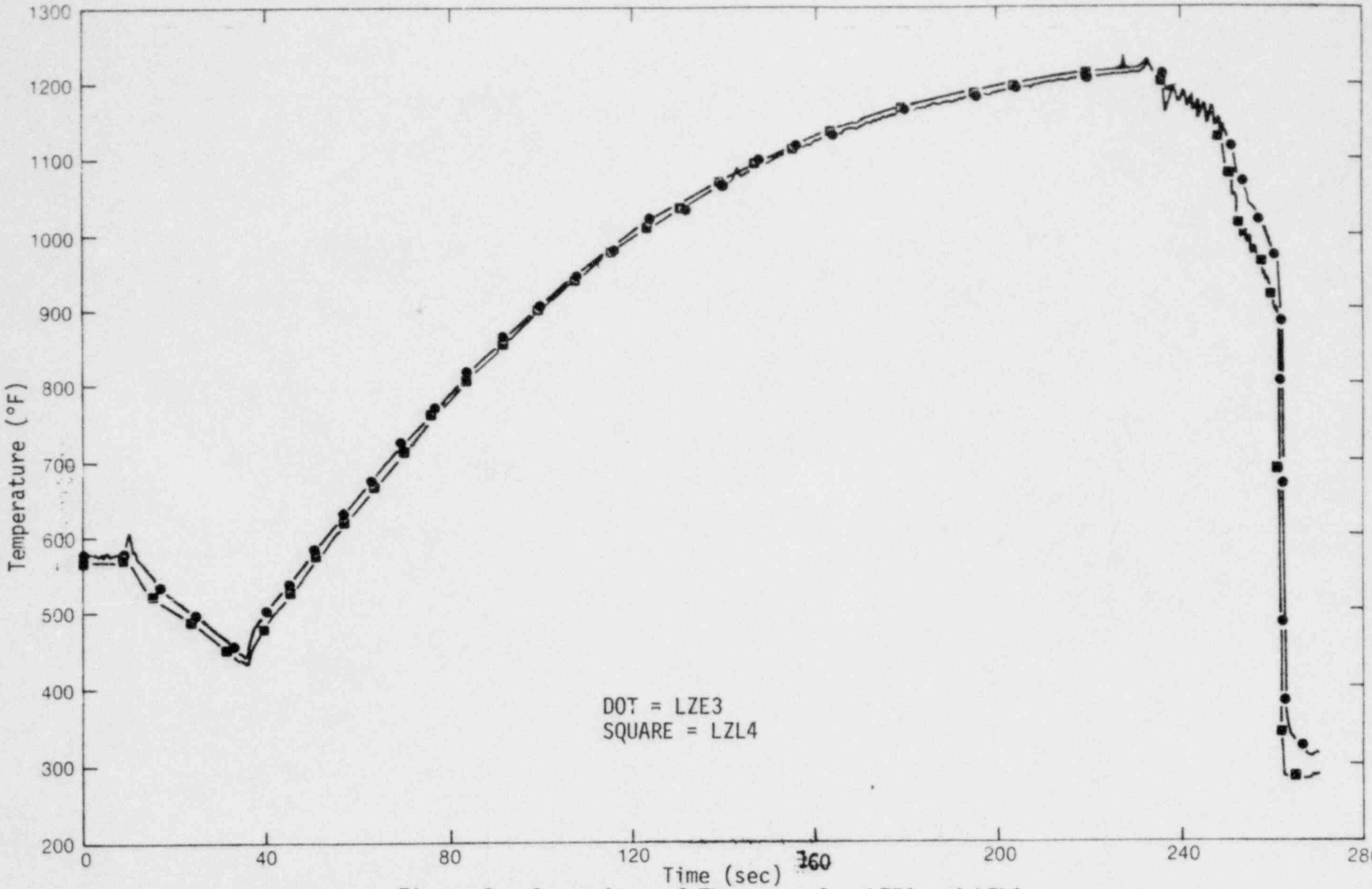

Figure 8. Comparison of Thermocouples LZE3 and LZL4

LTK 20-69

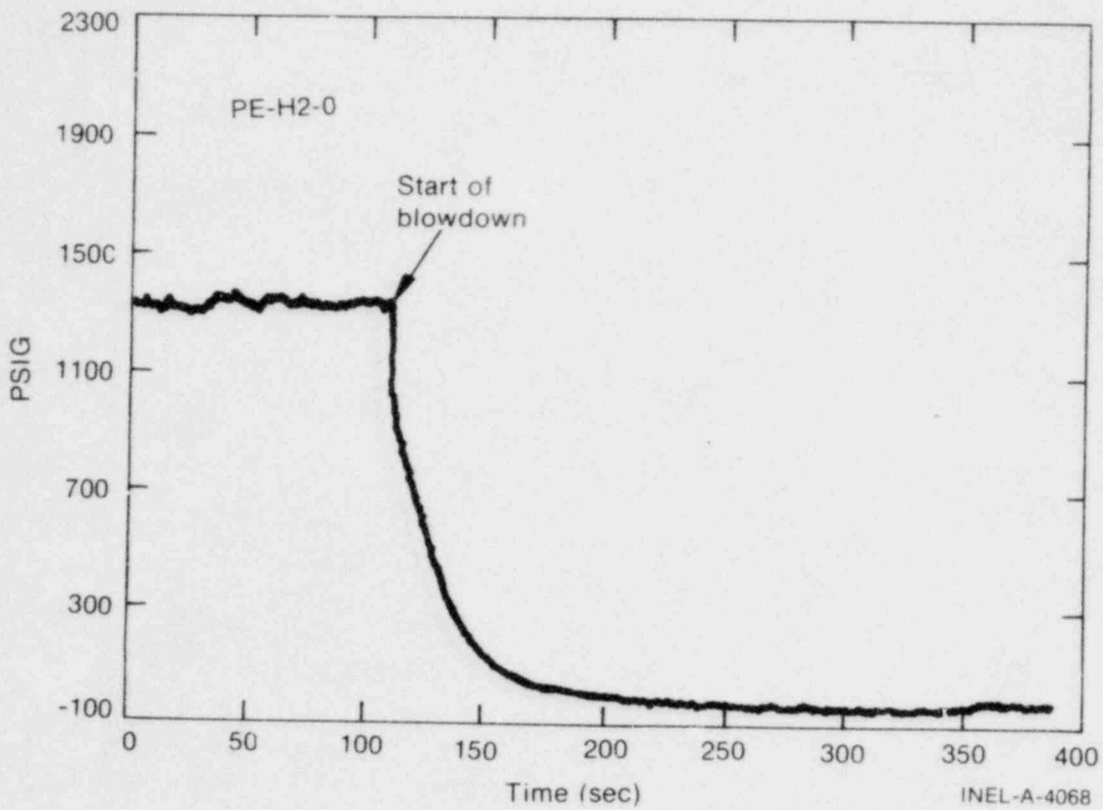

Figure 9. Typical Pressure History of Blowdown Facility During LOCA Test

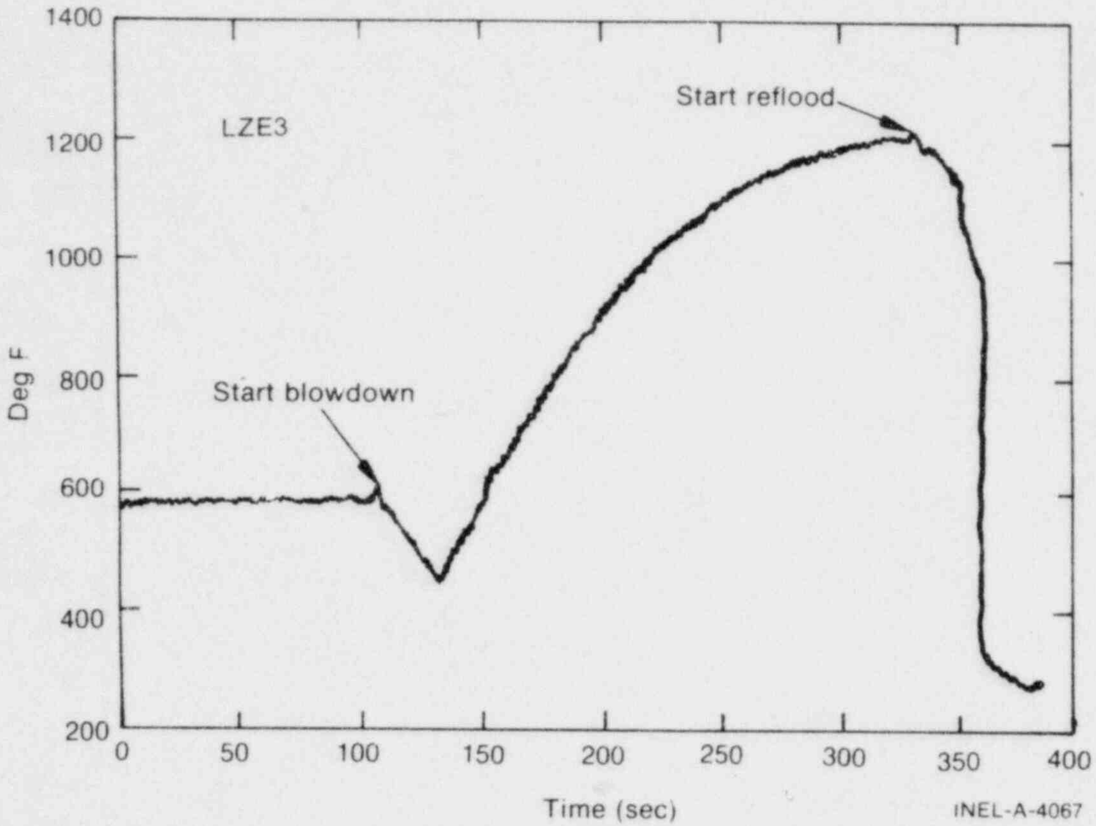

Figure 10. Typical Embedded Thermocouple Response During LOCA Test

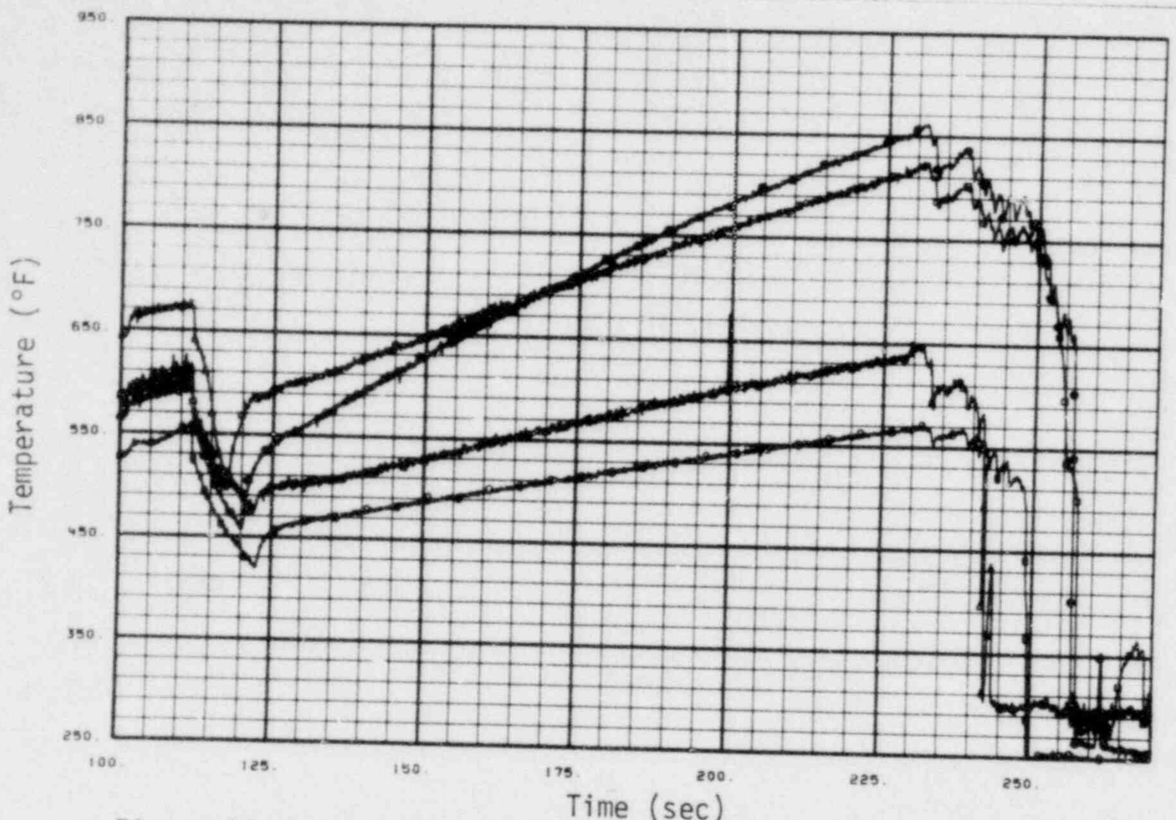

Figure 11. Comparison of Rod LH-5 Thermocouples During LOCE Test
DOT = LZL3, SQUARE = LZL4, TRIANGLE = LZL5, ZERO = LZL6

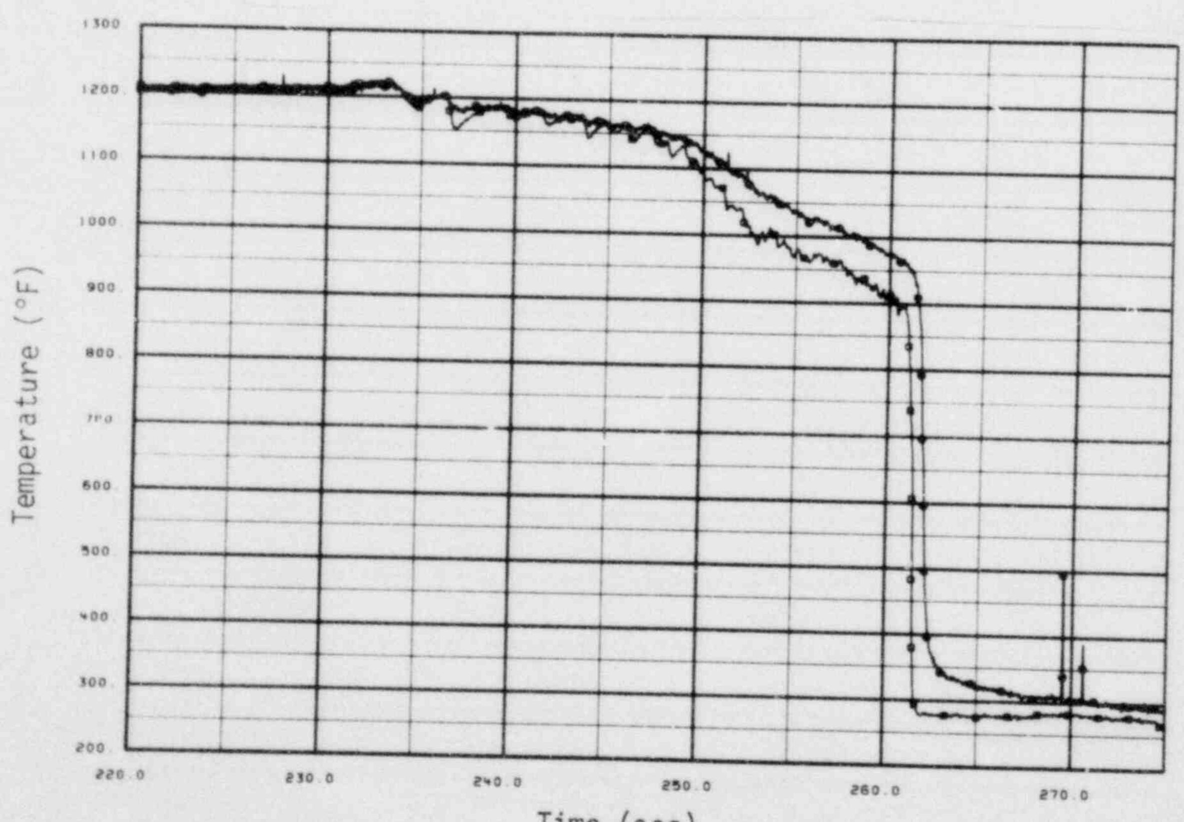

Figure 12. Comparison of Quench Measurement on Rod LH-5 During LOCE Test 4. DOT = LZE3, SQUARE = LZL4

6.0 REFERENCES

1. S. C. Wilkins, Embedded Cladding Surface Thermocouples on Zircaloy-Sheathed Heater Rods, LTR-141-55 (April 1977).

2. R. H. Meservey, and M. F. Jensen, LOFT Heater Pin Thermocouple Attachment Testing, LTR-141-6 (May 17, 1973).

3. A. G. Stephens, Cladding Thermocouples and Heater Rod Scoping Tests, LTR-141-53 (October 1976).

APPENDIX A

TEST MEASUREMENTS FOR LOW-POWER HEATER ROD TESTS

Test were performed on both test heater Rods LH-5 and LH-7. The test series included both steady state and LOCA testing. Variables in the tests were fluid conditions, rod power, and reflood initiation times.

1.0 TEST HEATER ROD LH-7

Test run conditions for test heater Rod LH-7 are given in Table A-I for the steady state conditions and Table A-II for the LOCA tests.

TABLE A-I

STEADY STATE TEST RUN CONDITIONS (ROD LH-7)

CONSTANT POWER				
Run	Duration (sec)	Housing Inlet Temp (°F ± 5°F)	Rod Power (kW + 0.5 kW)	Housing Flow (gpm + 5%)
1	10	350	5.0	8
2	10	350	5.0	12
3	10	350	5.0	16
4	10	350	5.0	20
5	10	350	5.0	24
6	10	350	5.0	28
7	10	350	5.0	32
8	10	350	5.0	36
9	10	350	5.0	40
10	10	350	9.0	8
11	10	350	9.0	12
12	10	350	9.0	16
13	10	350	9.0	20
14	10	350	9.0	24
15	10	350	9.0	28
16	10	350	9.0	32
17	10	350	9.0	36
18	10	350	9.0	40
19	10	550	5.0	8
20	10	550	5.0	12
21	10	550	5.0	16
22	10	550	5.0	20

TABLE A-I (continued)

CONSTANT POWER				
Run	Duration (sec)	Housing Inlet Temp (°F ± 5°F)	Rod Power (kW + 0.5 kW)	Housing Flow (gpm + 5%)
23	10	550	5.0	24
24	10	550	5.0	28
25	10	550	5.0	32
26	10	550	5.0	36
27	10	550	5.0	40
28	10	550	9.0	8
29	10	550	9.0	12
30	10	550	9.0	16
31	10	550	9.0	20
32	10	550	9.0	24
33	10	550	9.0	28
34	10	550	9.0	32
35	10	550	9.0	36
36	10	550	9.0	40

TABLE A-II

LOCA TEST RUN CONDITIONS

Run	Power (kW)	Reflood Temp (°F)	Cutoff Temp (°F)
1	0.7	800	1200
2	0.7	1000	1400
3	1.4	1200	1500
4	2.1	1450	1700
5	2.8	1700	1900

The steady state tests used fluid temperature, rod power, and fluid flow as test variables.

The LOCA tests used rod power level and reflood initiation temperature as test variables. The cutoff temperature in Table A-II refers to cladding temperature at which rod power was to be completely shut-off, if that temperature was reached.

During the steady state, constant power tests, data were recorded for 10-sec intervals. The mean values for each of the 36 test runs on heater Rod LH-7 are given in Table A-III.

TABLE A-III

STEADY STATE, CONSTANT POWER THERMOCOUPLE MEASUREMENTS ON HEATER ROD LH-7

	MEASUREMENTS				
Run	Pressure (psig)	LZC1 (°F)	LZE1 (°F)	LZE2 (°F)	LZL1 (°F)
1	1361	365	394	400	439
2	1355	364	389	392	435
3	1347	364	386	391	434
4	1346	364	385	391	437
5	1349	364	383	385	439
6	1349	363	381	384	440
7	1347	363	381	384	443
8	1351	363	381	386	447
9	1347	363	379	385	438
10	1365	365	415	426	467
11	1354	364	404	417	459
12	1354	363	399	408	455
13	1360	361	394	402	453
14	1362	361	393	399	455
15	1358	361	391	398	456
16	1353	361	439	397	455

TABLE A-III (continued)

MEASUREMENTS					
Run	Pressure (psig)	LZC1 (°F)	LZE1 (°F)	LZE2 (°F)	LZL1 (°F)
17	1348	360	388	394	455
18	1351	361	389	396	462
19	1348	565	591	593	661
20	1352	565	589	591	659
21	1353	565	586	589	658
22	1353	565	584	588	657
23	1350	565	583	587	656
24	1349	565	582	586	665
25	1347	565	581	585	666
26	1344	565	580	585	666
27	1342	564	579	584	668
28	1357	567	597	599	700
29	1373	567	601	600	697
30	1359	566	398	398	693
31	1351	565	592	595	690
32	1340	564	589	597	688
33	1334	564	588	595	688
34	1333	563	586	594	687
35	1339	562	585	596	694
36	1346	563	588	597	698

2.0 TEST HEATER ROD LH-5

The test run conditions on test heater Rod LH-5 are given in Table A-IV for the steady state runs and Table A-V for the LOCA. Test conditions are similar to those discussed for test Rod LH-7.

TABLE A-IV

STEADY STATE TEST RUN CONDITIONS (ROD LH-5)

CONSTANT POWER				
Run	Duration (sec)	Housing Inlet Temp (°F ± 5°F)	Rod Power (kW + 0.5 kW)	Housing Flow (gpm + 5%)
1	10	550	5.0	8
2	10	550	5.0	12
3	10	550	5.0	16
4	10	550	5.0	20
5	10	550	5.0	24
6	10	550	5.0	28
7	10	550	5.0	32
8	10	550	5.0	36
9	10	550	5.0	40
10	10	550	9.0	8
11	10	550	9.0	12
12	10	550	9.0	16
13	10	550	9.0	20
14	10	550	9.0	24
15	10	550	9.0	28
16	10	550	9.0	32
17	10	550	9.0	36
18	10	550	9.0	40

TABLE A-V

LOCA TEST RUN CONDITIONS

Run	Power (kW)	Reflood Temp (°F)	Cutoff Temp (°F)
1	0.7	800	1200
2	0.7	1000	1400
3	0.7	1000	1400
4	1.4	1200	1500
5	1.4	1200	1500
6	2.1	1450	1700
7	2.1	1450	1700
8	2.8	1700	1900
9	2.8	1700	1900
10	2.8	1850	2000

The steady state, constant power measured data are given in Table A-VI. The total number of test measurements for each test are given in Table A-VII.

TABLE A-VI

STEADY STATE, CONSTANT POWER THERMOCOUPLE MEASUREMENTS OF HEATER ROD LH-5

	MEASUREMENTS							
Run	Pressure (psig)	LZC3 (°F)	LZE3 (°F)	LZE4 (°F)	LZL3 (°F)	LZL4 (°F)	LZL5 (°F)	LZL6 (°F)
1	1331	541	588	582	584	565	577	543
2	1322	541	584	576	583	562	573	542
3	1322	540	579	567	583	561	572	541
4	1318	539	571	561	583	560	570	540
5	1359	537	561	555	579	557	566	538
6	1356	539	563	556	582	558	568	539
7	1358	546	572	567	583	559	567	540

TABLE A-VI (continued)

Run	Pressure (psig)	LZC3 (°F)	LZE3 (°F)	LZE4 (°F)	LZL3 (°F)	LZL4 (°F)	LZL5 (°F)	LZL6 (°F)
		MEASUREMENTS						
8	1352	568	573	569	584	560	568	540
9	1330	546	572	568	584	560	567	540
10	1338	549	593	586	596	576	583	549
11	1338	548	584	581	596	596	578	546
12	1338	549	584	580	596	570	578	546
13	1335	551	581	577	596	568	576	545
14	1332	547	582	577	596	567	575	545
15	1334	545	569	576	596	566	574	542
16	1344	546	578	572	594	565	572	541
17	1329	547	576	570	393	564	571	543
18	1276	489	525	528	535	501	513	485

TABLE A-VII

INSTRUMENT MEASUREMENTS FOR HEATER ROD TESTS

Measurement ID		Rod LH-7 Steady State	Rod LH-7 LOCA	Rod LH-5 Steady State	Rod LH-5 LOCA
1	DP4-7	X	X	X	X
2	TF-H2-Ø	X	X	X	X
3	TMV2+41	X	X	X	X
4	TMV2-25	X	X	X	X
5	TF-H2	X	X	X	X
6	TF-ACC		X		X
7	P-H2-Ø	X	X	X	X
8	TF-VESSEL		X	X	X
9	P-VESSEL		X	X	X
10	H2-VOLTS	X	X	X	X

TABLE A-VII (continued)

Measurement ID		Rod LH-7 Steady State	Rod LH-7 LOCA	Rod LH-5 Steady State	Rod LH-5 LOCA
11	DTT-FD-1	X	X	X	X
12	DTT-FD-2	X	X		
13	H2-AMPS	X	X	X	X
14	DTT-TURBINE		X	X	X
15	FT-ACC		X		X
16	P-ACC		X		X
17	FT-PVBP		X	X	X
18	FT-H1		X	X	X
19	P-NOZZLE		X	X	X
20	FT-H2	X		X	X
21	DE-AECL-1				X
22	DE-AECL-2				X
23	DE-AECL-3				X
24	DP-DTT		X		
25	DTT-TF	X	X		
26	DP-PUMP		X	X	
27	FT-BPW			X	
28	LZC1	X			
29	LZC2	X			
30	LZE1	X	X		
31	LZE2	X	X		
32	LZL1	X	X		
33	LZC3			X	X
34	LZC4			X	X
35	LZL4			X	X
36	LZL5			X	X
37	LZE3			X	X
38	LZE4			X	
39	LZL3			X	X
40	LZL6			X	X

APPENDIX B

EMBEDDED THERMOCOUPLE INSTALLATION FACTOR ANALYSIS

Nomenclature

a	Power peaking factor of rod at point of interest
c	Embedded thermocouple installation factor
d_1	Rod diameter, OD
d_2	Test section diameter, ID
G	Mass flux
h	Heat transfer coefficient (surface conductivity)
J'	Modified Colburn factor (the prime indicates modified)
K	Thermal conductivity of rod sheath
K_c	Thermal conductivity of coolant
l	Heated length of rod (heater length)
P	Electrical heater power
P_r	Prandtl number
Q	Heat flux
T_E	Temperature at a depth X below heater rod sheath surface
T_s	Temperature at surface of heater rod sheath
T_c	Temperature of coolant near heater rod at point of interest

$\Delta T = T_E - T_c$

$\Delta T_E = T_E - T_s$

$\Delta T_s = T_s - T_c$

X	Distance below surface of heater rod sheath
μ	Dynamic viscosity of coolant

1.0 THEORY

1.1 Fundamental Concepts

With reference to Figure B-1, the one-dimensional time-invariant form of the Fourier heat conduction law is

$$Q = -k \frac{dT}{dX} \simeq K \frac{\Delta T_E}{X} \tag{B-1}$$

where the approximate form is valid when no heat generation exists in the region of X. At the surface, the boundary conditions can be described by the Newton heat convection law which is

$$Q = h\ (T_s - T_c) = h\ \Delta T_s \tag{B-2}$$

and finally, from Figure B-1,

$$\Delta T = \Delta T_E + \Delta T_s \tag{B-3}$$

Now, combining Equations (B-1), (B-2) and (B-3) yields

$$\frac{\Delta T}{Q} = \frac{\Delta X}{k} + \frac{1}{h}\ . \tag{B-4}$$

Although Equation (B-4) is derived for the plane geometry of Figure B-1, it is also applicable to the heater rod cylindrical geometry as long as $d_1 > \Delta X$ which is the case for the rods tested.

In an electrically heated rod, the steady state heat flux in Btu/hr ft^2 is related to the rod power in watts by

$$Q = 3.4137 \frac{a}{\sqrt{d_1 \ell}}\quad P\ . \tag{B-5}$$

combining Equations (B-5) and (B-1) gives

$$\Delta T_E = CP \tag{B-6}$$

where C is a thermocouple installation factor given as

$$C = 3.4137 \frac{a}{\sqrt{d_1 \ell}} \quad \frac{\Delta X}{k} \ . \tag{B-7}$$

This installation factor is not a function of the fluid conditions at the rod surface. Noting that $\Delta T_E = T_E - T_s$, Equation (B-6) can be written in the form

$$T_s = T_E - CP \ . \tag{B-8}$$

If an embedded thermocouple were calibrated such that the installation factor (c) were known, then the surface temperature could be calculated from measurement of the temperature a small distance below the surface and the heater power.

Figure B-2 presents the electrical network analogy of the heater rod surface thermal conditions. The temperatures have been referenced to the coolant temperature. The surface resistance (1/h) is shown as a variable since it is a function of coolant conditions. The thermal resistance of the cladding ($\Delta X/k$) is the resistance from a depth (ΔX) to the surface. The temperature drop across this resistance is (CP). Equation (B-4) can now be interpreted as saying that the total thermal resistance ($\frac{\Delta T}{Q}$) is equal to a fixed resistance ($\frac{\Delta T}{K}$) over the distance (ΔX) plus a variable surface resistance (1/h). Equation (B-8) states that the surface temperature (T_s) is equal to the temperature (T_E) at a depth (ΔX) minus the temperature drop (CP) over the distance (ΔX) to the surface.

1.2 Heat Transfer Coefficient Correlation[B-1,B-2,B-3,B-4]

In the past, a large number of dimensional analysis correlations based on experimental data have been developed for the surface heat transfer coefficient. Recent work in the power reactor field has made use of the modified Colburn correlation to calculate the heat transfer coefficient for an internally heated annulus which is the case for heater rod testing. The correlation is of the form

$$h = J' \; G^{0.8} \tag{B-9}$$

where J' is the modified Colburn factor which is a function of coolant temperature and pressure and annulus size. The variable G is the mass flux of the coolant. The expression for J' is

$$J' = 0.02 \quad \frac{K_c \; P_r^{\;1/3}}{^{0.8}\;(d_2 - d_1)^{0.2}} \quad \frac{d_2}{d_1} \tag{B-10}$$

which applies to subcooled water conditions.

1.3 Embedded Thermocouple Installation Factor Determination[B-1,B-4,B-5]

With reference to Figure B-3 and Equation (B-4), note that this equation is the equation for a straight line. The surface resistance (1/h) as calculated from the modified Colburn correlation is considered the independent variable and is plotted on the x-axis. The factor ($\Delta T/Q$) is considered the dependent variable and is plotted on the y-axis. The slope of the line is unity and the y-intercept is ($\Delta X/k$).

If the surface resistance (1/h) is experimentally varied by changing the mass flux, and the dependent variable ($\Delta T/Q$) is determined from appropriate measurements, then sets of data points can be generated. Using the least squares method of fitting a straight line to the data (linear regression) allows a determination of a value for ($\Delta X/k$).

The value of $(\Delta X/k)$ determined in this manner is a constant (over a reasonable temperature range) for a given embedded thermocouple at a given point on that heater rod. It is a function of the thermocouple rod geometry and the apparent thermal conductivity in that region. Using Equation (B-7), the value of the installation factor (c) readily follows.

1.4 Experimental Data Analysis

Steady state calibration tests were run to determine the installation factors for the embedded thermocouples on Rods LH-7 and LH-5. The rod surface heat transfer coefficient was varied by adjusting the flow through the test heater vessel between 3.5×10^5 and 3.5×10^6 lbm/ft^2 hr. For each steady state condition, the flow, rod power, embedded thermocouple, temperature, coolant temperature, and coolant pressure were determined such that each data point could be plotted on a $\Delta T/Q$ versus $1/h$ plot as discussed earlier. In addition to changing the flow, data points were collected with the heater rod power both at 5 and 9 kW and with the heater vessel coolant inlet temperature at approximately 350 and 550°F.

Table B-I lists the data for embedded thermocouples on Rod LH-7, and Table B-II lists the data for Rod LH-5 embedded thermocouples. The data points from embedded thermocouple LZE1 on Rod LH-7 are plotted in Figure B-4 as $\Delta T/Q$ versus $1/h$. A straight line was fit to the data using a least squares linear regression analysis. The y-axis intercept $(\Delta X/k)$ is 2.38×10^{-4} °F ft^2 hr/Btu and the line has a slope of 1.01. It should be noted that this slope has excellent agreement to the unity slope predicted by the model of Equation (B-4).

TABLE B-I

PARAMETER ANALYSIS FOR ROD LH-7

Run	EI (Watts)	ΔT_1 (LZE1 LZC1) (°F)	ΔT_2 (LZE2 LZX2) (°F)	I/Q $\frac{°F\ hr\ ft^2}{Btu}$ ($\times 10^{-4}$)	1/h $\frac{°F\ hr\ ft^2}{Btu}$ ($\times 10^{-4}$)	$\Delta T_2/Q$ $\frac{°F\ hr\ ft^2}{Btu}$ ($\times 10^{-4}$)	Inlet Temp (°F)
1	4916	29.5	31.5	6.68	3.82	7.13	350
2	4915	25.1	24.6	5.68	2.76	5.57	350
3	4915	22.3	23.9	5.05	2.12	5.41	350
4	4913	21.3	23.3	4.82	1.77	5.28	350
5	4903	19.2	18.9	4.36	1.53	4.29	350
6	4890	18.6	18.1	4.23	1.34	4.12	350
7	4889	17.9	17.5	4.07	1.20	3.98	350
8	4876	17.6	19.4	4.02	1.09	4.43	350
9	4882	16.6	18.7	3.78	1.01	4.26	350
10	8922	49.2	56.2	6.13	3.96	7.01	350
11	8931	40.4	48.5	5.03	2.74	6.04	350
12	8920	35.8	40.8	4.46	2.16	5.09	350
13	8923	32.7	35.3	4.08	1.77	4.40	350
14	8942	31.4	31.9	3.91	1.55	3.97	350
15	8903	29.7	32.7	3.71	1.35	4.09	350
16	8910	29.0	30.7	3.62	1.21	3.83	350
17	8877	28.0	28.5	3.51	1.10	3.57	350
18	8886	27.4	29.1	3.43	1.01	3.64	350
19	4877	26.4	25.5	6.02	3.73	5.82	550
20	4878	23.4	22.7	5.34	2.65	5.18	550
21	4880	20.3	21.1	4.63	2.07	4.81	550
22	4880	18.5	20.2	4.22	1.70	4.60	550
23	4881	17.5	19.0	3.99	1.48	4.33	550
24	4876	17.3	18.5	3.95	1.29	4.22	550
25	4875	15.9	18.2	3.63	1.17	4.15	550
26	4870	14.4	17.4	3.09	0.96	3.97	550
27	4870	14.4	17.4	3.29	0.96	2.97	550
28[a]							
29	8787	33.7	29.9	4.27	2.68	3.79	550
30	8790	32.1	28.7	4.06	2.09	3.63	550
31	8786	27.1	27.3	3.43	1.73	3.46	550
32	8785	25.1	30.8	3.18	1.47	3.90	550
33	8787	23.7	29.4	3.00	1.30	3.72	550
34	8787	23.8	29.4	3.01	1.16	3.72	550
35	8771	23.2	32.7	2.94	1.05	4.15	550
36	8767	24.2	31.5	3.07	0.97	4.00	550

[a] Heater test housing differential pressure low, data eliminated.

TABLE B-II

PARAMETER ANALYSIS FOR ROD LH-5

	Run	ΔT (LZE3 LZC3)	EI (Watts)	Q $\frac{Btu}{hr\ ft^2}$ ($x\ 10^{-4}$)	ΔT/Q $\frac{°F\ hr\ ft^2}{Btu}$ ($x\ 10^{-4}$)	1/h $\frac{°F\ hr\ ft^2}{Btu}$ ($x\ 10^{-4}$)
	1	46.8	5323	4.785	9.78	5.76
	2	43.7	5317	4.779	9.14	4.08
	3	39.4	5317	4.779	8.24	3.33
	4	32.2	5303	4.767	6.76	2.80
	5	24.1	5289	4.754	5.07	2.33
	6	24.3	5275	4.742	5.13	2.06
	7	25.6	5234	4.705	5.44	1.91
[a]	8	4.6	5241	4.711	--	1.74
	9	26.2	5255	4.724	5.55	1.62
	10	44.3	9360	8.414	5.27	5.04
	11	35.3	9342	8.397	4.20	3.34
	12	34.9	9332	8.388	4.16	3.25
	13	35.3	9332	8.388	4.21	2.59
	14	34.5	9332	8.388	4.11	2.42
	15	24.0	9351	8.405	2.86	2.00
	16	32.1	9351	8.405	3.82	1.92
	17	29.0	9369	8.422	3.44	1.69
[b]	18	36.4	7098	6.380	5.71	1.73

[a] ΔT appears in gross error, data point eliminated.
[b] SD are very large, data point eliminated.

Further evaluation of Figure B-4 indicates that sets of data points where the coolant inlet temperature and heater rod power were kept constant exhibit a more linear characteristic than do all sets of data combined. This is shown in Table B-III where linear regression analysis results are tabulated for the individual data sets. The correlation coefficient is higher for conditions when the coolant temperature and rod power are held constant than when all data are combined. This effect is most pronounced for embedded thermocouple LZE3 on Rod LH-5.

TABLE B-III

REGRESSION ANALYSIS FOR HEATER ROD TEST DATA

Rod	T/C	Inlet Temp	Rod Power	Δx/k	σΔx/k	Slope	σ_{Slope}	Corr. Coeff
LH-7	LZE1	350	5	2.88	0.06	1.01	0.03	0.99+
	LZE1	350	9	2.49	0.02	0.92	0.01	1.00-
	LZE1	550	5	2.52	0.11	0.99	0.06	0.99
	LZE1	550	9	2.05	0.16	0.85	0.10	0.96
	LZE1 All Data:			2.38	0.16	1.01	0.08	0.90
LH-7	LZE2	350	5	3.00	0.25	1.05	0.12	0.95
	LZE2	350	9	2.33	0.15	1.23	0.07	0.84
	LZE2	550	5	3.36	0.04	0.67	0.02	0.99+
	LZE2[a]	550	9	4.06	0.22	-0.17	0.[illegible]	-0.46
	LZE2 All Data: (Excluding the 550°F, 9-kW Test)			2.89	0.15	1.00	0.07	0.94
LH-5	LZE3	550	5	3.05	0.68	1.29	0[illegible]1	0.93
	LZE3	550	9	2.46	0.38	0.56	0.[illegible]	0.87
	LZE3 All Data:			2.26	[illegible].06	1.11	0.34	0.66

[a] Coolant T/C appears failing, data eliminated.

Since the individual data sets exhibit good linearity, then the spread in the total data cannot be attributed to statistical variation or noise of the measurements. Instead it suggests that one of the parameter measurements was influenced by the heater rod power level. It is suspected that either the embedded thermocouple or thermocouples measuring the coolant temperature may have been slightly influenced to various degrees by the heater rod power. Induced errors of less than 1% could cause the data spreads but remain unnoticed throughout the testing. Two of the LOFT geometry thermocouples exhibited a dependence upon the heater rod power of a large enough magnitude (10%) to be identified during the testing. This is thought to be due to a point of low insulation resistance between one of the thermoelements and the thermocouple sheath at a location other than the grounded junction. A similar condition of a much smaller magnitude may have existed in the embedded or coolant thermocouples. All rods to be used in the future will be tested to determine if such an influence exists.

Table B-III contains the regression analysis data for the three embedded thermocouples on the rods tested. The slopes of the combined data for each thermocouple is close to unity. This indicates a close agreement to the model of Equation (4). The $\Delta X/k$ values for all three thermocouples are within 30% of each other. Thus, the consistency of the thermocouple embedding process appears good for a developmental area.

The magnitudes of $\Delta X/k$ result in embedded thermocouple installation factors (c) on the order of 2.5×10^{-3} °F/W. For low power levels used to simulate decay heat during a LOCE, the difference between the calculated surface temperature and the temperature measured by the embedded thermocouple is approximately 5°F. This is small enough to be neglected when compared to the magnitude of the noise on the embedded thermocouple signals of up to 20°F. In later tests of high power rods the temperature difference may be large enough to be significant due to the stored energy within the rod at the time of blowdown.

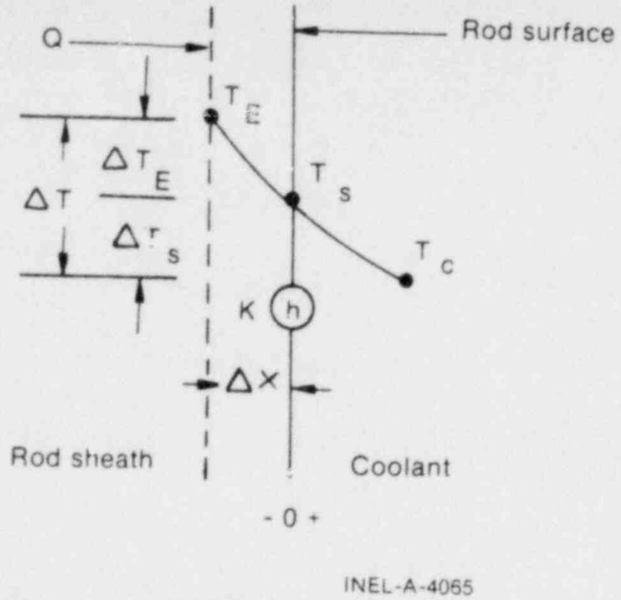

Figure B-1. Temperature Near Surface of Heater Rod

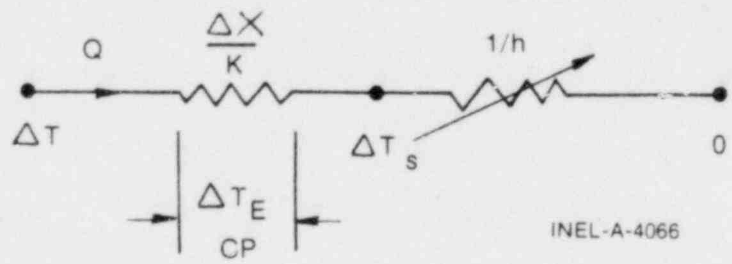

Figure B-2. Network Analogy

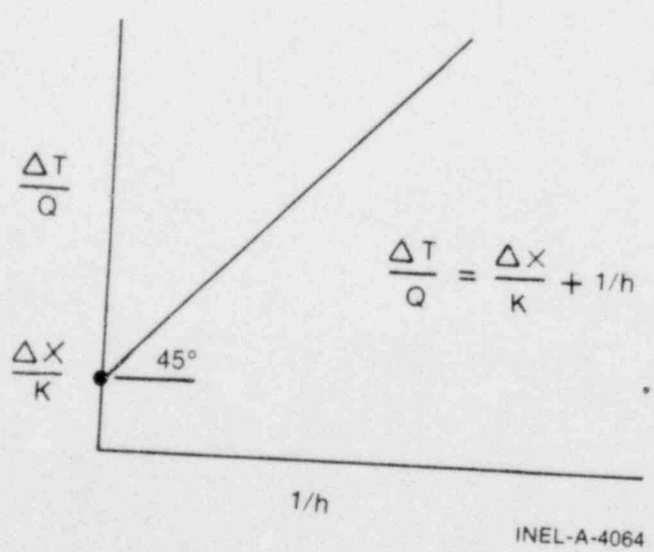

Figure B-3. Straight Line Relationship

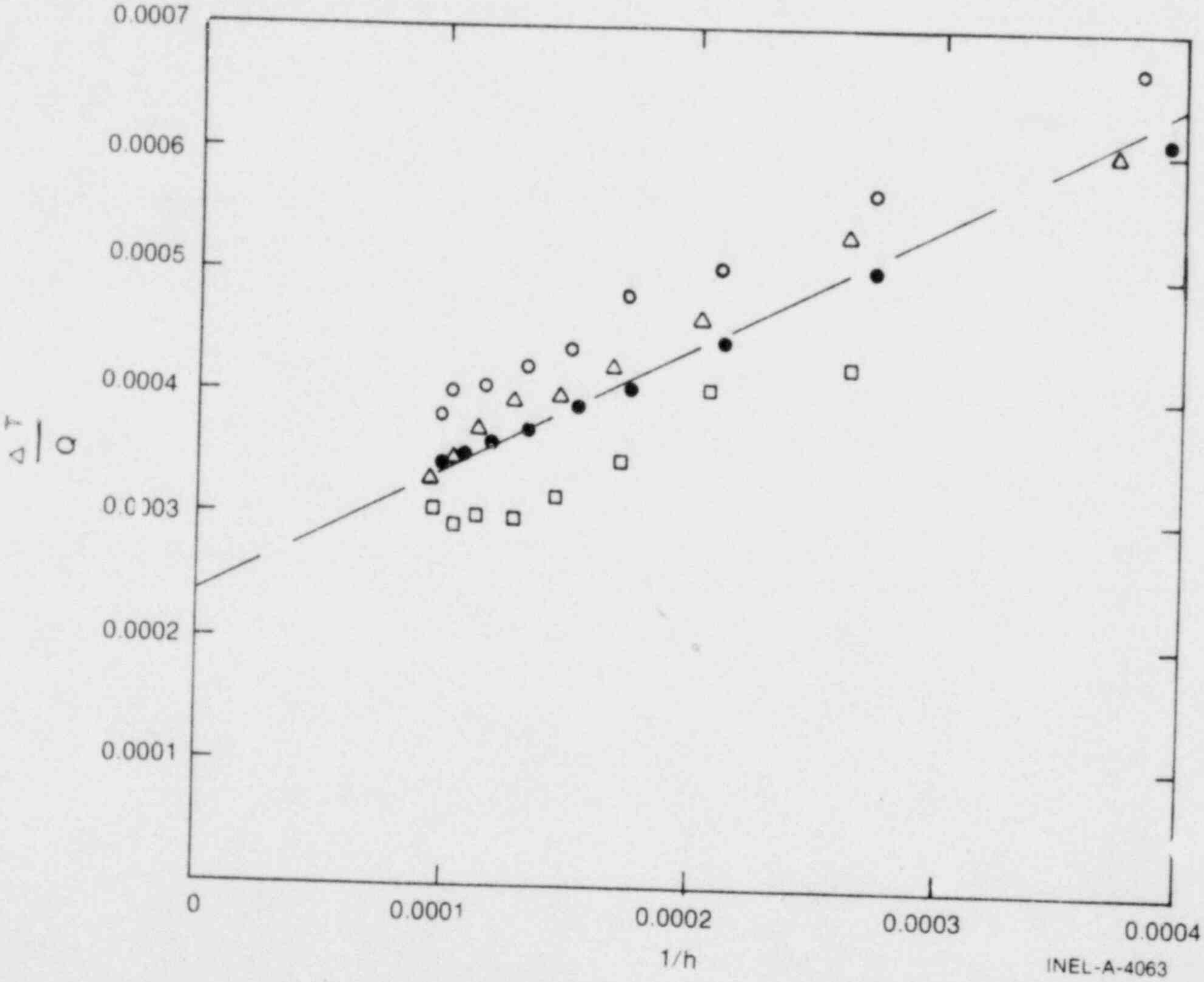

Figure B-4. Regression Fit of all Data For Thermcouple Pair LZE1, LZC1 for Rod LH-7

REFERENCES

B-1. E. O. Moeck, Surface Mounted and Embedded Thermocouples at Post Dryout Conditions, CRNL-454, Atomic Energy of Canada Limited, Chalk River (March 1970).

B-2. M. L. Nixon, Heat Transfer to Water Flowing Turbulently in Tubes and Annuli, CRNL-165, Atomic Energy of Canada Limited, Chalk River (February 1968).

B-3. R. P. Stein, and W. Begell, "Heat Transfer to Water in Turbulent Flow with Internally Heated Annuli," AICHE Journal (June 1958).

B-4. G. A. Wikhammer, E. O. Moeck, and I. P. L. MacDonald, Measurement Techniques in Two-Phase Flow, APPE-24, Atomic Energy of Canada Limited, Chalk River (October 1964).

B-5. J. G. Collier, A. D. Lane, R. D. Page, and E. E. Winter, "The First Experimental Irradiation of Fog Cooled Fuel," AECL-1819, EAES Symposium in Studsvik, Sweden, October 1963.