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**LARGE SCALE STEAM FLOW TEST: PRESSURE DROP
DATA AND CALCULATED PRESSURE LOSS COEFFICIENTS**

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ABSTRACT

This report presents the result of large scale steam flow testing, 3 million to 7 million lbs/hr., conducted at approximate steam qualities of 25, 45, 70 and 100 percent (dry, saturated). It is concluded from the test data that reasonable estimates of piping component pressure loss coefficients for single phase flow in complex piping geometries can be calculated using available engineering literature. This includes the effects of nearby upstream and downstream components, compressibility, and internal obstructions, such as splitters, and ladder rungs on individual piping components. Despite expected uncertainties in the data resulting from the complexity of the piping geometry and two-phase flow, the test data support the conclusion that the predicted dry steam K-factors are accurate and provide useful insight into the effect of entrained liquid on the flow resistance. The K-factors calculated from the wet steam test data were compared to two-phase K-factors based on the Martinelli-Nelson pressure drop correlations. This comparison supports the concept of a two-phase multiplier for estimating the resistance of piping with liquid entrained into the flow. The test data in general appears to be reasonably consistent with the shape of a curve based on the Martinelli-Nelson correlation over the tested range of steam quality.

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LARGE SCALE STEAM FLOW TEST REPORT

Contents

1. Introduction	1
2. Test Piping Description	1
3. Steam Facility Description	2
4. Flow Characteristics	4
5. Instrumentation	5
6. Discussion of Results	
- Data Presentation	10
- Pressure Loss Coefficients	13
7. Summary of Results	19

Figure 1 - Test Piping

Figure 2 - Steam Test Facility Diagram

Figure 3 - Instrumentation Locations

Appendix A - Test 1 (100% Quality) Data Plots

Appendix B - Test 2 (25% Quality) Data Plots

Appendix C - Test 3 (41% Quality) Data Plots

Appendix D - Test 4 (72% Quality) Data Plots

Appendix E - K-factor Formulas and Calculated Results

1. INTRODUCTION

This report presents results of large scale steam flow testing conducted at Energy Technology Engineering Center (ETEC) in Canoga Park, California from late 1989 into 1990. Pressure drop data was collected during high velocity single phase and two-phase steam flow in a complex geometry piping system. These tests were conducted at approximate steam qualities of 25, 45, 70 and 100 percent (dry, saturated). Pressure loss coefficients (K-factors), and related flowrate and pressure drop data upon which they are based are presented herein.

2. TEST PIPING DESCRIPTION

A sketch of the test piping is shown in Figure 1. Two large butterfly valves (termed valves V1 and V2) were located near the inlet and were separated by a 90 degree mitered bend. About 35 feet from the inlet, the 36 inch round pipe transitioned to a rectangular cross-section. A tee, located about 48 feet from the inlet, branched toward another large butterfly valve (termed valve V3). The rectangular cross-section transitioned back to round pipe just upstream of valve V3. A straight round section of pipe ran 17 feet downstream of the valve and discharged to the atmosphere via a 25.66 inch diameter orifice. Through the run of the tee, the rectangular cross-section continued through a check damper toward a water tank and terminated 27 feet below the surface of the water, about 105 feet from the inlet. Each of the three rectangular elbows had either one or three turning vanes.

A Komax static mixer, connected to the test piping inlet, was used to provide the desired steam quality. By

2. TEST PIPING DESCRIPTION (Cont'd)

measuring the flowrates and temperatures of steam and water entering the mixer, an accurate inlet steam quality was calculated.

The discharge tank was twenty feet in diameter, forty-four feet deep, and held about 103,000 gallons of water. During a test, the discharge water temperature increased by as much as 25°F. This increase slowed the rate of steam condensation at the steam/water interface and may have affected the test results. Evaluation of the complex condensation phenomena is beyond the scope of this report.

3. STEAM FACILITY DESCRIPTION

The steam and water source at ETEC included a propane fired boiler, a boiler feedwater system, two steam accumulator tanks, one steam/water accumulator tank, and downstream piping which delivered the steam/water mixture to the test piping. A simplified diagram of the steam facility is shown in Figure 2.

Deionized water was pumped from the feedwater system storage tank, T-3 (8,000 gallons), with pump P-3 (50 gpm) to the water supply tank, T-315 (4,000 gallons), under 25 psig nitrogen cover gas pressure. The steam/water accumulator, T-449 (38,400 gallons), and the two steam accumulators, T-313 (31,300 gallons) and T-314 (31,300 gallons), were initially purged with nitrogen and filled with water from the water supply tank. The accumulators were heated to test pressure (maximum of 450 psig) by continuous recirculation of water through the accumulators and through the boiler, H-1

3. STEAM FACILITY DESCRIPTION (Cont'd)

(4.9×10^6 BTU/hr), where steam was generated and injected into each vessel. Makeup water was pumped from the water supply tank with pump P-2 (50 gpm) to each accumulator hot water recirculation line where makeup water was mixed and heated during the filling process. The temperature of the recirculation water returning to the accumulators was maintained within 150°F of the accumulator water temperature. Each accumulator was equipped with a relief valve set at 500 psig, an automatic steam vent valve, crossover lines to allow pressure equalization between vessels, and instruments that monitored temperature, pressure, and water level.

Prior to steam blowdown, the upstream piping was preheated by opening valve V-1212. After the piping was preheated, steam flow from all three accumulators (for dry steam tests) was initiated by opening three accumulator isolation block valves (V-1201, V-1202, and V-1203). Steam flow was controlled by computer operation of three parallel hydraulically operated control valves (V-1208, V-1219, and V-1220). Additional pressure control was provided upstream of the test piping by computer controlled addition of steam through valve V-1207 and venting of steam through valves V-1217A and B. Also, relief valve PSV-TA (150 psig set point) and rupture disk RD-1 provided overpressure protection just upstream of the mixer (M-1).

For the wet steam tests, sub-cooled water was taken from T-449 to be mixed with steam from the other accumulators by opening V-1301A in lieu of V-1203. Accumulator pressure was maintained by supplying additional nitrogen cover gas. Water

3. STEAM FACILITY DESCRIPTION (Cont'd)

flow was controlled by computer operation of control valve V-1301B programmed to control water flow based on initial accumulator conditions. The steam/water mixture was further controlled to the desired quality by operation of steam control valves based on steam and water temperatures and pressures measured upstream and downstream of the mixer.

4. FLOW CHARACTERISTICS

The flowrate of dry saturated steam was about 3.0 million lb/hr, and of wet steam, 7.0 million lb/hr (at 23 percent quality). Other tests were conducted at intermediate targeted qualities of 45 and 70 percent.

The presence of entrained liquid in the wet steam introduces many variables to the flow characteristics that greatly complicate pressure drop predictions. Steam at 25 percent quality by definition means that the mass of the vapor phase is 25 percent of the total mixture and the mass of the liquid phase is 75 percent. On a volume basis however, the liquid phase comprises only about one percent (at 70 psig) of the flow. The great density difference between the phases allows other parameters to affect the flow characteristics. These include droplet size, droplet size distribution, and slip ratio (defined as the ratio of vapor velocity to liquid velocity). The problem of accurately accounting for the effects of these parameters on pressure drop is further compounded by the bends and area transitions. At every bend the larger droplets that are unable to negotiate the turn due to their inertia are deposited on the pipe wall. This liquid is pushed along the wall by the

4. FLOW CHARACTERISTICS (Cont'd)

viscous forces of the flow, and it varies the otherwise predictable friction effect of a dry wall. As the liquid traverses the piping, it is repeatedly deentrained and reentrained, disturbing the flow regime and varying the effect of the mechanisms that cause the pressure losses. Additional disturbances to the flow result from droplets flashing to vapor to maintain thermodynamic equilibrium as the pressure decreases throughout the piping length as well as from flashing and condensing of droplets due to localized pressure fluctuations. The complexity of, and the variability in the two-phase flow regime adds uncertainty to the K-factors calculated from wet steam test data compared to that of the dry steam.

5. INSTRUMENTATION

The test piping was instrumented to measure pressure, temperature, flowrate, and density. Figure 3 shows the general locations of the instrumentation discussed in this report. Each instrument is referred to by a tag number that describes its type and location. The first part of the tag number defines the type of instrument as follows: absolute pressure transducer (PT), pressure differential transducer (PDT), thermal element (TE), flow transducer (FT), and gamma densitometer (DE). The second part of the tag number includes the letters "TA", which differentiates "Test Article" instrumentation from that of the steam facility, followed by a "location" number from 1 to 19, except for the flow transducers and densitometers. Each location number defines a position along the piping where various instrument taps were located. Note that there is no PT-, TE-, or PDT-

5. INSTRUMENTATION (Cont'd)

TA4 since the only instrument at this location is the downstream tap for PDT-TA3-1. Instrument taps at locations 17 and 18 were deleted after the numbering system was determined. The PDT's were numbered according to the location number of the upstream tap. The location numbers for the annubars, pitot tubes, and densitometers are either 1, 2 or 3, if they are located upstream of the tee, in the atmospheric branch, or in the underwater branch, respectively. The final part of the tag number is simply to differentiate between redundant measurements at the same piping section.

Static pressure measurements were made at 13 positions throughout the piping, with two transducers at each position (on opposite sides of the piping) except one location used four transducers 90 degrees apart on the circumference.

Differential pressure transducers were installed to measure the delta pressures across selected sections of the piping. Two were located across valve V1 (one in the plane of the disc and the other in the plane perpendicular to the disc) and one was located across valve V3. Five more were located across major turns in the piping.

Fluid temperature measurements were made at 15 piping locations via a thermocouple at each pressure measurement location and at two intermediate locations in the underwater discharge branch. The additional measurements in this branch were to aid in determining the rate at which the water leg is expelled at the beginning of some tests and to provide data on condensation chugging. (Condensation chugging is a

5. INSTRUMENTATION (Cont'd)

repetitive intake and expulsion of water at the underwater discharge due to the rapid rate of condensation at the steam/water interface.) The temperatures were measured in conjunction with pressure to verify saturation conditions or to determine the amount of superheat, which can result from blowing down steam from an accumulator. The thermocouples also aided in determining whether or not liquid slugs were forming in the piping, which posed a hazard to the test equipment.

Primary mass flowrate measurements were made by venturi flowmeters in the steam and water supply lines to the test piping. Other flowrate instrumentation was installed at three locations in the piping--upstream of the tee branch and in each section downstream. At each of these locations an "S-type" pitot tube and an annubar were installed to measure dynamic pressure. The S-type pitot tube is specifically designed for two-phase flow. While not particularly suited for two-phase flow, the annubars were used as a redundant measurement having the advantage of averaging the dynamic pressure across the pipe diameter as opposed to the point measurement of the pitot tube. Mass flowrate at each location was calculated from these dynamic pressure measurements and an average density determined from a local temperature measurement or from gamma densitometers. The piping inlet density (steam quality) was also calculated based on measured steam supply conditions.

Three single beam gamma densitometers were used--one each installed just upstream of each annubar and pitot tube. The densitometers measure only an average density of the fluid that passes through the gamma ray beam. Therefore, for

5. INSTRUMENTATION (Cont'd)

non-homogenous flow, errors can be significant depending on how representative the geometry of the liquid-vapor distribution passing through the beam is of the entire flow field. The densitometers were oriented to best measure a representative flow.

A significant problem involved location of the static and differential pressure taps. A primary objective is to determine pressure loss coefficients for individual piping components. To do this, it is necessary to know the loss in total pressure due to the component, and the dynamic pressure at the component inlet. The main difficulty is attributing measured pressure loss to a specific component (or even some combination of components). Energy losses due to a component are not fully realized as a pressure loss until several pipe diameters downstream. Accordingly, the measured loss across a component (e.g. an elbow) likely includes some of the loss due to a component further upstream and only a partial loss due to the nearest component. Recognizing this, the pressure taps were located close to the upstream side of high loss components and as far as possible downstream without being affected by another bend or area transition.

More error is inherent in calculating local dynamic pressure, which is proportional to density and the square of the velocity. An average density is determined from the steam tables assuming saturated equilibrium at the measured static pressure, which therefore incorporates the pressure measurement error. An average velocity is calculated from the mass flowrate and density, again combining the respective

5. INSTRUMENTATION (Cont'd)

errors. Particularly for the wet steam tests, the assumption of an average velocity and average density adds uncertainty to the K-factor calculations. The difference in velocity of the liquid and vapor phases, characterized by the "slip ratio" (ratio of vapor velocity to liquid velocity), is uncertain but possibly significant. Also, since the slip ratio is partially a function of piping geometry, it probably varies throughout the piping. Given a pressure, the difference in phase densities is known but the effect of each phase on pressure loss is uncertain due largely to the complex interactions between the phases. The assumption of constant steam quality (inlet value) throughout the piping induces a further element of uncertainty in the local density used in K-factor calculation for the wet steam testing.

Another source of measurement uncertainty is the effect of non-axial fluid momentum. An accurate static pressure measurement requires the flow to be parallel to the pipe wall where the tap is located. The numerous flow disturbances likely result in some velocity component perpendicular to the wall, thus adding some component of dynamic pressure to the static pressure. For differential pressure measurements, the error at each tap is added to the measurement. Non-axial flow also affects the dynamic pressure measured by the pitot tubes and annubars. Although the S-type pitot tube is less sensitive to flow direction, its point measurement may less accurately reflect the average value of the entire cross section because of non-axial flow.

Other problems were created by the standoffs and sensing lines for the absolute and differential pressure transducers.

5. INSTRUMENTATION (Cont'd)

The lines were filled with water to protect the transducers from high temperature and to assure a liquid filled pressure coupling to the pressure tap. The long lines required for the delta pressure transducers were especially susceptible to oscillatory effects of the intense system vibration during a test. Also, although the sensing lines were regularly topped off with water, data for some tests indicates presence of a gas bubble in the line.

The data acquisition system scanned all test piping instrumentation at a rate of 10 to 15 samples per second.

6. DISCUSSION OF RESULTS
Data Presentation

Pertinent flow and pressure drop data are presented for four of the tests conducted at ETEC. Test 1 was a dry, saturated steam test at about 3.0 million lb/hr flow. Test 2 was with 25 percent quality steam at 7.0 million lb/hr. Test 3 averaged a quality of 41 percent (45 percent was the targeted value) and a flowrate of about 5.6 million lb/hr. Test 4 averaged a quality of 72 percent (70 percent target) and 3.5 million lb/hr. Data for Tests 1 through 4 are presented in Appendices A through D, respectively. From the tests conducted at each targeted quality, the smoothest test available is presented herein. Only one test was conducted at a 70 percent quality target. Oscillations in the control system for the steam supply valves were a recurrent problem, especially for the wet steam tests.

For each test, valves V1 and V2 remained open for the entire test and valve V3 was closed about 10 seconds before

6. DISCUSSION OF RESULTS (Cont'd)

the end of the test. The time at which valve V3 closed is apparent on the data plots by the sudden increase in pipe static pressure and temperature. Also for each test, plots of the following parameters are contained in the respective appendix: inlet mass flowrate, annubar and pitot tube measured dynamic pressures, calculated mass flowrates based on annubar and pitot tube measurements, inlet steam quality, gamma densitometer measured density, static pressures, static pressure drops, and temperatures. For the annubar and pitot tube dynamic pressures and flowrates, and the gamma densitometer measured density, data from all three of each measurement type are plotted together (for comparison) followed by separate plots (for better readability) of each instrument's data. Similarly, the two (or four) static pressure measurements at each pipe location are plotted both together and separately as are the two differential pressures across the upstream isolation valve (tag no. PDT-TA1). The temperatures are plotted together in varying size groups and again separately.

The inlet mass flowrate plotted is the sum of the steam and water flowrates (steam only for Test 1) as measured by the respective venturi flowmeters in the supply lines to the piping.

The piping inlet steam quality was calculated as follows. The steam and water mixer inlet enthalpies were extracted from steam table formulations given pressures and temperatures in the supply lines just upstream of the mixer. A combined mixture enthalpy was then determined based on the

6. DISCUSSION OF RESULTS (Cont'd)

flowrates of each phase as measured in the supply lines and on the separate phase enthalpies, and was assumed to remain constant through the mixer. Outlet enthalpies of each phase were determined based on the mixer outlet (piping inlet) temperature. The piping inlet quality was then calculated with the piping inlet vapor, liquid and mixture enthalpies.

The dynamic pressures measured by the annubars and pitot tubes are plotted for each location, as well as the mass flowrates that are based on these measurements. For Test 1, the density used to infer flowrate from dynamic pressure was that for saturated vapor at a locally measured temperature. For Tests 2, 3 and 4, the density used was that measured by the gamma densitometers. It is apparent from the resulting annubar and pitot tube flowrate calculations for the wet steam tests that some consideration must be given to the two-phase nature of the flow.

Gamma densitometer measured densities are plotted for all tests, however, these plots for Test 1 are provided for information only. Early in the test program many problems were encountered with the densitometers. These problems were mostly related to the mounting of the densitometers and were corrected gradually during the early testing. The problems included piping and support structure vibration; relative motion between the piping, gamma beam, and detector; beam orientation through the piping; and residual condensate affecting pretest calibrations. For Test 1, one or more of these problems caused the measured densities to go to zero shortly after the test was begun.

6. DISCUSSION OF RESULTS (Cont'd)

For the static pressure measurements, it is noted that plots of some transducers are erratic compared to those of the other transducer(s) at the same location. It should be cautioned that, in most cases, the erratic readings are most likely due to problems such as sensing line vibrations or gas bubbles in the sensing lines rather than real internal pressure fluctuations.

Some plots of the measured static pressure drops indicate negative values. An increase in static pressure occurs across piping sections containing transitions to larger cross-sectional areas because of the reduction in flow velocity, despite a loss in the total pressure. An increase in static pressure may also indicate non-axial or non-uniform flow.

The measured temperature plots are self-explanatory with no apparent anomalies.

Pressure Loss Coefficients (K-Factors)

Prior to the testing, pressure loss coefficients, or K-factors, for each piping component were estimated using accepted engineering literature. Then, using flowrate and pressure drop test data, K-factors were calculated for incremental sections of the test piping for comparison to predicted values. No loss coefficient calculations for the branch venting to atmosphere have been attempted at this time. Data provided by the annubars, pitot tubes, and densitometers, which are necessary to determine the percentage of flow through the atmospheric branch, contain

6. DISCUSSION OF RESULTS (Cont'd)

excessive uncertainty in the raw form. Further analysis is required to provide possible improvements to the agreement between redundant flowrate determinations, or otherwise determine a more accurate atmospheric branch flowrate (and density) for each test. For each test, all K-factors were calculated using data obtained during steady state conditions with valve V3 closed.

Data channels providing inlet and outlet pressure, inlet total mass flowrate (recorded by venturi flow meters), delta pressure and quality were measured and used to calculate the loss coefficients using equations (1), (2), and (3) in Appendix E. The derivation of equation (3) used the incompressible form of the equation for stagnation pressure, which agrees to within 5 percent of the compressible form for Mach numbers below about 0.45. This deviation is considered to be within the range of uncertainty in the data. The flow was assumed to be homogenous and adiabatic, and quality was assumed to be constant throughout the piping.

Average loss coefficients are presented in Table 1 of Appendix E. The loss coefficients for each section have been adjusted to a reference area and density based on the pipe inlet area and density at instrument location TA1 using equation (4) in Appendix E. The reference areas and densities, and the adjusted K-factors are shown in Table 1 and the area and density associated with each increment of piping are listed in Table 2.

To determine incremental densities for use in adjusting the predicted K-factors with the reference density, the "predicted" piping density distribution was determined

6. DISCUSSION OF RESULTS (Cont'd)

as follows: Given the tank discharge pressure under 27 feet of water (25.5 psia) and a flowrate of 2.4 million lbs/hr (chosen to approximate Mach numbers used for estimating compressibility effects on the K-factors), an iterative pressure drop calculation was performed for each section using the K-factors for that section and an assumed section inlet pressure, until the inlet pressure equaled the sum of the exit pressure and the calculated pressure drop. This calculation was made for each section beginning at the discharge and working upstream toward the inlet section, providing a pressure distribution based on the predicted resistance.

A comparison of the predicted pressure distribution to the test data for Test 1 showed a large discrepancy at the pipe discharge. The measured pressure drop from location 15 to the tank is more than a factor of six greater than that calculated with the predicted resistance. This large difference may be due in part to very high losses resulting from the possibly choked flow at the exit during the test as well as error in estimating the resistance of the louvered discharge (a geometry for which K-factor data was not available). Because this large error at the discharge affected the predicted density distribution throughout the rest of the system, this distribution was recalculated assuming a pressure at location 15 equal to the measured test pressure (54 psia), thus eliminating the effect of the discharge error. The resulting piping density distribution, listed in Table 2, provides a better basis of comparison of predicted vs. measured K-factors for the remainder of the piping.

Under compressible, high-velocity flow conditions (above about Mach 0.1), pressure loss K-factors may be effectively

6. DISCUSSION OF RESULTS (Cont'd)

larger than under turbulent incompressible flow conditions. Based on the data used for dry steam K-factor calculations, peak Mach numbers for the duct inlet and outlet were approximately 0.43 and 0.47, respectively. Therefore, it is expected that the effects of compressibility increased the K-factors for the high flow dry steam test above that which would be anticipated for incompressible flow. The predicted K-factors include compressibility corrections using Mach numbers of approximately 0.3.

Mach number calculations for wet steam are complicated by factors such as uncertainties in the slip ratio and liquid distribution. Calculations were not made for the wet steam tests presented in this report. However, qualitative reasoning for a homogenous two-phase flow would indicate that the highest Mach numbers achieved during the testing were with dry steam. The wet steam flowrates were higher than for dry steam, and the sonic velocity is lower in wet steam (in the range of qualities tested), tending to increase the Mach number. This tendency is offset by the fact that the wet steam density is much greater than the dry steam density, which decreases the flow velocity enough to result in a lower Mach number. A more thorough analysis accounting for velocity slip between the phases would be expected to increase the Mach number for wet steam compared to an analysis which assumes a homogenous flow regime.

Aside from the effects of compressibility on the loss coefficients, the presence of entrained liquid would be

6. DISCUSSION OF RESULTS (Cont'd)

expected to increase the K-factor for each component. Such a trend is evident in the calculated K-factors.

Figure E1 in Appendix E compares the predicted piping resistance to that calculated from the data collected from the four tests at varying steam qualities. The sum of the K-factors (using "PT" based adjusted values in Table 1) from the pipe inlet are plotted against pipe location (axial distance from the inlet) in order to contrast differences between measured and predicted values as well as to show the effect of liquid entrainment.

In comparing the measured resistance to predicted resistance for the dry steam test (Test 1) two deviations are readily apparent: the measured resistance is higher than predicted and there is an obvious lag in the measured resistance between locations 7 and 10. Both of these deviations can be explained by the fact that energy losses due to a component are not fully realized as a pressure loss until several pipe diameters downstream, as mentioned previously. Since the predicted resistance is plotted as though the pressure loss occurs completely at the end of each pipe section, a lag in pressure loss is apparent in Figure E1 in the vicinity of high loss components, such as between locations 8 and 10 (which include the check damper and the 110° bend) and at the piping inlet (mixer outlet).

Considering the section between locations 8 and 10, the predicted resistance exceeds the measured value because the losses of that section were not yet fully measurable. At

6. DISCUSSION OF RESULTS (Cont'd)

location 11, the remaining losses appear to have been accounted for since the total measured resistance between locations 7 and 11 is close to the predicted total.

Similarly, the deviation at the piping inlet is likely attributable to losses resulting from the mixer (a very high loss component) which are still being realized during the first several feet of the piping. Since the predicted resistance does not include any mixer resistance, any mixer losses being realized within the piping inlet add error to the measured resistance. Also, the higher Mach numbers (and therefore greater compressibility effects) during the test than those used in the predicted K-factors, as described previously, would also account for some increase in measured resistance.

Also seen in Figure E1 is a significant increase in measured resistance for all three wet steam tests. Like Test 1, there is a lag in pressure loss realization following high loss sections, although it appears that a greater length of piping is required before the losses can be measured, as would be expected for two-phase flow.

The Martinelli-Nelson two-phase pressure drop correlation, described in reference 1, was used as a basis for establishing a relative resistance ratio (K_{wet}/K_{dry}) for comparison to the test data. This ratio is a measure of the increase in pipe resistance caused by the liquid entrainment and is derived in Appendix E.

6. DISCUSSION OF RESULTS (Cont'd)

Figure E2 plots the relative resistance ratio as calculated by equation (5) of Appendix E as a function of steam quality at a constant pressure of 100 psia. Also plotted are the ratios for the three wet steam tests calculated as the sum of the pipe section K-factors for each wet steam test divided by that of the dry steam test. The data points for the 23 percent and 45 percent quality tests lie within 15 percent of the Martinelli curve, which is a typical range of uncertainty for two-phase pressure drop calculations. The point for the 75 percent quality test deviates about 25 percent from the Martinelli curve. No single factor is apparent to explain the magnitude of this deviation, therefore, it is suspected to result from a stack-up of uncertainties related to the measurement and manipulation of the data.

7. SUMMARY OF RESULTS

It is concluded from the test data that reasonable estimates of piping component pressure loss coefficients for single phase flow in complex piping geometries can be calculated using available engineering literature. Engineering literature does provide for accurate accounting of the effects of nearby upstream and downstream components, compressibility, and internal obstructions, such as splitters, and ladder rungs on individual piping components after accounting for the fact that energy losses due to each component are not fully realized as pressure losses until several diameters downstream of the component.

7. SUMMARY OF RESULTS (Cont'd)

No K-factor predictions were made that accounted for the presence of an entrained liquid phase, however, the liquid did increase the K-factors above those predicted and measured for single phase flow as expected. The K-factors calculated from the wet steam test data were compared to two-phase K-factors based on the Martinelli-Nelson pressure drop correlations. This comparison supports the concept of a two-phase multiplier for estimating the resistance of a piping system with liquid entrained into the flow. The test data in general appears to be reasonably consistent with the shape of a curve based on the Martinelli-Nelson correlation over the tested range of steam quality. An explicit correlation of the test data is likely a complex function of system geometry, steam quality, pressure, and flowrate.

Despite expected uncertainties in the data resulting from the complexity of the piping geometry and two-phase flow, the test data support the conclusion that the predicted dry steam K-factors are accurate and provide useful insight into the effect of entrained liquid on the flow resistance.

8. REFERENCES

- (1) R. C. Martinelli, D. B. Nelson, "Prediction of Pressure Drop During Forced Circulation Boiling of Water," Transactions of ASME, 695-702 (1948)

FIGURE 1 - TEST PIPING

NTS

FIGURE 2. STEAM TEST FACILITY DIAGRAM

LEGEND	
PDT-	PRESSURE DIFFERENTIAL TRANSDUCER
FT-	FLOW TRANSDUCER
DE-	DENSITOMETER

FIGURE 3 - INSTRUMENTATION LOCATIONS
NO TYPICAL SCALE

FOR CONT SEE DETAIL A-A

APPENDIX A

TEST 1

**3.0×10^6 LB/HR. DRY STEAM FLOW
100% QUALITY**

SHEET

PARAMETER

1	INLET TOTAL MASS FLOWRATE
2	INLET STEAM QUALITY
3-6	MEASURED ANNUBAR DYNAMIC PRESSURE
7-10	CALCULATED ANNUBAR MASS FLOWRATE
11-14	MEASURED PITOT TUBE DYNAMIC PRESSURE
15-18	CALCULATED PITOT TUBE MASS FLOWRATE
19-22	GAMMA DENSITOMETER MEASURED DENSITY
23-63	MEASURED STATIC PRESSURE
64-72	MEASURED STATIC PRESSURE DROP
73-91	MEASURED TEMPERATURE

TEST 1 TEST ARTICLE INLET TOTAL MASS FLOWRATE

— CFE-TAIN(LBS/HR)

TEST 1 STEAM QUALITY

— CQUAL1(PERCENT)

TEST 1
MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)	— FT-TA2-2(IN H2O)	— FT-TA3-2(IN H2O)

TEST 1 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)

TEST 1 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA2-2(IN H2O)

TEST 1 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA3-2(IN H2O)

TEST 1 ANNUBAR FLOWRATE

— CFE-TA1-2(LBS/HR)	— CFE-TA2-2(LBS/HR)	— CFE-TA3-2(LBS/HR)

TEST 1 ANNUBAR FLOWRATE

— CFE-TA1-2(LBS/HR)

TEST 1 ANNUBAR FLOWRATE

— CFE-TA2-2(LBS/HR)

TEST 1 ANNUBAR FLOWRATE

— CFE-TA3-2(LBS/HR)

TEST 1 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1(IN H2O)	— FT-TA2-1(IN H2O)	— FT-TA3--1(IN H2O)

TEST 1 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1(IN H2O)

TEST 1 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA2-1(IN H2O)

TEST 1 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA3-1(IN H2O)

TEST 1 PITOT TUBE FLOWRATE

— CFE-TA1-1(LBS/HR)	— CFE-TA2-1(LBS/HR)	— CFE-TA3-1(LBS/HR)

TEST 1 PITOT TUBE FLOWRATE

— CFE-TA1-1(LBS/HR)

TEST 1 PITOT TUBE FLOWRATE

— CFE-TA2-1(LBS/HR)

TEST 1 PITOT TUBE FLOWRATE

— CFE-TA3-1(LBS/HR)

TEST 1 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT3)	— DE-TA2-1B(LBS/FT3)	— DE-TA3-1B(LBS/FT3)

TEST 1 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT3)

TEST 1 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA2-1B(LBS/FT3)

TEST 1 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA3-1B(LBS/FT3)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA1-1(PSIA)	— PT-TA1-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA1-1(Psia)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA1-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA2-1(Psia) — PT-TA2-2(Psia)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA2-1 (PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA2-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA3-1(PSIA)	— PT-TA3-2(PSIA)	— PT-TA3-3(PSIA)	— PT-TA3-4(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA3-1(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA3-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

TEST 1 MEASURED STATIC PRESSURE

— PT-TA3-4(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA5-3(PSIA)	— PT-TA5-4(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA5-3(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA5-4(Psia)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA6-1(PSIA) — PT-TA6-2(PSIA)

**TEST 1
MEASURED STATIC PRESSURE**

TEST 1 MEASURED STATIC PRESSURE

— PT-TA6-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA7-1(PSIA) — PT-TA7-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA7-1(P5IA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA7-2(PsIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA8-1(PSIA)	— PT-TA8-2(PSIA)

**TEST 1
MEASURED STATIC PRESSURE**

NOTE: THIS PLOT INDICATES A FAILED TRANSDUCER.

TEST 1 MEASURED STATIC PRESSURE

— PT-TA8-2(Psia)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA10-1(PSIA)	— PT-TA10-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA10-1 (PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA10-2(PSIA)

TEST 1
MEASURED STATIC PRESSURE

— PT-TA11-1(PSIA)	— PT-TA11-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA11-1(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA11-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA13-1(Psia)	— PT-TA13-2(Psia)

TEST 1 MEASURED STATIC PRESSURE

TEST 1 MEASURED STATIC PRESSURE

— PT-TA13-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA15-1(PSIA)	— PT-TA15-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA15-1 (PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA15-2(Psia)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA16-1(PSIA) — PT-TA16-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA16-1(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA16-2(PsIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA19-1(PSIA)	— PT-TA19-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA19-1(Psia)

TEST 1 MEASURED STATIC PRESSURE

— PT-TA19-2(PSIA)

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA1-1(PSID) — PDT-TA1-2(PSID)

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA1-1(PSID)

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA1-2(PSID)

2 of 5

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA2-1(PSID)

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA3-1(PSID)

NOTE: THIS PLOT INDICATES A FAILED TRANSDUCER.

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA5-1(PSID)

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA6-1(PSID)

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA8-1(PSID)

TEST 1 MEASURED STATIC PRESSURE DROP

— PDT-TA16-1(PSID)

NOTE: THE MAXIMUM RANGE OF THE TRANSDUCER IS EXCEEDED AFTER THE VALVE V3 IS CLOSED.

TEST 1 MEASURED TEMPERATURE

TEST 1 MEASURED TEMPERATURE

— TE-TA1-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA2-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA3-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA5-1(DEGREESF)

TEST 1 **MEASURED TEMPERATURE**

— · TE-TA10-1(DEGREESF)			
— TE-TA6-1(DEGREESF)	— TE-TA7-1(DEGREESF)	— TE-TA8-1(DEGREESF)	

TEST 1 MEASURED TEMPERATURE

— TE-TA6-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

TEST 1 MEASURED TEMPERATURE

— TE-TA8-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA10-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

TEST 1 MEASURED TEMPERATURE

— TE-TA11-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA12-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA13-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA14-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA15-1(DEGREESF)

TEST 1 MEASURED TEMPERATURE

— TE-TA16-1(DEGREESF)	— TE-TA19-1(DEGREESF)

**TEST 1
MEASURED TEMPERATURE**

— TE-TA16-1(DEGREEF)

TEST 1 MEASURED TEMPERATURE

— TE-TA19-1(DEGREESF)

APPENDIX B

TEST 2

**7.0×10^6 LB/HR. WET STEAM FLOW
25% QUALITY**

<u>SHEET</u>	<u>PARAMETER</u>
1	INLET TOTAL MASS FLOWRATE
2	INLET STEAM QUALITY
3-6	MEASURED ANNUBAR DYNAMIC PRESSURE
7-10	CALCULATED ANNUBAR MASS FLOWRATE
11-14	MEASURED PITOT TUBE DYNAMIC PRESSURE
15-18	CALCULATED PITOT TUBE MASS FLOWRATE
19-22	GAMMA DENSITOMETER MEASURED DENSITY
23-63	MEASURED STATIC PRESSURE
64-72	MEASURED STATIC PRESSURE DROP
73-91	MEASURED TEMPERATURE

TEST 2 TEST ARTICLE INLET TOTAL MASS FLOWRATE

— CFE-TAIN(LBS/HR)

TEST 2 STEAM QUALITY

TEST 2 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)	— FT-TA2-2(IN H2O)	— FT-TA3-2(IN H2O)

TEST 2 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)

TEST 2 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA2-2(IN H2O)

TEST 2 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA3-2(IN H2O)

TEST 2
CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #3 FLOWRATE (LBS/HR)	
— ANNUBAR #1 FLOWRATE (LBS/HR)	— ANNUBAR #2 FLOWRATE (LBS/HR)

TEST 2 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #1 FLOWRATE (LBS/HR)

TEST 2 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #2 FLOWRATE (LBS/HR)

TEST 2 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #3 FLOWRATE (LBS/HR)

TEST 2 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1 (IN H2O)	— FT-TA2-1 (IN H2O)	— FT-TA3-1 (IN H2O)

TEST 2 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1(IN H2O)

TEST 2 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA2-1 (IN H₂O)

TEST 2 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA3-1(IN H2O)

TEST 2 CALCULATED PITOT TUBE MASS FLOWRATE

TEST 2 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #1 FLOWRATE (LBS/HR)

TEST 2 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #2 FLOWRATE (LBS/HR)

TEST 2 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #3 FLOWRATE (LBS/HR)

TEST 2 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT3)	— DE-TA2-1B(LBS/FT3)	— DE-TA3-1B(LBS/FT3)

TEST 2 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT3)

NOTE: THE MEASURED DENSITY APPARENTLY EXCEEDED THE 0.7 LBS/FT3 MAXIMUM RANGE SETTING OF THE DENSITOMETER FOR THIS TEST.

TEST 2 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA2-1B(LBS/FT3)

NOTE: THE MEASURED DENSITY APPARENTLY EXCEEDED THE 0.7 LBS/FT3 MAXIMUM RANGE SETTING OF THE DENSITOMETER FOR THIS TEST.

TEST 2 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA3-1B(LBS/FT3)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA1-1(PSIA)	— PT-TA1-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

TEST 2 MEASURED STATIC PRESSURE

— PT-TA1-2(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA2-1(PsIA) — PT-TA2-2(PsIA)

**TEST 2
MEASURED STATIC PRESSURE**

TEST 2 MEASURED STATIC PRESSURE

— PT-TA2-2(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA3-1(PsIA)	— PT-TA3-2(PsIA)	— PT-TA3-3(PsIA)	— PT-TA3-4(PsIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA3-1(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA3-2(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA3-3(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA3-4(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA5-3(PSIA)	— PT-TA5-4(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA5-3(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA5-4(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA6-1(PSIA)	— PT-TA6-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA6-1(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA6-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA7-1(PSIA)	— PT-TA7-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA7-1(PsIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA7-2(Psia)

TEST 2 MEASURED STATIC PRESSURE

TEST 2 MEASURED STATIC PRESSURE

— PT-TA8-1(PSIA)

NOTE: THIS PLOT INDICATES A FAILED TRANSDUCER.

TEST 2
MEASURED STATIC PRESSURE

— PT-TA8-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA10-1(PSIA)	— PT-TA10-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA10-1(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA10-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA11-1(Psia) — PT-TA11-2(Psia)

**TEST 2
MEASURED STATIC PRESSURE**

TEST 2 MEASURED STATIC PRESSURE

— PT-TA11-2(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA13-1(PSIA)	— PT-TA13-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

TEST 2 MEASURED STATIC PRESSURE

— PT-TA13-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA15-1(PSIA)	— PT-TA15-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA15-1(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA15-2(PsIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA16-1 (PSIA) — PT-TA16-2 (PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA16-1 (PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA16-2(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA19-1(Psia)	— PT-TA19-2(Psia)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA19-1(PSIA)

TEST 2 MEASURED STATIC PRESSURE

— PT-TA19-2(Psia)

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA1-1(PSID) — PDT-TA1-2(PSID)

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA1--1(PSID)

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA1-2(PSID)

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA2-1(PSID)

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA3-1(PSID)

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA5-1(PSID)

3 of 5

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA6-1(PSID)

TEST 2 MEASURED STATIC PRESSURE DROP

— PDT-TA8-1 (PSID)

**TEST 2
MEASURED STATIC PRESSURE DROP**

NOTE: THE MAXIMUM RANGE OF THE TRANSDUCER IS EXCEEDED AFTER THE VALVE V3 IS CLOSED.

TEST 2 MEASURED TEMPERATURE

— · TE-TA5-1 (DEGREES F)			
— TE-TA1-1 (DEGREES F)	— TE-TA2-1 (DEGREES F)	— TE-TA3-1 (DEGREES F)	

TEST 2 MEASURED TEMPERATURE

— TE-TA1-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA2-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA3-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA5-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

TEST 2 MEASURED TEMPERATURE

— TE-TA6-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA7-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA8-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA10-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA14-1(DEGREES F)	— TE-TA15-1(DEGREES F)	
— TE-TA11-1(DEGREES F)	— TE-TA12-1(DEGREES F)	— TE-TA13-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA11-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA12-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA13-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA14-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA15-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA16-1(DEGREES F) — TE-TA19-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA16-1(DEGREES F)

TEST 2 MEASURED TEMPERATURE

— TE-TA19-1(DEGREES F)

APPENDIX C

TEST 3

**5.6×10^6 LB/HR. WET STEAM FLOW
41% QUALITY**

SHEET

PARAMETER

1	INLET TOTAL MASS FLOWRATE
2	INLET STEAM QUALITY
3-6	MEASURED ANNUBAR DYNAMIC PRESSURE
7-10	CALCULATED ANNUBAR MASS FLOWRATE
11-14	MEASURED PITOT TUBE DYNAMIC PRESSURE
15-18	CALCULATED PITOT TUBE MASS FLOWRATE
19-22	GAMMA DENSITOMETER MEASURED DENSITY
23-63	MEASURED STATIC PRESSURE
64-72	MEASURED STATIC PRESSURE DROP
73-91	MEASURED TEMPERATURE

TEST 3 TEST ARTICLE INLET TOTAL MASS FLOWRATE

— CFE-TAIN(LBS/HR)

TEST 3 STEAM QUALITY

— CQUAL1(PERCENT)

TEST 3 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)	— FT-TA2-2(IN H2O)	— FT-TA3-2(IN H2O)

TEST 3 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)

TEST 3 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA2-2(IN H2O)

TEST 3 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA3-2(IN H2O)

TEST 3 **CALCULATED ANNUBAR MASS FLOWRATE**

TEST 3 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #1 FLOWRATE (LBS/HR)

TEST 3 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #2 FLOWRATE (LBS/HR)

TEST 3 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #3 FLOWRATE (LBS/HR)

TEST 3 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1 (IN H2O)	— FT-TA2-1 (IN H2O)	— FT-TA3-1 (IN H2O)

TEST 3 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1 (IN H2O)

TEST 3 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA2-1(IN H2O)

TEST 3

MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA3-1(IN H2O)

TEST 3 CALCULATED PITOT TUBE MASS FLOWRATE

TEST 3 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #1 FLOWRATE (LBS/HR)

TEST 3 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #2 FLOWRATE (LBS/HR)

TEST 3

CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #3 FLOWRATE (LBS/HR)

TEST 3 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT³)	— DE-TA2-1B(LBS/FT³)	— DE-TA3-1B(LBS/FT³)

TEST 3 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT3)

TEST 3 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA2-1B(LBS/FT3)

TEST 3 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA3-1B(LBS/FT3)

**NOTE: SPIKE EXTENDING BEYOND MAXIMUM RANGE
IS DUE TO ONE ERRANT DATUM POINT.**

TEST 3 MEASURED STATIC PRESSURE

— PT-TA1-1(Psia)	— PT-TA1-2(Psia)

TEST 3 MEASURED STATIC PRESSURE

TEST 3 MEASURED STATIC PRESSURE

— PT-TA1-2(PsIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA2-1 (PSIA) — PT-TA2-2 (PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA2-1 (PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA2-2(PSIA)

TEST 3
MEASURED STATIC PRESSURE

— PT-TA3-1(PSIA)	— PT-TA3-2(PSIA)	— PT-TA3-3(PSIA)	— PT-TA3-4(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA3-1 (PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA3-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA3-3(PsIA)

TEST 3 MEASURED STATIC PRESSURE

TEST 3 MEASURED STATIC PRESSURE

— PT-TA5-3(PSIA)	— PT-TA5-4(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA5-3(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA5-4(Psia)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA6-1(PsIA) — PT-TA6-2(PsIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA6-1(Psia)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA6-2(Psia)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA7-1(PSIA)	— PT-TA7-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA7-1(Psia)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA7-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA8-1(PSIA)	— PT-TA8-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA8-1(PSIA)

TEST 3 MEASURED STATIC PRESSURE

TEST 3 MEASURED STATIC PRESSURE

— PT-TA10-1(PSIA) — PT-TA10-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA10-1(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA10-2(Psia)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA11-1(PSIA)	— PT-TA11-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA11-1(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA11-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA13-1(PSIA)	— PT-TA13-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA13-1(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA13-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA15-1(PSIA) — PT-TA15-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA15-1(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA15-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA16-1(PSIA) — PT-TA16-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA16-1(PSIA)

TEST 3 MEASURED STATIC PRESSURE

TEST 3
MEASURED STATIC PRESSURE

TEST 3
MEASURED STATIC PRESSURE

— PT-TA19-1 (PSIA)

TEST 3 MEASURED STATIC PRESSURE

— PT-TA19-2(PSIA)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA1-1(PSID)	— PDT-TA1-2(PSID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA1-1 (PSID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA1-2(PSID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA2-1(PSID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA3-1(P'SID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA5-1(PSID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA6-1(PSID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TAB-1(PSID)

TEST 3 MEASURED STATIC PRESSURE DROP

— PDT-TA16-1(PSID)

NOTE: THE MAXIMUM RANGE OF THE TRANSDUCER IS EXCEEDED AFTER THE VALVE V3 IS CLOSED.

4 of 5

TEST 3 **MEASURED TEMPERATURE**

TEST 3 MEASURED TEMPERATURE

— TE-TA1-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA2-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA3-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA5-1(DEGREES F)

TEST 3 **MEASURED TEMPERATURE**

-- TE-TA10-1(DEGREES F)			
— TE-TA6-1(DEGREES F)	— TE-TA7-1(DEGREES F)	— TE-TA8-1(DEGREES F)	

TEST 3 MEASURED TEMPERATURE

— TE-TA6-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA7-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA8-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA10-1(DEGREES F)

TEST 3 **MEASURED TEMPERATURE**

— · TE-TA14-1(DEGREES F)	— · TE-TA15-1(DEGREES F)	
— TE-TA11-1(DEGREES F)	— TE-TA12-1(DEGREES F)	— TE-TA13-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA11-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA12-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA13-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA14-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA15-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA16-1(DEGREES F)	— TE-TA19-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA16-1(DEGREES F)

TEST 3 MEASURED TEMPERATURE

— TE-TA19-1(DEGREES F)

APPENDIX D

TEST 4

**3.5×10^6 LB/HR. WET STEAM FLOW
72% QUALITY**

<u>SHEET</u>	<u>PARAMETER</u>
1	INLET TOTAL MASS FLOWRATE
2	INLET STEAM QUALITY
3-6	MEASURED ANNUBAR DYNAMIC PRESSURE
7-10	CALCULATED ANNUBAR MASS FLOWRATE
11-14	MEASURED PITOT TUBE DYNAMIC PRESSURE
15-18	CALCULATED PITOT TUBE MASS FLOWRATE
19-22	GAMMA DENSITOMETER MEASURED DENSITY
23-63	MEASURED STATIC PRESSURE
64-72	MEASURED STATIC PRESSURE DROP
73-91	MEASURED TEMPERATURE

TEST 4 TEST ARTICLE INLET TOTAL MASS FLOWRATE

— CFE-TAIN(LBS/HR)

TEST 4 STEAM QUALITY

— CQUAL1(PERCENT)

TEST 4 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)	— FT-TA2-2(IN H2O)	— FT-TA3-2(IN H2O)

TEST 4 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA1-2(IN H2O)

TEST 4 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA2-2(IN H2O)

TEST 4 MEASURED ANNUBAR DYNAMIC PRESSURE

— FT-TA3-2(IN H2O)

TEST 4 CALCULATED ANNUBAR MASS FLOWRATE

TEST 4 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #1 FLOWRATE (LBS/HR)

TEST 4 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #2 FLOWRATE (LBS/HR)

TEST 4 CALCULATED ANNUBAR MASS FLOWRATE

— ANNUBAR #3 FLOWRATE (LBS/HR)

TEST 4 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1(IN H2O)	— FT-TA2-1(IN H2O)	— FT-TA3-1(IN H2O)

TEST 4 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA1-1(IN H2O)

TEST 4 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA2-1(IN H2O)

TEST 4 MEASURED PITOT TUBE DYNAMIC PRESSURE

— FT-TA3-1(IN H2O)

TEST 4
CALCULATED PITOT TUBE MASS FLOWRATE

TEST 4 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #1 FLOWRATE (LBS/HR)

TEST 4 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #2 FLOWRATE (LBS/HR)

TEST 4 CALCULATED PITOT TUBE MASS FLOWRATE

— PITOT TUBE #3 FLOWRATE (LBS/HR)

TEST 4 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT3)	— DE-TA2-1B(LBS/FT3)	— DE-TA3-1B(LBS/FT3)

TEST 4 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA1-1B(LBS/FT3)

TEST 4 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA2-1B(LBS/FT3)

TEST 4 GAMMA DENSITOMETER MEASURED DENSITY

— DE-TA3-1B(LBS/FT3)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA1-1 (PSIA) — PT-TA1-2 (PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA1-1 (PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA1-2(PsIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA2-1(PSIA)	— PT-TA2-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

TEST 4 MEASURED STATIC PRESSURE

— PT-TA2-2 (PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA3-1(PsIA)	— PT-TA3-2(PsIA)	— PT-TA3-3(PsIA)	— PT-TA3-4(PsIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA3-1 (PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA3-2(Psia)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA3-3(PsIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA3-4(PSIA)

TEST 4
MEASURED STATIC PRESSURE

— PT-TA5-3(PSIA)	— PT-TA5-4(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA5-3(PsIA)

TEST 4 MEASURED STATIC PRESSURE

TEST 4 MEASURED STATIC PRESSURE

— PT-TA6-1 (PSIA) — PT-TA6-2 (PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA6-1(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA6-2 (PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA7-1(PSIA)	— PT-TA7-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA7-1(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA7-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA8-1(PSIA) — PT-TA8-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA8-1(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA8-2(PsIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA10-1(PSIA)	— PT-TA10-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA10-1(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA10-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA11-1(PSIA)	— PT-TA11-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA11-1(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA11-2(PsIA)

TEST 4 MEASURED STATIC PRESSURE

TEST 4 MEASURED STATIC PRESSURE

TEST 4 MEASURED STATIC PRESSURE

— PT-TA13-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA15-1(Psia) — PT-TA15-2(Psia)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA15-1(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA15-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA16-1(PSIA)	— PT-TA16-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA16-1 (PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA16-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA19-1(PSIA)	— PT-TA19-2(PSIA)

TEST 4 MEASURED STATIC PRESSURE

-- PT-TA19-1(Psia)

TEST 4 MEASURED STATIC PRESSURE

— PT-TA19-2(PsIA)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA1-1(PSID) — PDT-TA1-2(PSID)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA1-1(PSID)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA1-2(PSID)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA3-1(PSID)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA2-1 (PSID)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA5-1 (PSID)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA6-1(PSID)

**NOTE: SPIKE EXTENDING BEYOND MAXIMUM RANGE
IS DUE TO ONE ERRANT DATUM POINT.**

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA8-1 (PSID)

TEST 4 MEASURED STATIC PRESSURE DROP

— PDT-TA16-1(PSID)

NOTE: THE MAXIMUM RANGE OF THE TRANSDUCER IS EXCEEDED AFTER THE VALVE V3 IS CLOSED.

TEST 4 **MEASURED TEMPERATURE**

TEST 4 MEASURED TEMPERATURE

— TE-TA1-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA2-1(DEGREES F)

5 of 5

TEST 4 MEASURED TEMPERATURE

— TE-TA3-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA5-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

--- TE-TA10-1(DEGREES F)			
— TE-TA6-1(DEGREES F)	— TE-TA7-1(DEGREES F)	— TE-TA8-1(DEGREES F)	

TEST 4 MEASURED TEMPERATURE

— TE-TA6-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA7-1 (DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TAB-1 (DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA10-1(DEGREES F)

TEST 4
MEASURED TEMPERATURE

TEST 4 MEASURED TEMPERATURE

— TE-TA11-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA12-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA13-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA14-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA15-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA16-1(DEGREES F)	— TE-TA19-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA16-1(DEGREES F)

TEST 4 MEASURED TEMPERATURE

— TE-TA19-1(DEGREES F)

APPENDIX E

K-FACTOR FORMULAS AND RESULTS

K-FACTOR DERIVATIONS

Symbols		Subscripts
A	flow area, ft ²	1 inlet
g _c	32.17 $\frac{\text{ft lbm}}{\text{lbf sec}^2}$	2 outlet
K	K-factor or loss coefficient, unitless	d dynamic
M	mass flowrate, lbm/hr	o stagnation
P	static pressure, psia	f liquid
ΔP _o	delta total pressure	g gas
V	velocity, ft/sec	
x	steam quality	
ρ	density, lbm/ft ³	
v	specific volume, 1/ρ	

$$\text{Eqn. (1)} \quad K = \frac{\Delta P_o}{\rho V^2 / 2g_c}$$

$$\text{Eqn. (2)} \quad 1/\rho = v = v_f + x (v_g - v_f)$$

$$\begin{aligned} \Delta P_o &= P_{o1} - P_{o2} \\ &= (P_1 + P_{d1}) - (P_2 + P_{d2}) \\ &= (P_1 - P_2) + (P_{d1} - P_{d2}) \end{aligned}$$

$$\text{Eqn. (3)} \quad \Delta P_o = P_1 - P_2 + \rho_1 V_1^2 / 2g_c - \rho_2 V_2^2 / 2g_c$$

Using steam table values and measured quality, density is calculated for inlet and outlet locations with Eqn. (2).

Velocity is then calculated using: $V = M / (3600\rho A)$

Substituting Eqn. (3) into Eqn. (1) and applying unit conversions:

$$K = \frac{(P_1 - P_2) + (\rho_1 V_1^2 - \rho_2 V_2^2) (1/2g_c) (1 \text{ ft}^2/144 \text{ in}^2)}{\rho_1 V_1^2 (1/2g_c) (1 \text{ ft}^2/144 \text{ in}^2)}$$

$$K = \frac{(P_1 - P_2) + (\rho_1 V_1^2 - \rho_2 V_2^2)/9265}{\rho_1 V_1^2/9265}$$

$$K = \frac{9265(P_1 - P_2) + \rho_1 V_1^2 - \rho_2 V_2^2}{\rho_1 V_1^2}$$

Prior to adding incremental K-factors calculated by this equation for use in Figure E1, each K-factor must be adjusted to a reference area and density by the following equation:

$$\text{Eqn. (4)} \quad K_{\text{ADJUSTED}} = K_{\text{INCREMENT}} \left(\frac{A_{\text{REFERENCE}}}{A_{\text{INCREMENT}}} \right)^2 \left(\frac{\rho_{\text{REFERENCE}}}{\rho_{\text{INCREMENT}}} \right)$$

Derive an expression for a relative resistance ratio, $K_{\text{WET}}/K_{\text{DRY}}$, based on the Martinelli-Nelson two-phase pressure drop correlation. The two-phase frictional pressure drop can be expressed as:

$$\Delta P_{\text{TP}} = \left[\frac{f_1 L}{D} \frac{\rho_m}{\rho_1} \phi_{\text{LO}}^2 \right] \frac{G^2}{2 \rho_m}$$

where: G = mass velocity
 ρ_m = two-phase mixture density (calculated by equation (2))
 ρ_1 = saturated liquid density
 L = length of flow path
 D = hydraulic diameter
 ϕ_{LO}^2 = Martinelli-Nelson two-phase correlating factor

$$= \frac{(dP/dL)_{\text{TPF}}}{(dP/dL)_0}, \text{ which is plotted in Figure 3 of the Martinelli paper referenced in the text.}$$

f_1 = isothermal friction factor for saturated liquid

Considering the term in brackets to be a two-phase resistance K-factor analogous to equation (1), the ratio of resistance for wet steam flow to that for dry steam flow would be:

$$\frac{K_{WET}}{K_{DRY}} = \frac{[(f_1 L/D) (\rho_m/\rho_l) (\phi_{LO}^2)]_{WET}}{[(f_1 L/D) (\rho_g/\rho_l) (\phi_{LO}^2)]_{DRY}}$$

where the subscripts "WET" and "DRY" when associated with ϕ_{LO}^2 refer to the value of the term ϕ_{LO}^2 for the specified steam quality ($x = 1.0$ for "DRY") from Figure 3 of Martinelli, tabulated below for 100 psia. For fixed geometry, pressure, and mass velocity, after cancelling terms, the relative resistance ratio is given by:

$$\text{Eqn. (5)} \quad \frac{K_{WET}}{K_{DRY}} = \frac{\rho_m (\phi_{LO}^2)_{WET}}{\rho_g (\phi_{LO}^2)_{DRY}}$$

x	ϕ_{LO}^2 (@100 psia)
0.1	26.5
0.2	51.5
0.3	82.0
0.4	111
0.5	137
0.6	167
0.7	191
0.8	211
0.9	204
1.0	153

Test Number		1		2		3		4		* Prediction
Total Mass Flow (million lbm/hr)		2.8		7.0		5.6		3.2		2.4
Quality (%)		100		23		45		75		100
Reference Area (ft ²)		6.586		6.586		6.586		6.586		6.586
Reference Density (lbm/ft ³)		0.1827		1.0412		0.6498		0.3365		0.1707
Measurement Location	Delta Pressure Measurement	PT	PDT	PT	PDT	PT	PDT	PT	PDT	PT
1-2	Valve 1	0.47	0.80	0.22	0.46	0.27	0.51	0.57	0.75	0.26
2-3	Valve 2 & Elbow	0.50	0.69	1.14	1.00	1.02	0.94	1.41	1.41	0.48
3-4(PDT) 3-5(PT)	2nd Elbow	0.55	0.09	1.27	0.80	1.16	0.75	1.5	1.22	0.32
5-6	Round to Rectangular Transition & Elbow	0.44	0.46	0.93	0.43	0.84	0.46	0.69	0.04	0.24
6-7	4th Elbow	0.00	X	0.35	X	0.28	X	0.51	X	0.10
7-8	T Section	0.05	X	0.30	X	0.27	X	0.35	X	0.15
6-8	4th Elbow & T Section	X	0.16	X	0.73	X	0.43	X	0.86	----
8-10	Check Damper & 5th Elbow	0.37	0.15	0.90	0.93	0.71	0.73	0.88	1.00	0.92
10-11	5th Elbow Outlet to Transition Inlet	0.86	X	0.74	X	0.58	X	0.86	X	0.09
11-13	Transition	0.11	X	0.70	X	0.61	X	0.78	X	0.15
13-15	Transition Outlet to Duct Exit	0.12	X	0.10	X	0.14	X	0.09	X	0.18

Delta pressure was measured from DP transducers(PDT) or calculated from the inlet and outlet absolute pressure transducers(PT). An 'X' indicates no transducer available for a particular geometry.

* Predicted values based on subsonic(M<0.3), compressible, and adiabatic flow through the entire system.

TABLE 1 - MEASURED AND PREDICTED ADJUSTED K-FACTORS

Test No.	1			2		
Total Mass Flow	2.8x10 ⁶ lbm/hr			7.0x10 ⁶ lbm/hr		
Quality	100 %			23 %		
Measurement Location	Incremental Area (ft ²)	Incremental Density (lbm/ft ³)	Adjusted K-Factor	Incremental Area (ft ²)	Incremental Density (lbm/ft ³)	Adjusted K-Factor
1-2	6.5862	0.1827	0.47	6.5862	1.0412	0.22
2-3	6.5862	0.1784	0.50	6.5862	1.0164	1.14
3-5	6.7771	0.1611	0.55	6.7771	0.9334	1.27
5-6	6.8736	0.1546	0.44	6.8736	0.8417	0.93
6-7	8.5417	0.1524	0.00	8.5417	0.8082	0.35
7-8	8.5417	0.1503	0.05	8.5417	0.7746	0.30
8-10	8.5417	0.1481	0.37	8.5417	0.7409	0.90
10-11	8.5417	0.1416	0.86	8.5417	0.6731	0.74
11-13	8.5417	0.1306	0.11	8.5417	0.6306	0.70
13-15	8.8333	0.1306	0.12	8.8333	0.5621	0.10

Test No.	3			4			* Prediction		
Total Mass Flow	5.6x10 ⁶ lbm/hr			3.2x10 ⁶ lbm/hr			2.4x10 ⁶ lbm/hr		
Quality	45 %			75 %			100 %		
Measurement Location	Incremental Area (ft ²)	Incremental Density (lbm/ft ³)	Adjusted K-Factor	Incremental Area (ft ²)	Incremental Density (lbm/ft ³)	Adjusted K-Factor	Incremental Area (ft ²)	Incremental Density (lbm/ft ³)	Adjusted K-Factor
1-2	6.5862	0.6498	0.27	6.5862	0.3365	0.57	6.5862	0.1707	0.26
2-3	6.5862	0.6395	1.02	6.5862	0.3277	1.41	6.5862	0.1620	0.48
3-5	6.7771	0.5729	1.16	6.7771	0.2981	1.50	6.7771	0.1561	0.32
5-6	6.8736	0.5214	0.84	6.8736	0.2684	0.69	6.8736	0.1519	0.24
6-7	8.5417	0.4956	0.28	8.5417	0.2535	0.51	8.5417	0.1484	0.10
7-8	8.5417	0.4696	0.27	8.5417	0.2445	0.35	8.5417	0.1469	0.15
8-10	8.5417	0.4541	0.71	8.5417	0.2295	0.88	8.5417	0.1440	0.92
10-11	8.5417	0.4333	0.58	8.5417	0.2145	0.86	8.5417	0.1329	0.09
11-13	8.5417	0.3914	0.61	8.5417	0.1964	0.78	8.5417	0.1316	0.15
13-15	8.8333	0.3493	0.14	8.8333	0.1873	0.09	8.8333	0.1292	0.18

* Predicted values based on subsonic(M~.3), compressible, and adiabatic flow through the entire system.

TABLE 2 – INCREMENTAL AREAS AND DENSITIES FOR ADJUSTED K-FACTORS

**FIGURE E1:
COMPARISON OF CUMULATIVE PREDICTED
AND MEASURED K-FACTORS**

PLOTTED TEST DATA OBTAINED FROM ABSOLUTE PRESSURE TRANSDUCERS (PT).

**FIGURE E2:
EFFECT OF LIQUID ENTRAINMENT
ON PIPING RESISTANCE**

**DATE
FILMED**

1/31/94

END