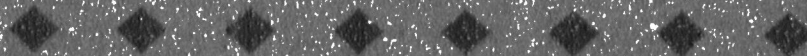


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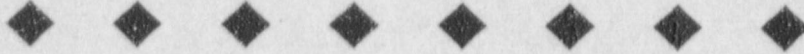
# AP600 Test Program ADS Phase B1 Test Analysis Report

Westinghouse Energy Systems



9804140109 980407  
PDR ADOCK 05200003  
A PDR

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WCAP-14306  
Revision 2

**AP600 Test Program  
ADS Phase B1  
Test Analysis Report**

Westinghouse Energy Systems



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WCAP-14306  
Revision 2

**AP600 TEST PROGRAM**  
**ADS PHASE B1 TEST ANALYSIS REPORT**

L. E. Conway

April 1998

WESTINGHOUSE ELECTRIC COMPANY  
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## NOMENCLATURE

A	area
$C_v$	valve coefficient
e	specific internal energy
H	enthalpy
$H_{fg}$	enthalpy of vaporization
K	pressure loss coefficient
$\dot{m}$	mass flow rate
M	mass
P	pressure
$q_{if}'''$	interface-liquid heat transfer rate
$q_{iv}'''$	interface-vapor heat transfer rate
q	conductive heat transfer
$Q_{wl}'''$	wall-liquid heat transfer
$Q_{wv}'''$	wall-vapor heat transfer
t	time
U	velocity
V	volume
v	specific volume
x	quality
X	pressure drop ratio
Y	expansion factor

### Greek

$\alpha$	void fraction
$\Gamma$	net rate of evaporation
$\phi_{fo}^2$	two-phase multiplier for pressure drop
$\rho$	density

### Subscripts

L	liquid
mix	mixture
PRZ	pressurizer (supply tank)
v	vapor
w $\ell$	wall to liquid
wv	wall to vapor
2 $\phi$	two phase
$\Gamma$	phase change
1 $\phi$	single phase
1	stage 1
2	stage 2
3	stage 3

### Superscripts

T	turbulent
'''	per unit volume

---

## SUMMARY

This report provides the analysis and methodology to calculate the single-phase flow resistance of the ADS valve/piping package, the effective flow area of the ADS valve package components for choked flow conditions, and the flow quality and two-phase flow multipliers as a function of location for the ADS Phase B1 two-phase 200- and 300-series matrix tests.

A set of pressure loss coefficients for the ADS valves and orifices were calculated using the four 100-series single-phase steam flow tests and found to provide consistent results with the loss coefficients measured in the ADS cold flow testing (Reference 1) performed with cold water. The overall loss coefficient for the ADS valve/piping package measured in both this steam test and the testing with cold water was somewhat higher than the calculated overall loss coefficient. This higher than calculated loss was included in the NOTRUMP and WCOBRA/TRAC code analyses. These pressure loss coefficients were used to estimate the flow splits through the operating ADS stages in the ADS package for the two-phase flow tests (200- and 300-series) in which the flow was not choked.

Using the flow splits and loss coefficients from the 100-series tests, the two-phase flow multipliers for the ADS valves and orifices were calculated to be a function of quality and pressure, as expected. As the quality increased, the two-phase flow multiplier increased. As the pressure increased, the two-phase flow multiplier decreased, which is consistent with trends observed in the literature. In comparing the measured two-phase flow multipliers to the predicted two-phase flow multipliers from the Martinelli-Nelson two-phase flow pressure drop multiplier correlation (Reference 2), which is used in the NOTRUMP and WCOBRA/TRAC codes, the measured multipliers are consistently less than or equal to the predicted pressure drop multipliers. Thus the ADS Phase B1 testing supports the fact that the code-predicted flows in the safety analysis are less than or equal to actual flows.

Critical or choked flow in the ADS package was evaluated in three different ways. The assessment shows consistent results, in that when critical flow was calculated to occur in the ADS package using the Henry-Fauske/homogeneous equilibrium choked flow model, the critical pressure ratio was less than the typical value of 0.55, and the observed two-phase flow multiplier was higher than the multiplier calculated by the Martinelli-Nelson correlation.

The ADS tests obtained the needed information on the ADS behavior, pressure drops, flows, and two-phase multipliers, as identified in the PIRT. The data and associated analysis validate the ADS flow and pressure drop models used in the NOTRUMP and WCOBRA/TRAC codes.

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## 1.0 INTRODUCTION

### 1.1 Background

The AP600 is a Westinghouse advanced light water reactor designed with plant safety features that minimize negative consequences of human error and allow significant simplification of the plant systems equipment and operation. The plant uses passive safety systems that rely on driving forces, such as gravity, convection, and natural circulation. The plant is characterized by a lower power core density than standard pressurized water reactor (PWR) designs and by a new reactor coolant loop configuration.

The AP600 utilizes an automatic depressurization system (ADS) to ensure that the reactor coolant system (RCS) is depressurized and long-term gravity injection will be initiated and maintained for passive reflood and core cooling. The AP600 passive safety systems design is shown in Figure 1-1. The ADS design consists of four flow paths, two of which are connected to the top of the pressurizer and a flow path from each of the two RCS hot legs. During an emergency, the two paths from the pressurizer discharge steam and/or water from the RCS into the in-containment refueling water storage tank (IRWST) through spargers located underwater. The two flow paths from the hot legs discharge directly to containment.

Each of the two pressurizer piping flow paths is made up of a 14-in. pipe that connects to three parallel paths/stages (one 4 in. and two 8 in.), creating the ADS piping loop. These three parallel paths each have two normally closed valves in series. The three parallel paths connect to a single 16-in. discharge line, which ends at a submerged sparger. When the ADS is operated, the closed valves are sequentially opened to provide a staged, controlled depressurization of the RCS from operating conditions at 2250 psia/650°F to saturated conditions at approximately 25 psia. This staged valve opening limits the maximum mass flow rate through the sparger and also limits the loads imposed on the quench tank, which is always maintained at containment pressure. The AP600 ADS operation for each stage consists of first opening the upstream (isolation) valve and then opening the downstream (flow control) valve.

The ADS Phase B test was a full-scale simulation of one of the two AP600 ADS pressurizer flow paths from upstream of the ADS valves to the sparger and was designed to duplicate or conservatively bound the operational conditions of the ADS valves and sparger. The ADS Phase B test was performed at ENEA's VAPORE test facility in Casaccia, Italy, where the Phase A portion of the ADS test was performed in 1992. The Phase B test program was subdivided into two parts, B1 and B2.

One of the main objectives for the ADS Phase B1 tests, specified in Reference 3, was to simulate the AP600 thermal-hydraulic performance of the ADS following design basis events and to generate experimental data for validation of the safety analysis computer codes used in support of obtaining design certification for the AP600. The tests involved blowdown of saturated steam or two-phase steam and water mixtures from a supply tank through a control valve to the simulated ADS

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valve/piping package and into the simulated sparger. The ADS valves (or simulated valves) were fully open and flow initiation was accomplished by an isolation valve in the supply tank saturated steam or saturated water discharge line upstream of the actual ADS piping ring.

This report describes the analysis of the data from the Phase B1 tests for the ADS piping package to be used to support the safety analysis. The analysis of hydrodynamic forces generated in the quench tank due to sparger operation and the application of the loads to the AP600 are not covered in this report. The B2 portion of the ADS tests was performed to demonstrate ADS valve operability as part of a test program separate from AP600 design certification.

## 1.2 Facility Description

A full facility description for the ADS Phase B1 tests is provided in Reference 4. Figure 1-2 is a simplified flow diagram of the VAPORE facility, as arranged for the tests. The major components of the facility consist of the steam/water supply tank, steam supply line with moisture separator, saturated water supply line, ADS valve/piping package, discharge line to quench tank, quench tank (simulated IRWST), sparger, and associated valves and instrumentation.

In more detail, the major components are:

- A 1400-ft<sup>3</sup> steam/water supply tank. This tank is initially filled approximately 60-80 percent with water, which is then heated to saturated conditions at the desired initial test pressure.
- A 12-in. diameter saturated water supply pipe from the bottom of the steam/water supply tank to the ADS test valve/piping package. This pipe contains two 12-in. gate valves, one upstream valve (an Edwards valve), and one downstream valve (an Atwood & Morrill valve). The upstream valve, nearest to the supply tank, is fully closed and opens to initiate water flow. The downstream valve is preset at a partially open position that is determined in conjunction with the supply tank's initial conditions to achieve a desired pressure, flow rate, and fluid quality through the ADS valve/piping package.
- A 12-in. diameter steam supply pipe that runs from the top of the steam/water supply tank via an isolation and control valve and a moisture separator to the ADS test valve/piping package.
- The ADS test valve/piping package, which is similar to the AP600 ADS package and includes:
  - A 14-in., Schedule 160 piping supply line with loop seal
  - A 4-in., Schedule 160 piping flow path containing one 4-in. globe valve simulating ADS stage 1
  - Two 8-in., Schedule 160 piping flow paths, each containing one 8-in. gate valve, simulating ADS stages 2 and 3

---

Each of the ADS stage 1, 2, and 3 flow paths contains a set of flanges with a full pipe bore spacer/spool piece. Valves were installed in place of these spacers in the Phase B2 tests. For some of the Phase B1 tests, an orifice was installed at each spool piece to simulate the fully open flow area and resistance of the missing valve.

- A 16-in., Schedule 80 discharge line from the ADS valve/piping package, which utilizes two 10-in. pipes to connect to a 16-in. line running to the AP600 ADS sparger submerged in the quench tank.
- An ADS sparger that has four arms made from [ ]<sup>a,c</sup> pipe, each perforated with [ ]<sup>a,c</sup> diameter holes. The arms are connected to the sparger body at a downward slant of [ ]<sup>a,c</sup> from the horizontal position. The sparger is positioned vertically in the center of the quench tank, [ ]<sup>a,c</sup> below the surface of the water (measured from the centerline of the sparger body to arm connection).
- A 25-ft. diameter cylindrical quench tank containing 24 ft. of water. The quench tank is constructed of concrete.

To obtain the desired information from the tests, temperatures, pressures, differential pressures, and levels were monitored at various locations in the supply tank piping system, sparger, and quench tank by process instrumentation. Data were recorded at up to 1000 samples per second, then reduced offline to 4 samples per second (sps) to make the data file size manageable; the data reduction process is described in Reference 4.

### 1.3 Pre-Operational Tests

Pre-operational tests were carried out to characterize the 12-in. Atwood & Morrill gate valve and determine the pressure drop across it at various openings. This information was used to derive cold water friction factors for input to this analysis work and to the NOTRUMP and WCOBRA/TRAC models for performing the test simulations. The friction factor derivation is provided in Reference 4 and is outside the scope of this report.

### 1.4 Matrix Tests

The matrix tests were performed in four groups:

- 100-series tests: blowdowns of saturated steam from the top of the steam/water supply tank; orifices installed at ADS spool pieces to simulate fully open valves; cold quench tank
- 200-series tests: blowdowns of saturated water from the bottom of the steam/water supply tank; orifices installed at ADS spool pieces to simulate fully open valves; cold quench tank

- 
- 300-series cold tests: blowdowns of saturated water from the bottom of the steam/water supply tank; no orifices installed at ADS spool pieces; cold quench tank
  - 300-series hot tests: blowdowns of saturated water from the bottom of the steam/water supply tank; no orifices installed at ADS spool pieces; quench tank at saturation temperature

The full test matrix is shown in Table 1-1. The objectives of each test are explained in Reference 3.

The matrix test results, presented in Reference 4, were used to perform the subject test analysis. Throughout this report, the test numbering scheme involves seven characters: the first character, A, refers to the ADS; the next three characters refer to the test sequence number; and the last three characters refer to the test matrix number (from Table 1-1).

### 1.5 Analysis Objectives

The objectives of the data analysis for the ADS Phase B1 tests are to calculate and evaluate the key thermal-hydraulic parameters of the ADS components. The thermal-hydraulic parameters will be used with NOTRUMP and WCOBRA/TRAC models of the test facility in the code validation effort. These models will be used in evaluation of the AP600 plant passive safety system performance.

The thermal-hydraulic parameters of interest are:

- Single-phase loss coefficients of ADS valve/piping ring components.
- Choked and non-choked flow splits through the parallel ADS stages.
- The effective flow area of the ADS stage 1 globe valve and stage 2 and 3 orifices simulating globe valves, during choked flow conditions.
- Non-choked two-phase pressure drop and two-phase multipliers for ADS valve/piping package components
- Two-phase fluid quality at particular points in the test facility

The single-phase loss coefficient, effective flow area, and flow split calculations are presented in Section 2.0. The two-phase test analysis methodology is described in Section 3.0, and results are presented in Section 4.0.

- 1 A simple energy equation was used to analyze the test data and calculate fluid quality at points in the flow path for each two-phase blowdown test (to obtain the local thermal-hydraulic conditions). The ADS test facility is a once-through facility with the pressurizer discharging through the system into the simulated IRWST. A system mass and energy balance was not a requirement of the test specification, and there was no method of measuring the exit boundary condition.

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Because of the difficulty of two-phase flow measurement, the mass flow rate through the ADS valve/piping package for the two-phase blowdown tests was determined from the rate of change of steam/water supply tank mass (measured by a level instrument). In the steam blowdown tests, the mass flow rate through the ADS valve/piping package was also determined from differential pressure measurements in a venturi flow meter. The mass flow rate measured by the venturi flow meter may not be equal to the steam/water supply tank mass rate of change throughout the test run because the discharge from the steam/water supply tank initially contains water carryover due to level swell. This water is removed by the moisture separator located upstream of the venturi flow meter and the valve/piping package.

The fluid discharged through the sparger was cooled/condensed and collected in the quench tank. It was not possible to measure the increase in quench tank water mass during a test run because the sparger discharge caused surface perturbations. Also, in certain cases, some of the water evaporated and escaped to the atmosphere or was ejected from the tank. Consequently, a mass balance or flow rate comparison based on the fluid being discharged into the quench tank cannot be performed. A similar situation exists for the energy balance; without a mass balance, no energy balance based on discharge flow into the quench tank can be performed.

#### **1.6 ADS Test Relationship to the Small-Break LOCA PIRT**

The AP600 small-break LOCA phenomena identification ranking table (PIRT) was developed in Reference 5. The AP600 small-break LOCA PIRT identifies ADS stages 1 to 3 as a component of interest. The ADS is a key component that should be simulated in the AP600 small-break transient. The phenomena of interest include choking or critical flow behavior of the valves and sparger, two-phase pressure drop through the ADS piping, and subcritical flow behavior of the ADS once IRWST injection begins.

The ADS is ranked high during the blowdown and natural circulation phase of the transient, to address the inadvertent opening of an ADS valve. In this case, the valve effectively becomes the break, and the critical flow through the valve will determine the depressurization rate of the system.

For the majority of the small-break LOCA transients, the ADS is ranked high during the ADS blowdown phase, where the break in another location has depressurized and drained the RCS, and ADS is initiated when the core makeup tank (CMT) has partially drained. At this time, the ADS valves open and control system depressurization. The key thermal-hydraulic phenomena of interest include choked flow in the valves and sparger and two-phase pressure drop in the ADS piping. The NOTRUMP code critical flow models and two-phase pressure drop models have been validated against the analyzed test data. Once the ADS blowdown phase is complete, ADS stages 1 to 3 are less important since ADS stage 4 will have opened and the primary vent path out of the RCS will be through the stage 4 valves. ADS stages 1 to 3 still provide a secondary vent path, which is available for the long-term cooling of the reactor.

---

The ranges of the flows and the qualities have been compared to the expected ranges for the AP600 plant for different transients (see subsection 4.4.4) to assure that the safety analysis code validation activities using the ADS test data sufficiently cover the range of ADS thermal-hydraulic conditions expected in a postulated small-break LOCA for the AP600 plant.

**TABLE 1-1  
ADS PHASE B1 TEST ANALYSIS REPORT  
SPECIFIED ADS PERFORMANCE TEST MATRIX**

Facility Configuration	Matrix Test No.	ADS Simulation	Supply Tank Pressure	A&M Valve Flow Area
Saturated water blowdowns from bottom of supply tank, no orifices in spool pieces, cold quench tank water	310	Stages 1, 2, & 3 open	2235 psig	7 in. <sup>2</sup>
"	311	Stages 1, 2, & 3 open	1200 psig	3.5 in. <sup>2</sup>
"	312	Stages 1, 2, & 3 open	500 psig	14 in. <sup>2</sup>
"	330	Stages 1 & 2 open	1800 psig	7 in. <sup>2</sup>
"	331	Stages 1 & 2 open	1200 psig	21 in. <sup>2</sup>
"	340	Stage 2 open (inadvertent opening)	2235 psig	35 in. <sup>2</sup>
Saturated water blowdowns from bottom of supply tank, orifices installed in spool pieces	250	Stage 2 open (inadvertent opening)	1200 psig	7 in. <sup>2</sup>
"	210	Stage 1 open	2235 psig	1.4 in. <sup>2</sup>
"	211	Stage 1 open	2235 psig	2.1 in. <sup>2</sup>
"	212	Stage 1 open	2235 psig	3.5 in. <sup>2</sup>
"	220	Stages 1 & 2 open	1200 psig	3.5 in. <sup>2</sup>
"	221	Stages 1 & 2 open	2235 psig	3.5 in. <sup>2</sup>
"	230	Stages 1 & 3 open	1200 psig	3.5 in. <sup>2</sup>
"	231	Stages 1 & 3 open	2235 psig	3.5 in. <sup>2</sup>
"	240	Stages 1, 2, & 3 open	1200 psig	3.5 in. <sup>2</sup>

**TABLE I-1 (Cont.)  
ADS PHASE B1 TEST ANALYSIS REPORT  
SPECIFIED ADS PERFORMANCE TEST MATRIX**

Facility Configuration	Matrix Test No.	ADS Simulation	Supply Tank Pressure	A&M Valve Flow Area
Saturated water blowdowns from bottom of supply tank, orifices installed in spool pieces	241	Stages 1, 2, & 3 open	500 psig	3.5 in. <sup>2</sup>
"	242	Stages 1, 2, & 3 open	500 psig	7 in. <sup>2</sup>
Saturated steam blowdowns from top of supply tank, orifices installed in spool pieces	110	Stage 1 open	2500 psig	N/A
"	120	Stages 1 & 2 open	1600 psig	N/A
"	130	Stages 1 & 3 open	1200 psig	N/A
"	140	Stages 1, 2, & 3 open	1600 psig	N/A
Saturated water blowdowns from bottom of supply tank, no orifices in spool pieces, quench tank water at 212°F (100°C)	320	Stages 1, 2, & 3 open	2235 psig	7 in. <sup>2</sup>
"	321	Stages 1, 2, & 3 open	1200 psig	8.4 in. <sup>2</sup>
"	322	Stages 1, 2, & 3 open	500 psig	14 in. <sup>2</sup>
"	350	Stages 1 & 2 open	1800 psig	14 in. <sup>2</sup>
"	351	Stages 1 & 2 open	1200 psig	21 in. <sup>2</sup>



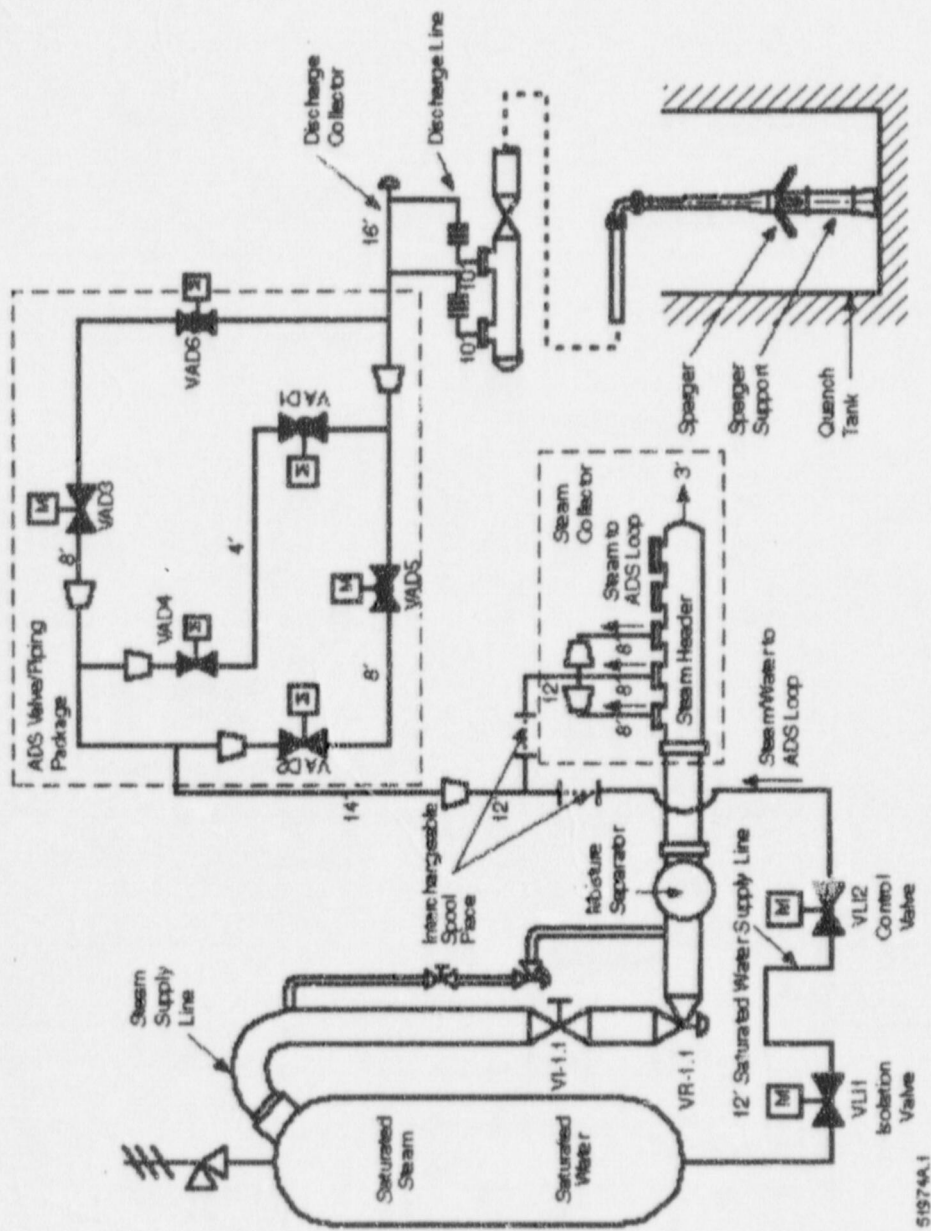


Figure 1-2 Schematic of VAPORE Facility Arrangement for ADS Phase B1 Tests

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## 2.0 COMPONENT SINGLE-PHASE LOSS COEFFICIENT AND EFFECTIVE FLOW AREA CALCULATIONS

The component and overall valve/piping package single-phase loss coefficients and effective flow areas of limiting components during choked flow have been derived from the 100-series steam blowdown tests. These loss coefficients are compared to the loss coefficients obtained with single-phase water flow (Reference 1).

The objectives of the single-phase loss coefficient calculation are to:

- Demonstrate that expected single-phase loss coefficients of the piping sections containing valves and orifices and the overall loss coefficient of the ADS valve/piping package are obtained from the steam flow testing.
- Predict the flow splits between the parallel flow paths in tests with single-phase and two-phase non-choked flow.

The objectives of the effective flow area calculation are to:

- Demonstrate that expected effective flow areas of the ADS valves and orifices are calculated to occur during choked flow conditions.
- Predict the flow splits between the parallel flow paths in tests with single-phase and two-phase choked flow.

The above loss coefficient and flow split results are used in the analysis of the 200-series and 300-series two-phase tests to obtain two-phase flow  $\Delta P$  multipliers for the valves and orifices. The two-phase flow  $\Delta P$  multipliers obtained during the test are then compared to those multipliers based on the Martinelli-Nelson correlation (Reference 2).

Section 2.1 describes the tests and Sections 2.2 through 2.7 describe the calculation methodology and present the calculation.

### 2.1 100-Series Steam Blowdown Tests Description

The 100-series tests were conducted to obtain data to determine the single-phase flow characteristics of the ADS and key components using saturated steam blowdowns. As discussed in Section 1.2, the tests were conducted in a full-size test facility operated at expected plant conditions. The overall test facility arrangement is illustrated in Figure 1-2, showing the steam supply vessel, the moisture separator, the steam supply header, the valve/piping package, and the quench tank.

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Sketches of the valve/piping package are presented in Figures 2-1, 2-2, and 2-3. Figure 2-1 provides pipe information; Figure 2-2, valve information; and Figure 2-3, orifice information.

The valve/piping package arrangement consists of three parallel paths referred to as stages 1, 2, and 3. In the 100-series tests, each parallel path included a valve and an orifice. More specifically:

Stage 1: A low-resistance orifice simulating a fully open gate valve followed by a globe valve, VAD1.

Stage 2: A gate valve, VAD2, followed by an orifice simulating a fully open globe valve.

Stage 3: A gate valve, VAD3, followed by an orifice simulating a fully open globe valve.

Note that the second component in each case was the component with higher resistance.

The 100-series tests were run with saturated steam drawn from the top of the supply vessel. (The 200-series and 300-series tests were run with saturated water drawn from the bottom of the vessel. As saturated water passed through the system, it became a two-phase mixture due to the decreasing pressure.)

Four 100-series tests were conducted:

Test 110: All flow through stage 1

Test 120: Flow through stages 1 and 2 in parallel

Test 130: Flow through stages 1 and 3 in parallel

Test 140: Flow through all three stages, stages 1, 2, and 3, in parallel

Data from these four tests are presented in this section as part of the calculations. The data correspond to the time after the maximum pressure, as measured at the inlet to the valve/piping package (location 6 on Figure 2-1 and PT-6W on Figure 3-1) is achieved; and when the flow, pressure drops, and fluid conditions have been established through the entire ADS piping to the sparger.

## **2.2 Test A039140, Flow Through Stages 1, 2, and 3**

### **2.2.1 Approximate Overall ADS Valve/Piping Package Resistance Based on Test A039140**

To assess and demonstrate that the test data from test A039140 are appropriate for determining the resistances of the ADS valve/piping package components, the overall pressure drop across the package from location 6 to location 16, as shown in Figure 2-1, was used to determine an approximate overall loss coefficient. The pertinent test data and resulting overall  $K$  for various times throughout the test are provided in Table 2-1. Note that the  $K$  derived from the test data remains constant throughout the test over a wide range of flow rates. Also, an examination of the  $\Delta P$ s across the individual ADS

**TABLE 2-1**  
**ADS PHASE B1 TEST A039140 OVERALL K DATA ANALYSIS**

Time (sec.)	P <sub>UP</sub> (psia) PT-6W	P <sub>DN</sub> (psia) PE-16W	ΔP (psi)	ΔP/P <sub>UP</sub> Ratio	Expan. Fac. Y*	Steam ρ (lbs/ft <sup>3</sup> )	Flow (lb/s) FT-15	Overall K
5.2								
10.2								
20.2								
30.2								
40.2								
50.2								
60.2								

Notes:

\* The expansion (Y) factors above are based on the ΔP/P<sub>UP</sub> ratio across the entire valve/piping package and the expansion factor used is for a single-port, wing-guided globe valve as presented in Reference 6.

a,b,c

valve/piping package components shows that the ratio of downstream pressure (P<sub>DN</sub>) vs. upstream pressure (P<sub>UP</sub>) is > 0.55 throughout the test, which indicates that the steam flow is not choked at any location. Therefore Ks based on a ΔP ∝ KρV<sup>2</sup> relationship are valid.

The overall Ks were calculated using Equation 2-15 from Reference 7;

$$q = YCA \sqrt{\frac{\Delta P(2g)(144)}{\rho}}$$

then

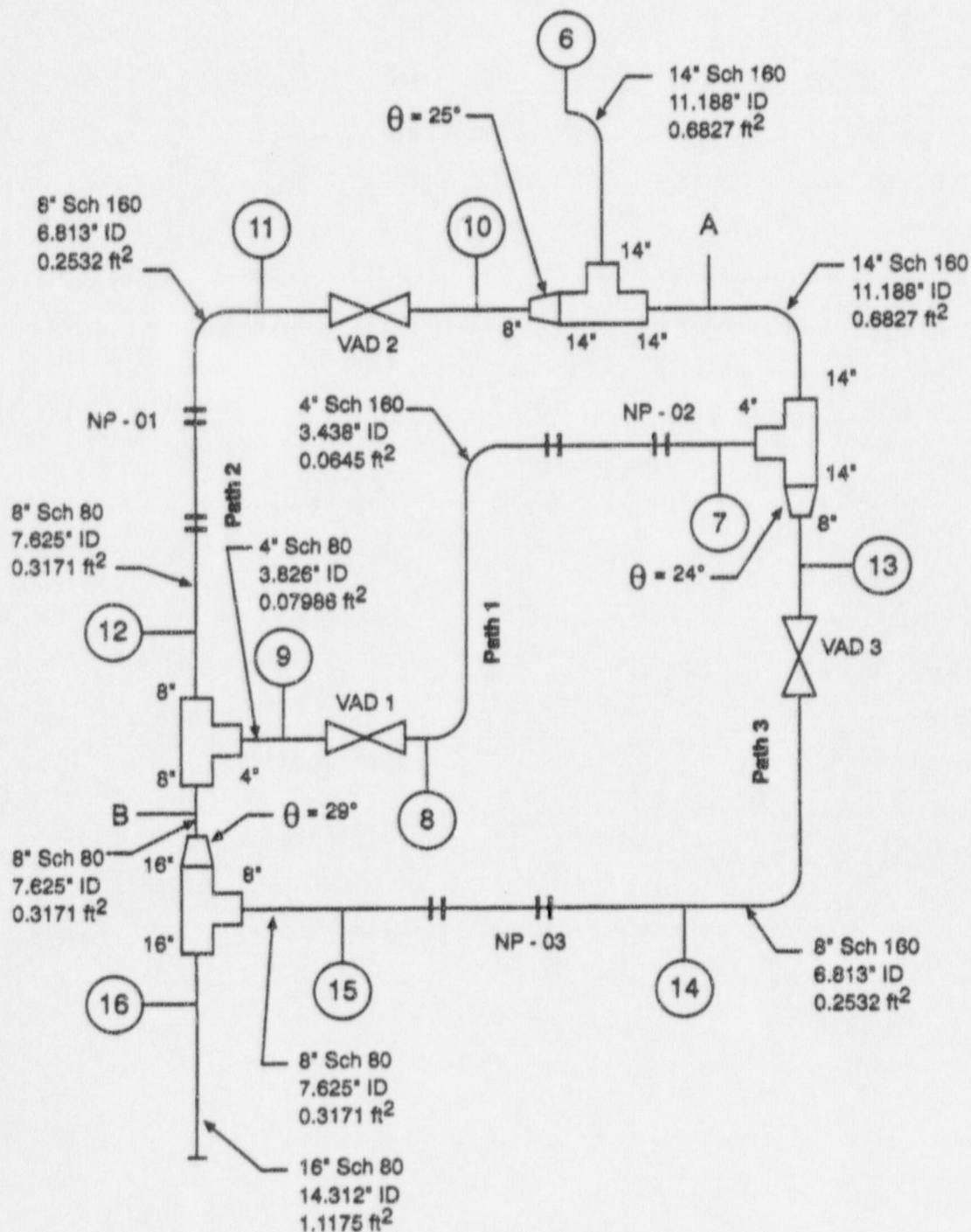
$$K = \frac{1}{C^2} = Y^2 A^2 \frac{\Delta P(2g)(144)(\rho)}{(\dot{m})^2}$$

where: A = 0.6827 ft.<sup>2</sup> (14-in. Schedule 160 pipe area)

$\dot{m}$  = flow, lbs/sec

It should be noted that the above overall K of ~8.7 is sensitive to the expansion factor, and using Ys based on the overall ΔP/P<sub>UP</sub> may have introduced some error (e.g., if Y = 1.0, the overall K would increase to ~14.5). Therefore, the overall valve/piping package K is determined using more detailed evaluations in subsection 2.2.2.

## Pipe Data

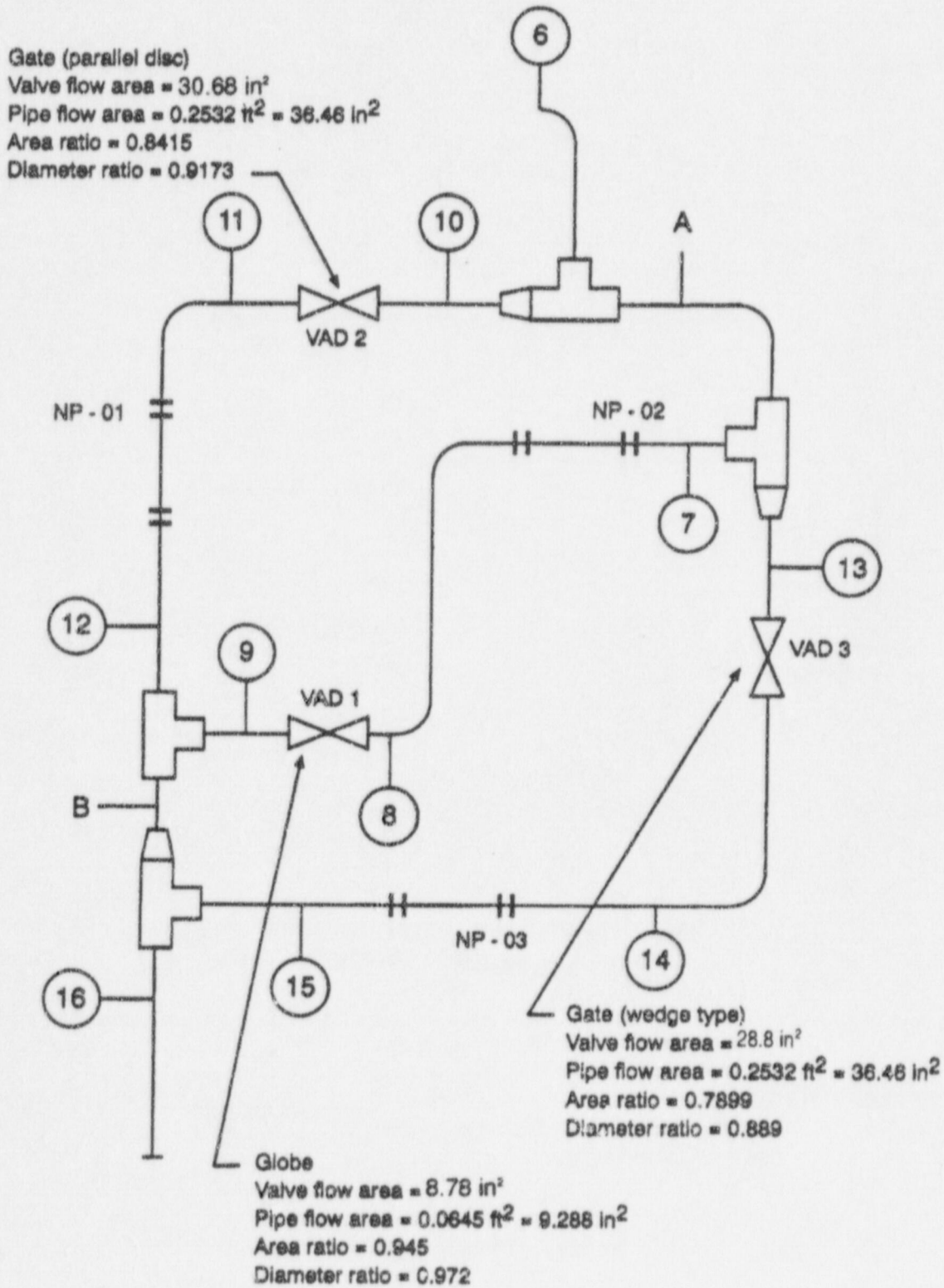


Reducing, expanding section  $\theta$ 's scaled from V.A.P.O.R.E. Plant  
 Phase B, VAP 0001DMBX2260001. Use  $\theta = 30^\circ$  where  $\theta$  is included angle.

52316A.1

Figure 2-1 Pipe Data

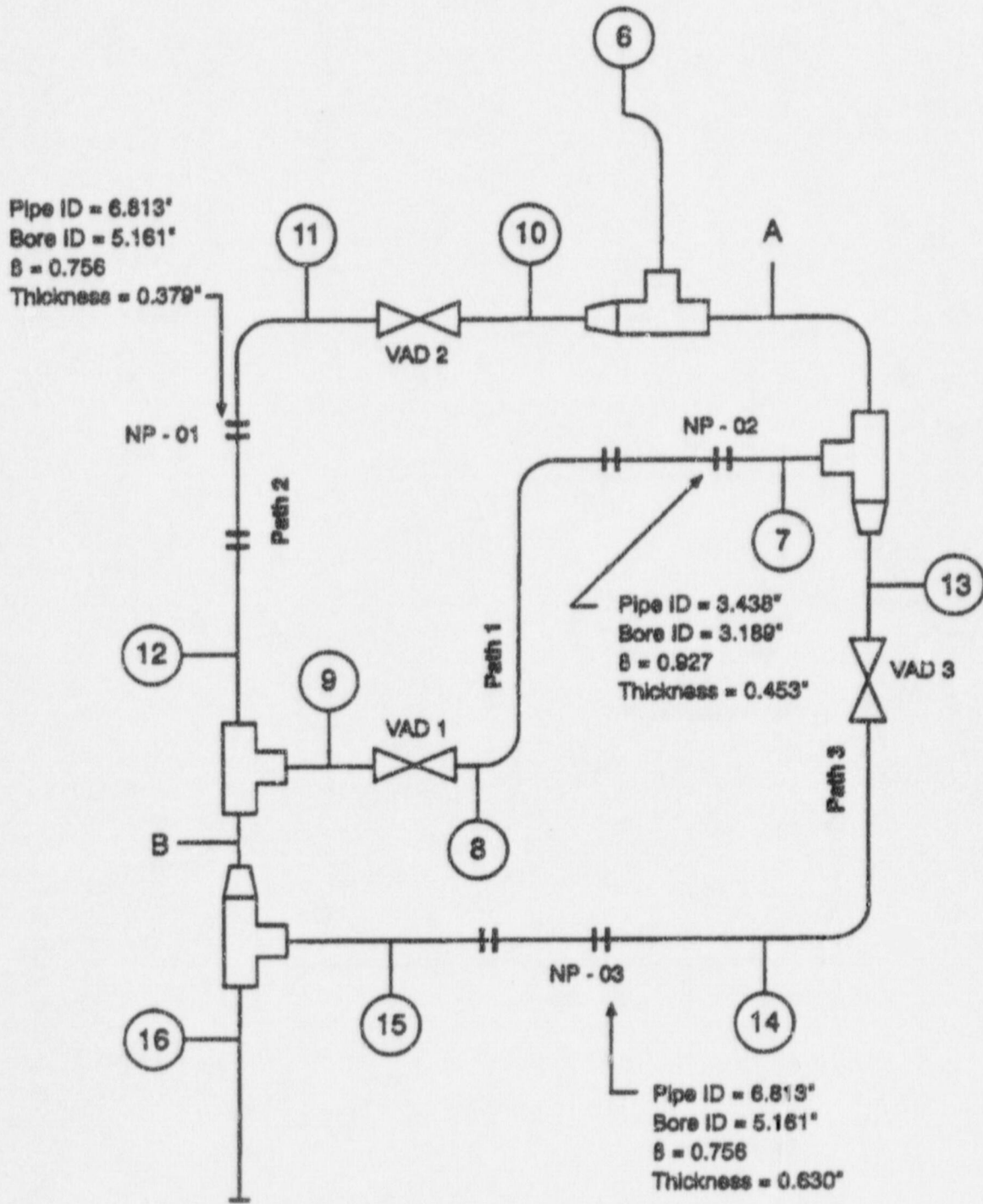
## Valve Data



52316A.2

Figure 2-2 Valve Data

## Orifice Data



52316A.3

Figure 2-3 Orifice Data

### 2.2.2 Individual Component Resistances Based on Test A039140

A more detailed analysis of the A039140 test data is performed below for one time step (40.2 sec.), which includes the calculation of K for each piping section/valve/orifice.

Since the flow rate through each of the individual ADS stages is not known in test A039140, data from the cold flow tests (Reference 1) were used to establish the stage 1 flow rate. The stage 1 flow was selected to obtain the same calculated K achieved in the cold flow tests (i.e.,  $K = \sim 700$  referenced to 14-in., Schedule 160 pipe). The stage 2 and 3 flows were then each assumed to have half of the remaining flow since these stages are similar and both contain identical restrictive orifices. Based on a total flow rate of 131.33 lbs/s, the resulting stage 1 flow is 13.0 lbs/s, and the stage 2 and 3 flows are 59.165 lbs/s each; and the following Ks are calculated (see Table 2-2).

Individual expansion factors used for each component or piping section were based on the following:

- Piping only - 60° Butterfly valve curve from Reference 6
- Gate valves - 60° Butterfly valve curve from Reference 6
- Globe valve - Single-port, wing-guided globe valve curve from Reference 6
- Orifices - p. A-21 for  $k = 1.3$  from Reference 7

Note that because of the limited number of pressure instruments on the ADS valve/piping package, the pressure losses (and Ks) from the common 14-in. inlet pipe to the start of each of the ADS stages, and from the end of the individual stages to the common 16-in. discharge line, cannot be directly calculated. In this calculation, the  $\Delta P$ s from PT-6W (ADS common 14-in. inlet) to the first pressure sensor in each stage (i.e., PT-6W to PE-7W for stage 1, PT-6W to PT-10W for stage 2, and PT-6W to PE-13W for stage 3) are used with the flow through that stage to establish the contribution of the inlet piping losses to the resistance of that stage. The same method is used to determine the resistances of the piping from the last pressure sensor in each individual stage to PE-16W in the 16-in. common discharge line. This methodology is based on the assumption that most of the inlet and exit pressure losses occur in the smaller piping in each stage, rather than in the large common inlet and discharge piping. An alternate method would be to take the averaged  $\Delta P$  from PT-6W to PT-10W, PE-7W, and PE-13W and determine a K based on the total flow rate. The same could be done for the discharge side of the valve/piping package; where the average  $\Delta P$  from PE-9W, 12W, and 15W to PE-16W is used. Either method provides comparable results.

$$\text{The Ks are calculated using } K = \frac{1}{C^2} = \frac{Y^2 A^2 \Delta P (2g)(144)(\rho)}{(\dot{m})^2}$$

where  $A = 0.6827 \text{ ft}^2$  for 14-in. Schedule 160, ADS inlet piping  
 $= 0.06447 \text{ ft}^2$  for 4-in. Schedule 160, stage 1 piping  
 $= 0.2532 \text{ ft}^2$  for 8-in Schedule 160, stage 2 and 3 piping

---

$\rho$  = density of steam at upstream pressure,  $P_{UP}$

$\dot{m}$  = lb/sec mass flowrate

### 2.2.3 Comparison of Component Ks Derived from A039140 and Cold Flow Test KV6

The Ks that were obtained from the KV6 cold flow test (all 3 stages open, using a total flow of 583 lbs/s) are shown in Table 2-3. The Ks from the KV6 test and test A039140 are both referenced to 14-in., Schedule 160 pipe and are shown in Table 2-4. It can be seen that there is reasonable agreement between these two tests. Also the overall resistances of the ADS valve/piping package were determined using the following equation and are listed in Table 2-5.

$$\frac{1}{K_{\text{overall}}} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} + 2\left(\frac{1}{K_1 K_2}\right)^{1/2} + 2\left(\frac{1}{K_1 K_3}\right)^{1/2} + 2\left(\frac{1}{K_2 K_3}\right)^{1/2}$$

This reasonable agreement between the cold water flow test and the 100-series steam flow test results provides confidence that the single-phase steam tests are valid and that the pressure instrumentation is reasonably accurate. Note the cold flow tests were performed with actual valves installed in place of the orifices used in A039140, and with limited range  $\Delta P$  measurements across the components rather than full pressure instrumentation. Also, the good agreement between these two different tests indicates that the flow split assumed to develop the A039140 component Ks is reasonably correct.

**TABLE 2-2  
CALCULATION OF INDIVIDUAL Ks BASED ON  $\Delta P$ s FROM A039140 @ 40.2 sec.**

Component Description	$P_{UP}$ (psia)	$P_{DN}$ (psia)	$\Delta P$ (psia)	$\Delta P/P_{UP}$ Ratio	Y	$\rho_{stage}$ (lb/ft <sup>3</sup> )	K	K Referenced to 14-in. pipe
1) Stage 1 entrance PT-6W to PE-7W								
Stage 1 orifice & pipe PE-7W to 8W								
Stage 1 globe & pipe PE-8W to 9W								
Stage 1 exit PE-9W to 16W								
2) Stage 2 entrance PT-6W to PT-10W								
Stage 2 gate & pipe PT-10W to PE-11W								
Stage 2 orifice & pipe PE-11W to 12W								
Stage 2 exit PE-12W to 16W								
3) Stage 3 entrance PT-6W to PE-13W								
Stage 3 gate & pipe PE-13W to 14W								
Stage 3 orifice & pipe PE-14W to 15W								
Stage 3 exit PE-15W to 16W								

a,b,c

**TABLE 2-3  
CALCULATION OF INDIVIDUAL Ks BASED ON  $\Delta P$ s FROM A089KV6**

See Ref. 16, Table E-1 and C-3

Stage 1 flow = 79 lb/s, Stage 2 flow = 319 lb/s, Stage 3 flow = 185 lbs/s

Component Description	Measured $\Delta P$	K	K Referenced to 14-in. Pipe
1) Stage 1 entrance – DP67 Stage 1 gate valve & pipe – DP78 Stage globe valve & pipe – DP89 Stage 1 disch. piping – DP916			
2) Stage 2 entrance – DP610 Stage 2 gate valve & pipe – DP1011 Stage 2 globe valve & pipe – DP1112 Stage 2 disch. piping – DP1216			
3) Stage 3 entrance – DP613 Stage 3 gate valve & pipe – DP1314 Stage 3 globe valve & pipe – DP1415 Stage 3 disch. piping – DP1516			

a,b,c

\* K of 103.23, obtained in KV6 for the stage 3 piping section containing the overly restrictive Crane globe valve, replaced with the K obtained for stage 2.

**TABLE 2-4  
COMPARISON OF ADS COMPONENT Ks FROM TEST A039140 AND A089KV6\***

Component Description	A039140 K	Stm. Test Total	A089KV6 K	Water Test Total
1) Stage 1 entrance Stage 1 orifice/gate & pipe Stage 1 globe & pipe Stage 1 disch. piping				
2) Stage 2 entrance Stage 2 gate & pipe Stage 2 orifice/globe & pipe Stage 2 disch. piping				
3) Stage 3 entrance Stage 3 gate & pipe Stage 3 orifice/globe & pipe Stage 3 disch. piping				

a,b,c

\*K's are referenced to 14-inch, Sch 160 pipe.

**TABLE 2-5  
COMPARISON OF THE OVERALL RESISTANCE OF THE ADS  
VALVE/PIPING PACKAGE BASED ON TEST A039140 AND A089KV6**

Section Description	A039140 Stm. Test K	A089KV6 Water Test K
Combined Entrance	[	]
Valves/Orifices and Associated Piping		
Combined Discharge		
Overall Package		]

a,c

\* See comment on Stage 3 K, in Table 2-3.

Note: All Ks referenced to 14-in., Schedule 160 piping.

## 2.3 Test A040110 (Stage 1 Only, Steam Only Blowdown)

### 2.3.1 Calculated Stage 1 Orifice Resistance

Prior to looking at the A040110 test data, the calculated K of the orifice is determined below using the method presented in Crane (Reference 7).

$$\text{The } \beta \text{ ratio of the orifice is } = \frac{3.189 \text{ in.}}{3.438 \text{ in.}} = 0.9276.$$

From p.A20 the estimated C = -0.9, which is equivalent to a K of 1.23 using  $K = \frac{1}{C^2}$ . This K corresponds to the maximum  $\Delta P$  that occurs across the orifice plate. The K that corresponds to the permanent  $\Delta P$  is:

$$K_{\text{permanent}} = K_{\text{max}}(1 - \beta^2) = 0.172$$

Referencing the K to the area/flow velocity of the 4-in. Schedule 160 piping:

$$K_{\text{permanent}} \text{ 4-in Schedule 160 pipe} = 0.172 \left( \frac{d_{\text{pipe}}}{d_{\text{orifice}}} \right)^4 = 0.232$$

This  $K_{\text{permanent}}$  corresponds to an L/D of 14 ( $F = 0.0165$ ), which closely matches the L/D of a standard gate valve.

### 2.3.2 Stage 1 Orifice and Piping Resistance

The A040110 test data indicate that the  $K_{\text{permanent}}$  of the stage 1 orifice and piping (PE-7W to 8W) is [ ]<sup>a,b,c</sup>. The pertinent test data is shown below:

Time (sec.)	P <sub>UP</sub> (psia) PE-7W	P <sub>DN</sub> (psia) PE-8W	ΔP (psi)	ΔP/P <sub>UP</sub> Ratio	Y Factor	Flow Rate (lbs/s)	K (Ref. to 4-in. Pipe)
[ ]							]a,b,c

This K of [ ]<sup>a,c</sup> agrees well with the K of [ ]<sup>a,c</sup> obtained from the cold flow test KV1 for PE-7W to 8W which included an actual gate valve instead of the orifice (included a K of 0.38 for the gate valve and a K of 0.36 for piping).

### 2.3.3 Stage 1 Globe Valve Resistance

The ΔP across the stage 1 globe valve and piping (PE-8W to PE-9W) during matrix test A040110 was large and the ratio of the downstream pressure vs. upstream pressure was ~0.35. Typically, a ΔP ratio less than 0.55 indicates that the flow is choked. Since it is apparent that choked flow is occurring, a ΔP ∝ (flow)<sup>2</sup> relationship cannot be used to determine the valve resistance, and flow is only dependent on the flow area and the fluid conditions upstream of the globe valve.

Since the resistance of the globe valve [ ]<sup>a,c</sup> and associated piping [ ]<sup>a,c</sup> has been determined by the cold flow test, and since the A039140 test (in which the flow was not choked) shows good agreement with these stage 1 resistances; no further evaluation of this test data for stage 1 globe valve resistance is required. (See Section 2.6 for discussion of effective flow area.)

## 2.4 Test A038130 (Stages 1 and 3, Steam Only Blowdown)

### 2.4.1 Stage 3 Gate Valve and Piping Resistance

The pertinent test data from test A038130 for the piping and gate valve between PE-13W to 14W and the resulting K of ~0.7 is shown in Table 2-6:

Time (sec.)	P <sub>UP</sub> (psia) PE-13W	P <sub>DN</sub> (psia) PE-14W	ΔP (psi)	ΔP/P <sub>UP</sub> ** Ratio	ρ Stm. (lbs/ft <sup>3</sup> )	Stage 3* flow (lbs/s)	K**(Ref. to 8-in. Pipe)
10.2							
20.2							
30.2							
40.2							
50.2							
60.2							

Notes:

- \* Stage 3 flows obtained from choked flow effective flow area calculation in Section 2.8.
- \*\* Expansion coefficient (Y) assumed to be 1.

a,b,c

---

The Ks for the piping and Westinghouse gate valve between PE-13W and 14W show reasonable consistency throughout the A038130 test. This K agrees with the K of [ ]<sup>a,b,c</sup> measured during the cold flow test KV3, where the stage 3 gate valve contribution was determined to be 0.38.

#### 2.4.2 Calculated Stage 3 Orifice Resistance

Prior to looking at the A038130 test data for the piping and orifice between PE-14W and PE-15W, the calculated K of the orifice is documented below using the method presented in Crane (Reference 7).

$$\text{Orifice } \beta \text{ ratio} = \frac{d \text{ orifice}}{d \text{ pipe}} = \frac{5.16 \text{ in.}}{6.813 \text{ in.}} = 0.7575$$

From p. A-20,  $C = 0.728$ ; and the  $K_{\max} = \frac{1}{C^2} = 1.887$ .

The K for the permanent pressure loss, referenced to 8-in., Schedule 160 pipe is:

$$K_{\text{permanent}} = K_{\max} (1 - \beta^2) \left( \frac{6.813}{5.161} \right)^4 = 0.804 (3.037) = 2.44$$

Note that, as expected, this K of 2.44 is smaller than the K of [ ]<sup>a,b,c</sup> measured for an actual globe valve (stage 2, Edwards globe) in the ADS cold flow test. This K of 2.44 is equivalent to an L/D of 168 ( $f = 0.0145$ ).

The K of 2.44 for the orifice, plus the K of the piping between PE-14W and 15W from the cold flow test results, provides a total K for the PE-14W to 15W piping and orifice of  $2.44 + 0.32$  or 2.76. This K is somewhat less than the K of [ ]<sup>a,b,c</sup> for the orifice and piping measured in test A039140 shown in Table 2-2.

Note that the calculated stage 3 orifice K of 2.44 applies to the stage 2 orifice, which is the same size.

#### 2.4.3 Stage 3 Orifice and Piping Resistance

The data obtained in test run A038130 are summarized below in Table 2-7. Note that the peak flow was achieved at ~5 seconds, and the steam quality was close to 100% from ~10 seconds until the end of the recorded data. Flow was measured using FT-15.

TABLE 2-7 TEST A038130 DATA, AND ANALYSIS OF STAGE 3 ORIFICE AND PIPING					
Time (sec.)	P <sub>UP</sub> (psia) PE-14W	P <sub>DN</sub> (psia) PE-15W	P <sub>DN</sub> /P <sub>UP</sub> Ratio	ΔP (psi)	Total 1 & 3 Flow (lb/s)
5.2					a,b,c
10.2					
20.2					
30.2					
40.2					
50.2					
60.2					

The ΔP across the stage 3 orifice and piping (PE-14W to PE-15W) during this test is large and the ratio of the downstream pressure vs. upstream pressure was ~0.40. Typically, a ΔP ratio less than 0.55 indicates that the flow is choked. Since it appears that choked flow is occurring, a  $\Delta P \propto (\text{flow})^2$  relationship cannot be used to determine the orifice and piping K, and flow is only dependent on the orifice flow area and the fluid conditions upstream of the orifice.

Since the resistance of the orifice ( $K = 2.44$ ) and associated piping ([ ]<sup>a,b,c</sup> total K) has been determined by the cold flow test, and since the A039140 test (in which the flow was not choked) shows reasonable agreement this resistance; no further evaluation of this test data for the stage 3 orifice resistance is required. (See Section 2.6 for discussion of effective flow area.)

## 2.5 Test A041120 (Stage 1 and 2, Steam Only Blowdown)

### 2.5.1 Stage 2 Gate Valve Resistance Based on Test A041120 Data

The stage 2 Anchor Darling gate valve resistance was determined to be [ ]<sup>a,b,c</sup>, based on the K of [ ]<sup>a,b,c</sup> for the piping and valve (PT-10W to PE-11W), obtained in the cold flow test 84KV2.

The K, derived from the A041120 test data, for the piping and valve (PT-10W to PE-11W) and pertinent test data used for its determination are shown below in Table 2-8.

**TABLE 2-8  
TEST A041120 DATA AND INFORMATION  
TO DETERMINE STAGE 2 GATE VALVE AND PIPING RESISTANCE**

Time (sec.)	PUP (psia) PT-10W	PDN (psia) PE-11W	$\Delta P$ (psi)	$\Delta P/P_{UP}$ Ratio	Y*	$\rho$ Stm. (lbs/ft <sup>3</sup> )	Stage 2 flow (lb/s)	K (Ref. to 8" Pipe)
5.2								
10.2								
20.2								
30.2								
40.2								
50.2								
60.2								

a,b,c

\*Y calc using Reference 6 where  $Y = 1 - .33 (X/F [.74])$

These Ks do not remain constant with changing flow and pressure, and are 2 to 3 times higher than the cold flow test K. The high K values as however appear consistent with the K of [ ]<sup>a,b,c</sup> obtained from the A039140 test data in Table 2-2.

### 2.5.2 Calculated Stage 2 Orifice Resistance

The stage 2 orifice, which simulates a globe valve, was the same hole diameter as the stage 3 orifice (see subsection 2.4.2) and its calculated K is 2.44.

This calculated K, plus the resistance of the piping between PE-11W and 12W determined from the cold flow test results, gives a K for the piping and orifice (PE-11W to 12W) of [ ]<sup>a,b,c</sup>. This K is somewhat less than the K of [ ]<sup>a,b,c</sup> from the results of test A039140 in Table 2-2.

### 2.5.3 Stage 2 Orifice and Piping Resistance

The pressure transducer at PE-12W did not function during this test. However, as shown in Table 2-9 below, the  $P_{DN}/P_{UP}$  ratio across the stage 1 globe valve throughout this test was ~0.51, which is less than 0.55. Also the ratio of PE-9W ( $P_{DN}$  for the stage 1 globe valve) vs. PE-11W is ~0.5 throughout the test, which should be a conservatively high  $P_{DN}/P_{UP}$  ratio for the stage 2 orifice. It is therefore likely that the flow throughout this test is choked across the stage 2 orifice. Therefore, no determination of  $\Delta \rho \propto (\text{mass})^2$  should be made using this data. The effective flow area of the stage 2 orifice will be verified using the A041120 data (see Section 2.6).

**TABLE 2-9  
TEST A041120 DATA**

Time (sec.)	Stage 1 Globe Valve and Piping			Stage 2 Orifice and Piping		Total 1 & 2 Flow (lb/s)
	P <sub>UP</sub> (psia) PE-8W	P <sub>DN</sub> (psia) PE-9W	P <sub>DN</sub> /P <sub>UP</sub> Ratio	P <sub>UP</sub> (psia) PE-11W	P <sub>DN</sub> /P <sub>UP</sub> (using PE-9W)	
5.2						
10.2						
20.2						
30.2						
40.2						
50.2						
60.2						
70.2						

a,b,c

## 2.6 Effective Flow Area Calculations

The effective flow area is defined as the flow area of a component required for agreement between the calculated critical mass flux and the test measured flow rate at choked flow conditions. For these 100 series ADS tests with steam, the critical mass flux was calculated using Reference 8.

The effective flow area at choked flow conditions, for the most restrictive, downstream component in each of the ADS stage flowpaths are determined based on the following 100 Series test runs:

- Stage 1 globe valve: Test A064800 (Phase B2 Testing) with confirmation with A040110 data.
- Stage 2 orifice: Test A041120 with Stage 1 results.
- Stage 3 orifice: Test A038130 with Stage 1 results.

In each of the above tests, choked flow through the restrictive downstream components was indicated by the fact that the downstream over upstream pressure ratio was less than 0.55. In each of the calculations below; the stagnation enthalpy of the fluid upstream of the valve package was based on the assumption that the fluid in the 35 ft<sup>3</sup> steam header (See Figure 1-2, also called the steam test drum or steam collector) was 100 percent steam. This steam header is just downstream of the moisture separator (assuring separation of any carry-over moisture from the supply tank), and the steam header's large volume and cross-sectional area provides a low velocity steam inventory just upstream of the ADS valve package.

---

The steam quality just upstream of an ADS valve or orifice (for example, location 8 in Figure 2-1 just upstream of the Stage 1 globe valve, VAD-1) was determined based on the energy equation, assuming steady, adiabatic conditions and negligible kinetic energy:

$$x = \frac{H_v - H_L}{H_{fg}} \quad (2-1)$$

where  $x$  = steam quality as a fraction

$H_v$  = saturated steam enthalpy in the steam header based on the header measured pressure

$H_L$  = saturated water enthalpy just upstream of the valve component based on the measured static pressure

$H_{fg}$  = enthalpy of vaporization based on the static pressure measured just upstream of the valve component.

- | Calculations were performed to quantify the kinetic energy of the fluid upstream of the valves (or
- | orifices) and its effect on the quality determined using the above energy equation (see subsection 4.4.1).

### 2.6.1 Stage 1 Globe Valve Effective Flow Area

As stated in the ADS Phase B1 Final Data Report (Reference 4), there was some question about the validity of the FT-15 flow measurement due to the fact that the  $\Delta P$  instruments/flow venturi used in test A040110 were for higher steam flow rates than the flow obtained. In fact, use of the FT-15 flow rates, with the methodology used below, would indicate that the effective flow area of the stage 1 globe valve is  $\sim 8.7 \text{ in}^2$ . This corresponds to the actual flow area of the valve but is much higher than the effective flow area the vendor (Anchor-Darling) predicts. Due to this uncertainty in the flow measurement, an alternate determination of the stage 1 globe valve effective flow area based on the cold flow test data with confirmation using Phase B2 test data is provided below.

#### Alternate Effective Flow Area Calculated With the Cold Flow Test Data (Reference 1)

The cold flow test for stage 1 determined that the resistance between PE-8W and 9W was 4.88 for the globe valve and 5.47 for the valve and piping at non-choked single-phase (cold water) flow conditions. From Table C-2, Run 85KV1, 125 seconds, DP89; the stage 1 globe valve and piping had a  $\Delta P$  of 50.0 psi at a flow rate of [ ]<sup>b</sup> lbs/sec. and the resulting  $\Delta P$  across only the valve would be [ ]<sup>b</sup> psi. Based on this data, the stage 1 globe valve provides the same  $\Delta P$  that would be obtained with a 4.4 in<sup>2</sup> orifice. This simple analogy provides evidence that FT-15 flow rates measured in test A040110 (and the resulting 8.7 in<sup>2</sup> effective flow area at choked conditions) are too high.

**Effective Flow Area Calculated with ADS Phase B2 Test Data (Reference 9)**

The ADS Phase B2, stage 1, steam only blowdown test (A064800) was performed at conditions similar to A040110, and in this test the steam flow measurement venturi  $\Delta P$  instrumentation was modified. Note that this test was performed to demonstrate the operability of the stage 1 globe valve during actual valve operation from full closed to full open. Thus, much of this test involves opening the globe valve, and data during the valve opening are not comparable to the Phase B1 test A040110. However, once the globe valve was fully open, the test arrangement is identical to A040110.

Based on data from Reference 9:

- Time at which stage 1 globe valve fully open is 49 sec.
- Stage 1 average flow rate from 49 through 55 seconds - [ ]<sup>a,b,c</sup>
- Steam header average pressure (PT-10) from 49 to 55 seconds - [ ]<sup>a,b,c</sup>
- PE-8W average pressure ( $P_{UP}$ ) from 49 through 55 seconds - [ ]<sup>a,b,c</sup>
- PE-9W average pressure ( $P_{DN}$ ) from 49 through 55 seconds - [ ]<sup>a,b,c</sup>

The ratio of the pressure downstream of the Stage 1 globe valve (PE-9W) over the pressure upstream of the valve (PE-8W) was used as a guide to indicate when choked flow was occurring; i.e.,  $P_{DN}/P_{UP}$  is less than 0.55. In this case,  $P_{DN}/P_{UP} = [ ]^b$ , which indicates that flow is choked and this is the same ratio obtained in the B1 test run A040110.

The stagnation enthalpy in the steam header based on PT-10 is 1145.2 Btu/lb<sub>m</sub>; and the steam quality upstream of the globe valve calculated to be 98%, based on the PE-8W measured pressure.

The effective flow area is determined based on the critical mass flux obtained from Reference 8, Figure 14 with the above  $P_{UP}$  and stagnation enthalpy, compared to the above test flow rate. This calculation is simply:

$$(\text{area}) (\text{critical mass flux}) = (\text{measured mass flow rate})$$

The resulting Stage 1 globe valve effective flow area is [ ]<sup>a,c</sup> in<sup>2</sup>.

This [ ]<sup>a,c</sup> effective flow area is [ ]<sup>a,c</sup> larger than the flow area calculated above by assuming the globe valve is an orifice.

Using this [ ]<sup>a,c</sup> effective flow area for the globe valve (VAD-1), the flow rate during test A040110 can be calculated based solely on the upstream pressure.

These calculated flows are reasonably close to the flow rates measured by LT-1B in A040110, and this further indicates that the FT-15 flow rates are not correct (see Table 2-10).

1 This [ ]<sup>a,c</sup> effective flow area will be used in subsequent sections of this calculation and to evaluate the performance of the stage 2 and 3 orifices in test runs A041120 and A038130 where the  $P_{DN}/P_{UP}$  across the orifices simulating globe valves also indicated choked flow.

**TABLE 2-10  
STAGE 1 AVERAGE FLOW RATES VS. TIME FOR TEST A040110**

Time (sec.)	Measured by FT-15 (lb/s)	Measured by LT-1B (lb/s)	Calculated w/[4.7] <sup>a,c</sup> in. <sup>2</sup> EFA (lbs/s) <sub>a,b,c</sub>
30.1 - 40.1			
40.1 - 50.1			
50.1 - 60.1			
60.1 - 70.1			
70.1 - 80.1			
80.1 - 90.1			
90.1 - 100.1			
100.1 - 110.1			

### 2.6.2 Stage 3 Orifice Effective Flow Area Based on A038130 Test Results

The data obtained in test run A038130 is summarized in Table 2-11. Note that the peak flow was achieved at ~5 seconds, and the steam quality was close to 100% from ~10 seconds until the end of the recorded data. Flow was measured using FT-15.

Since the flow through the stage 1 globe valve is also choked throughout this test, the effective flow area of the stage 3 orifice is calculated below based on the flow obtained after subtracting the stage 1 flow calculated based on its [ ]<sup>a,c</sup> in.<sup>2</sup> effective flow area. Again, Reference 8 is used with the stagnation enthalpy and  $P_{UP}$  values for each component, as described above in subsection 2.6.1, to calculate the stage 1 choked flow and the resulting stage 3 effective flow area.

As shown in the right-most column, the effective flow area of the [ ]<sup>a,c</sup> in.<sup>2</sup> stage 3 orifice is [ ]<sup>a,c</sup> in.<sup>2</sup>. This also confirms that the [ ]<sup>a,c</sup> in.<sup>2</sup> EFA of stage 1 is correct.

### 2.6.3 Stage 2 Orifice Effective Flow Area Based on A041120 Test Results

Data obtained in test A041120 was summarized in Table 2-9. Note that peak flow was achieved at ~5 seconds and the measured steam quality was ~99% at 10 seconds and did not reach 100% until ~30 seconds. Flow was measured using FT-15.

**TABLE 2-11**  
**STAGE 3 ORIFICE EFFECTIVE**  
**FLOW AREA BASED ON TEST A038130 DATA**

Time (sec.)	Steam Header H <sub>U</sub> (Btu/lb)	Total Flow (lbs/S)	Stage 1 (4.7 in. <sup>2</sup> EFA)			Stage 3 Orifice			Calc EFA (in. <sup>2</sup> )
			P <sub>UP</sub> (psia) PE-8W	Quality Fraction	Flow (lb/s)	P <sub>UP</sub> (psia) PE-14W	Quality Fraction	Flow (lb/s)	
5 - 10									
15 - 20									
25 - 30									
35 - 40									
45 - 50									
55 - 60									
65 - 70									

a,b,c

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The data and results from test run A041120 used to determine the orifice effective flow area are summarized in Table 2-12. As for stage 1 and 3 test A038130, since the flow through the stage 1 globe valve is choked, the effective flow area of the stage 2 orifice is calculated based on the flow obtained after subtracting the stage 1 flow based on its [ ]<sup>a,c</sup> in<sup>2</sup> effective flow area, and is confirmed to be ~21 in<sup>2</sup>.

## 2.7 Evaluation of the VAPORE Facility ADS Valve/Piping Package Resistances Using Crane Methodology

The Ks (fL/D's) of the ADS tests valve/piping package were determined directly from the test facility as-built piping drawings. The Ks are determined using Crane Tech Paper 410 methodology.

This analysis provides additional insight into the test results discussed above.

### 2.7.1 Overall Phase B1 ADS Valve Package Resistance Based on Crane Calculation

The resistances for each piping section (referenced to 14-inch, Schedule 160 pipe) were calculated using Crane Technical Paper 410 methodology and are compared with the resistances obtained from the steam only blowdown tests in Table 2-13.

The overall resistance that results from this Crane type calculation for the test facility valve/piping package is 7.3 (referenced to 14-inch pipe).

The flow splits for each stage from the above resistances, with all three stages operating are:

Stage 1 flow split	=	7.9%
Stage 2 flow split	=	46.9%
Stage 3 flow split	=	<u>45.2%</u>
		100.00%

Note that these flow splits are not greatly different than the flow splits originally assumed for test A039140 in subsection 2.2.2.

**TABLE 2-12**  
**STAGE 2 ORIFICE EFFECTIVE**  
**FLOW AREA BASED ON TEST A041120 DATA**

Time (sec.)	Steam Header H <sub>v</sub> (Btu/lb)	Total Flow (lbs/S)	Stage 1 (4.7 in. <sup>2</sup> EFA)			Stage 2 Orifice			
			P <sub>UP</sub> (psia) PE-8W	Quality Fraction	Flow (lb/s)	P <sub>UP</sub> (psia) PE-10W	Quality Fraction	Flow (lb/s)	Calc EFA (in. <sup>2</sup> )
5 to 10	[ ]								
15 to 20									
25 to 30									
35 to 40									
45 to 50									
55 to 60									
65 to 70									

a,b,c

---

## 2.7.2 Overall ADS Valve Package Resistance for the Cold Water Flow Test (Manufacturer's Valve L/Ds Used Instead of Orifices) Calculated Using Crane Methodology

The resistances for each piping section (referenced to 14-inch Schedule 160 pipe) were calculated using Crane Technical Paper 410 methodology and are compared with the resistances obtained from the cold flow tests in Table 2-13 below. This calculation differs from the Crane calculation in subsection 2.7.1 in that:

- Stage 1 The orifice with K of 0.23 replaced with gate valve L/D of 13 ( $K = 13 (.0165) = 0.2145$ ); so that the K of the portion of stage 1 between PE-7W and 8W becomes 0.5925 (referenced to 4-in. pipe) or 66.447 (referenced to 14-in. pipe).
- Stage 2 The orifice with K of 2.44 replaced with globe valve L/D of 270 ( $K = 270 (.0145) = 3.915$ ), so K of the portion of stage 2 between PE-11W to 12W becomes 4.311 (referenced to 8-in. pipe) or 31.350 (referenced to 14-in. pipe).
- Stage 3 As in stage 2, orifice with K of 2.44 replaced with globe valve L/D of 270 ( $K = 3.915$ ), so the K of the portion of stage 3 between PE-14W to 15W becomes 4.028 (referenced to 8-in. pipe) or 29.292 (referenced to 14-in. pipe).

The overall K calculated using the Crane methodology with all three stages open is calculated to be 9.359. The calculated flow splits for each stage from the resistances are:

Stage 1 flow split	=	9.14%
Stage 2 flow split	=	46.02%
Stage 3 flow split	=	<u>44.84%</u>
		100.00%

## 2.8 Summary of Results

### 2.8.1 Flow Resistances with Non-Choked Flow

Table 2-13 summarizes and compares the resistances of the ADS valve/piping package obtained by testing, and calculated using Crane methodology for both the ADS Phase B1 Test ADS package (with orifices) and for the ADS package used in the cold flow test (with orifices replaced with valves).

This table shows, both for the steam only blowdown tests and the cold flow test, that the calculated overall resistance with all three ADS stages operating is ~33% lower than the resistance obtained from the test data. This underprediction of the overall ADS valve piping package resistance has been considered in the resistance of the ADS used in the AP600 safety analyses as described below:

**TABLE 2-13  
SUMMARY OF VAPORE ADS VALVE/PIPING  
COMPONENT MEASURED AND CALCULATED RESISTANCES**

ADS Package Component Description	Steam Blowdown Tests				Cold Water Flow Tests				Comment		
	Calc. by Crane (orifices installed)	Stages 1, 2, 3	Stage 1	Stages 1 & 2	Stages 1 & 3	Stages 1 & 2	Stages 1 & 3	Stage 1		A089KV6 Stages 1, 2, 3	Calc by Crane (valves installed)
1) Stage 1										a,b,c	Ref. to 14-in. Sch. 160 Pipe
PE6W to 7W											Ref. to 4-in. Sch. 160 Pipe
PE7W to 8W											Ref. to 4-in. Sch. 160 Pipe
PE8W to 9W											Ref. to 14-in. Sch. 160 Pipe
PE9W to 16W											Ref. to 14-in. Sch. 160 Pipe
2) Stage 2											
PT6W to 10W											
PT10W to PE11W											Ref. 8-in. Sch. 160 Pipe
PE11W to 12W											
PE12W to 16W											Ref. to 14-in. Sch. 160 Pipe
3) Stage 3											
PT6W to PE13W											
PE13W to 14W											Ref. to 8-in. Sch. 160 Pipe
PE14W to 15W											
PE15W to 16W											Ref. to 14-in. Sch. 160 Pipe
Overall K											

\* Assumed value, based on Stage 2 with Edwards globe valve

The plant piping resistances are calculated using Crane methodology and the maximum valve resistances specified in the valve specification documents. The piping straight length L/Ds and elbow/tee L/Ds are increased by one-third to obtain maximum resistances for use in the safety analyses. (These maximum resistances are decreased by one-half to obtain minimum resistances for use in the safety analyses.)

Using the above method, the calculated maximum resistances of the test ADS valve/piping package were compared to the ADS cold flow test results (Reference 1). The maximum calculated resistances were shown to be ~20% higher than the test data for all ADS flow path combinations, except when all three stages (1, 2, and 3) were operating together. In this case, the resistance based on test data was 13% higher than the calculated maximum. In order to maintain the ~20% margin in the maximum resistances used in the safety analysis; the calculated plant maximum resistances were therefore increased by an additional 35%, when all three stages operate.

Note that the single-phase, non-choked flow resistances are also used to determine an observed  $\Delta P$  multiplier for the Series 200 and 300 tests which have two-phase flow conditions. As discussed in Section 3.3, the observed multipliers are compared to the two-phase flow  $\Delta P$  multipliers calculated using the Martinelli-Nelson correlation (Reference 2). This comparison shows that Martinelli-Nelson theoretical  $\Delta P$  multipliers are equal to or higher than the observed multipliers. Since NOTRUMP and WCOBRA/TRAC utilize the Martinelli-Nelson correlation to determine two-phase, non-choked flow  $\Delta P$  multipliers, and the Martinelli-Nelson multipliers are conservatively high (see Section 1.9 of Reference 14), and the single-phase resistances are conservatively high; the minimum ADS 1, 2, 3 non-choked flowrates calculated in the safety analyses are conservatively low.

### 2.8.2 Flow Splits with Non-Choked Flow

The non-choked flow splits between ADS stages 1, 2, and 3, when all three stages are operating and with the orifices installed (Series 100 and 200 tests), based on testing and calculations are summarized and compared below:

ADS Stage	Calc. by Crane (orifices installed)	Steam Flow Test A039140*	Water Flow Test A089KV6**	Calc by Crane (valves installed)
1				
2				
3				

a,c

\* Flow split values based on simplified assumption

\*\* Flow splits calculated using Edwards globe valve resistance (Crane valve high resistance not used)

- 1 The non-choked, flow splits between ADS stages 1 and 2, and stages 1 and 3 for the series 100 and 200 tests (orifices installed), based on the loss coefficients obtained from steam flow test A039140 are summarized below:

ADS Stages	Stages 1 and 2 Operating	Stages 1 and 3 Operating
1	]	a,c
2		
3		

- 1 The non-choked, flow splits between the ADS stages for the 300-series tests (no orifices installed), based on the loss coefficients obtained from steam flow test A039140 adjusted to remove the orifice Ks, are summarized below:

ADS Stages	Stages 1, 2, and 3 Operating	Stages 1 and 2 Operating
1	]	a,c
2		
3		

### 2.8.3 Effective Flow Areas with Choked Flow

The effective flow areas of the most restrictive flow area component in the downstream portion of each ADS stage are summarized below:

Component	Phase B1 A040110	Phase B1 A041120	Phase B1 A038130
Stage 1 globe valve	]		a,c
Stage 2 orifice			
Stage 3 orifice			

\*With supporting data from Phase B2 test, A064800 and cold flow test KV1

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### 3.0 TWO-PHASE TEST ANALYSIS METHODOLOGY

#### 3.1 Introduction

The first part of the two-phase test data analysis is to calculate the fluid quality at locations throughout the ADS test facility. This includes the inlet to the ADS valve/piping package (Figure 3-1, location 6), locations upstream of each ADS valve and simulated valve (Figure 3-1, locations 7, 8, 10, 11, 13 and 14), and locations downstream of the valve/piping package to the ADS sparger.

The second part of the analysis deals with two-phase pressure drop multipliers of the piping sections containing the ADS valves and orifices. The measured total mass flow with the single-phase pressure loss coefficients (*K* factors) and flow splits derived from steam test results (Section 2.0) are used to calculate single-phase pressure drops of the components, assuming the flow is liquid. The two-phase multipliers of the components are then calculated from measured two-phase pressure drop data. The two-phase multipliers obtained from the test data are compared with the Martinelli-Nelson two-phase flow  $\Delta P$  multiplier correlation (Reference 2).

Finally, an assessment is made of whether the ADS valve/piping package components are choked. The two-phase multiplier results are reviewed in light of this assessment.

#### 3.2 Fluid Quality Calculation Method

For each two-phase steam/water blowdown test, the steam quality at the ADS inlet and other locations was based on the following relationship (adiabatic energy equation assuming negligible kinetic energy):

$$\text{Quality} = \frac{H_{L-TK} - H_L}{H_{fg}} \quad (3-1)$$

where:

$H_{L-TK}$	=	Water enthalpy at the exit of the supply tank (PT-1W or TE-1W, see below)
$H_L$	=	Saturated water enthalpy at the desired location, based on the measured pressure
$H_{fg}$	=	Vaporization enthalpy at the desired location, based on the measured pressure

The fluid enthalpy exiting the bottom of the supply tank ( $H_{L-TK}$ ) was based on saturated water as measured by pressure sensor PT1W located in the discharge piping upstream of valve VLI-1; or was based on the water enthalpy as measured by temperature sensor TE-1W: whichever was less (see Figure 3-1). It is noted that in seven of the twenty-four two-phase blowdown tests, the temperature measured by TE-1W indicated that the water exiting the tanks was slightly subcooled. In most of the remaining fourteen tests the fluid temperature measured by TE-1W was within several degrees of the

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saturation temperature corresponding to the pressure measured by PT-1W. In all fourteen of these tests the fluid was assumed to be saturated water at zero quality. It is also noted that the pressure measured by PT-1W agreed well with the supply tank pressure (PT-4) plus the elevation head of the liquid and steam in the tank.

This quality calculation assumes adiabatic flow conditions and a homogeneous equilibrium flow through the test facility. The measured pressures/temperatures and the derived quality are calculated based on the average values measured during the quasi-steady state flow period of interest for each test.

### 3.3 Two-Phase Multiplier Calculation

The greatest pressure losses in the ADS occur at valves, orifices, and the sparger. The pressure drop in two-phase flow is commonly computed by multiplying the pressure drop (computed by assuming that the flow is all liquid) by a two-phase multiplier. Since the transient two-phase pressure drop is measured and the fluid quality is calculated at locations just upstream of each component in the test, both an observed and the theoretical calculated two-phase flow  $\Delta P$  multipliers can then be obtained from the test data.

The single-phase pressure drop that would occur with only water (no steam) is computed by:

$$\Delta P_{1\phi,L} = K \frac{\dot{m}_{mix}^2}{2g_c \rho_L A^2} \quad (3-2)$$

where:

$\dot{m}_{mix}$	=	mass flow rate
$\rho_L$	=	density of water
K	=	resistance of the piping and valve determined in Section 2 from test A039140 data
A	=	pipe flow area

As seen from Table 1-1, the ADS Phase B tests can be grouped into five cases:

- Case 1, ADS stage 1 valve open
- Case 2, ADS stages 1 and 2 valves open
- Case 3, ADS stages 1 and 3 valves open
- Case 4, ADS stages 1, 2, and 3 valves open
- Case 5, ADS stage 2 valve open

In cases 2, 3, and 4, there is more than one flow path through the ADS valve/piping package (locations 7 through 15 in Figure 3-1). Since there is no measurement of flow rate at these locations,

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the flow rate through each ADS path is unknown. To compute the two-phase multipliers, a flow split between the open stages, based on the single-phase flow split (Section 2.8), is assumed. Given the measured total mass flow rate, the flow rate in each stage,  $\dot{m}_{mix}$  in Equation 3-2 is then derived.

The observed two-phase multiplier for the pressure drop,  $\phi_{fo}^2$ , is defined as:

$$\phi_{fo}^2 = \frac{\Delta P_{2\phi}}{\Delta P_{1\phi,L}} \quad (3-3)$$

where:

$\Delta P_{2\phi}$  = two-phase pressure drop as measured in test  
 $\Delta P_{1\phi,L}$  = single-phase pressure drop assuming all flow is liquid

In computing the observed two-phase multiplier from Equation 3-3, first compute  $\Delta P_{1\phi,L}$  from Equation 3-2. Since there are no differential pressure cells in the ADS test facility; the test two-phase pressure drop  $\Delta P_{2\phi}$  is obtained from the absolute pressure data at two locations, one upstream and one downstream of each component.

- | The theoretical two-phase flow  $\Delta P$  multiplier is determined based solely on the measured pressure and the calculated fluid quality just upstream of the piping section/component; using the Martinelli-Nelson
- | correlation (Reference 2). The application of this correlation in the NOTRUMP computer code is
- | discussed in Section 1.9, "Hydraulic Resistance Model" of Reference 14.

The calculation of two-phase multipliers is performed in LOTUS spreadsheets that contain the test data averaged over the quasi-steady state flow period of interest for each test and appropriate equations. Two-phase multipliers are not computed for the sparger body-arms or sparger arms-pool because these locations are always choked.

### 3.4 Critical Flow Assessment

The possibility of choking at the ADS valves and orifices is examined using three methods:

- Comparison of downstream/upstream measured static pressure ratio with a critical value.
- Comparison of the calculated two-phase flow multiplier with the multiplier observed to have occurred in the test. Choked flow is indicated whenever the observed multiplier is significantly greater than the calculated multiplier.

- Comparison of the measured mass flow (using the flow split fractions based on the effective flow areas in Section 2) with the critical mass flow predicted by the Henry-Fauske (Reference 11)/homogeneous equilibrium model (Reference 12) for the conditions averaged during the quasi-steady state period of the test.

For the downstream/upstream static pressure ratio comparison, a value of 0.55 was taken as the critical pressure ratio. If the component's downstream/upstream static pressure ratio at the time of quasi-steady mass flow was less than or equal to 0.6 (0.55 plus allowance for data and methodological uncertainties), it is assessed to be choked. The 0.55 value is the typical critical pressure ratio for steam, derived as follows:

$$r_{p(\text{crit})} = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \quad (3-4)$$

where  $\gamma = 1.3$

Although this pressure ratio varies for two-phase conditions, the constant value is considered to be a reasonable value as an indicator of choked conditions.

Figure 3-2 shows that for flashing of saturated water into the two-phase mixture, the critical pressure ratio is also 0.55 for  $L/D > 12$ . For smaller  $L/D$ , the critical pressure ratio is smaller (Reference 13).

The Henry-Fauske/homogeneous equilibrium model takes the component averaged upstream pressure and fluid quality as its input, and predicts a critical mass flux,  $G_c$  (lbm/ft<sup>2</sup> sec.) for a convergent nozzle. To assess whether a component is choked, critical mass flow is calculated from the critical mass flux as determined using the Henry-Fauske/homogeneous equilibrium model and the flow area,  $A_c$ , then compared with the averaged measured mass flow for the location by means of a ratio, defined as follows:

$$\text{mass flow ratio} = \frac{\dot{m}_{\text{data}}}{G_c A_c} \quad (3-5)$$

A mass flow ratio of close to unity indicates choked flow. In the assessment, a ratio of 0.9 or greater (to allow for data and methodological uncertainties) is taken to indicate choking. Note that for fluid qualities  $\geq 10\%$ , the homogeneous equilibrium model is utilized.

No correction for the kinetic energy of the fluid upstream of the component is included in the calculation of the critical mass flow ratio, that is, the flow quality upstream of the component is calculated using Equation 3-1. (See subsection 4.4.1).

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For the series 200 tests, the stage 1 globe valve and stage 2 and 3 orifice flow areas,  $A_c$ , are taken to be the effective flow areas of these components obtained from the 100-series tests 110, 120, and 130 in Section 2.6. For the 300-series tests where no orifices are installed,  $A_c$  is taken to be the manufacturer-specified flow area for the stage 2 and 3 gate valves, the pipe areas where no orifices are installed, and the stage 1 globe valve effective flow area.

In the branches of the ADS valve/piping package, the local mass flow,  $\dot{m}_{data}$ , is obtained by multiplying the total measured mass flow by the relevant flow split which is calculated based on the ratio of the stage effective flow area to the total effective flow area of the stages in operation. These flow splits are listed in Table 3-1.

**TABLE 3-1  
FLOW SPLITS USED IN CRITICAL FLOW ASSESSMENT**

Test Series	Open Stages	Flow Split			
		Stage 1	Stage 2	Stage 3	
200	1	┌			└ a,b,c
	2				
	1, 2				
	1, 3				
	1, 2, 3				
300	1	┌			└
	2				
	1, 2				
	1, 2, 3				

**Note:** In 200-series tests, most likely choke points were: stage 1 globe valve, stage 2 orifice, stage 3 orifice. In 300-series tests, most likely choke points were: stage 1 globe valve, stage 2 gate valve and stage 3 gate valve.

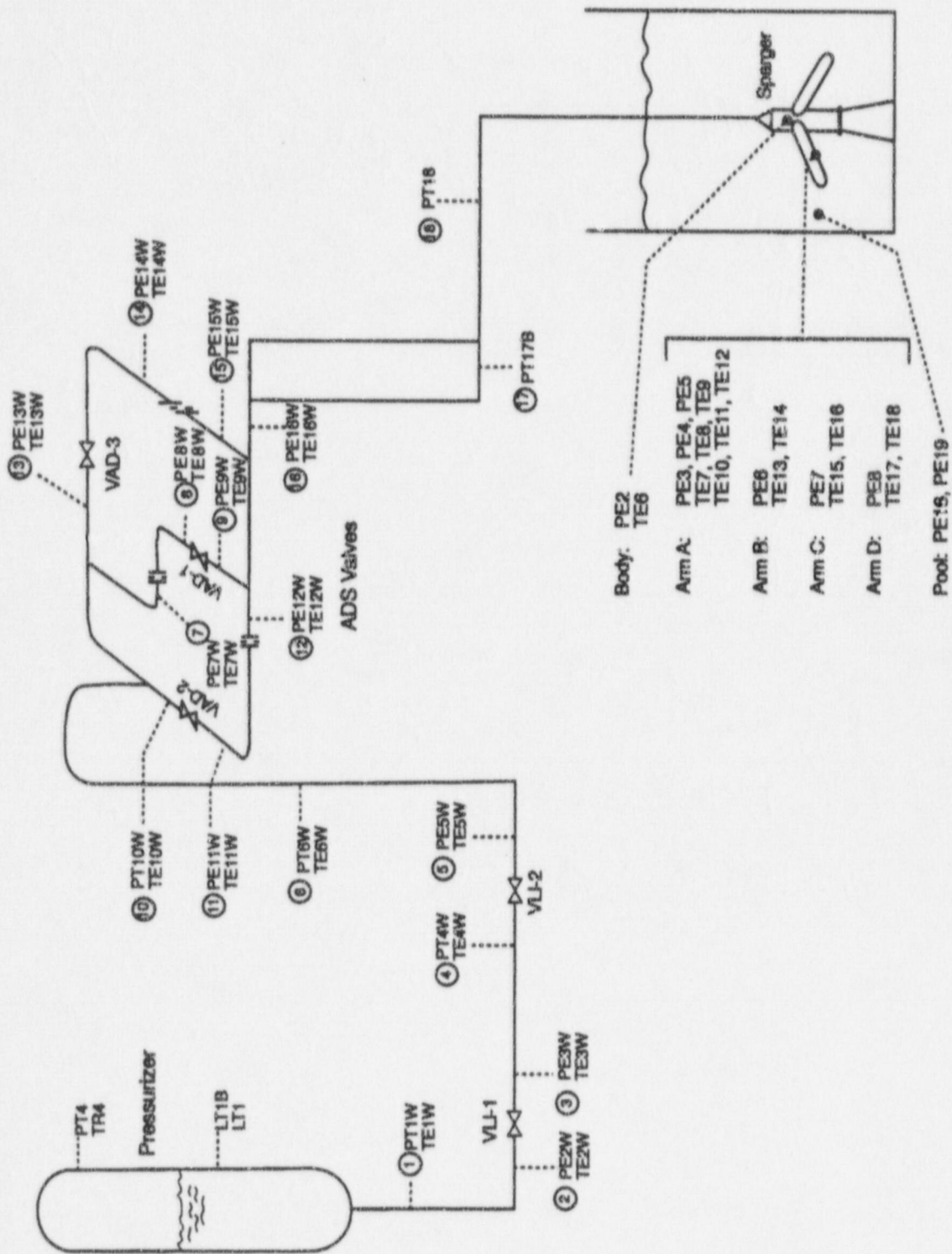


Figure 3-1 Pressure Gauge and Thermocouple Locations on ADS Phase B1 Test Facility

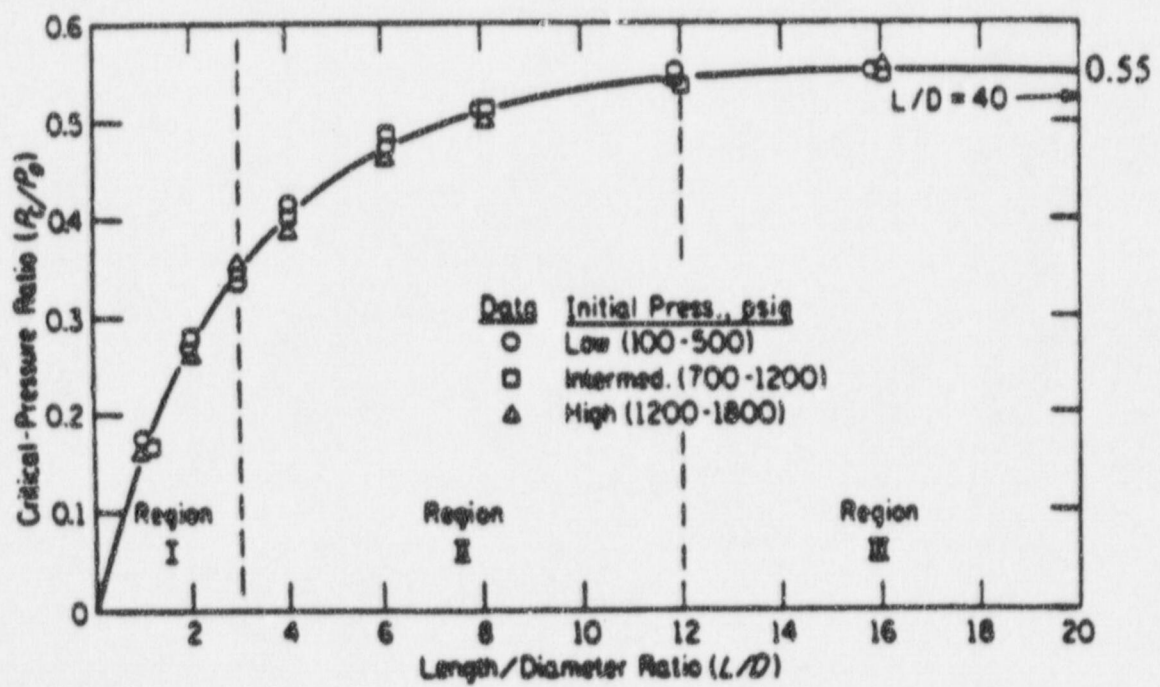


Figure 3-2 Experimental Critical Pressure Ratio Data as a Function of Length/Diameter Ratio (Reference 13)

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## 4.0 TWO-PHASE BLOWDOWN MATRIX TEST RESULTS

The following subsections provide the results of the data evaluation that was previously described in Section 3.0. Included are the measured pressure distribution, calculated quality, and two-phase flow multipliers for the key locations in the flow path. Also included are the results of the critical flow assessment. Each of the 24 tests is reported separately.

An evaluation of the calculated results is provided in Section 4.4 for all tests.

### 4.1 200-Series Tests

The 200-series tests were performed with a valve and an orifice in each ADS path. The orifice was designed to simulate the full open area of one of the two AP600 plant valves in each stage. The quench tank was maintained at a temperature of  $\leq 120^{\circ}\text{F}$  for all tests. There were 11 acceptable tests performed in this series.

#### Test A026211

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-1. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-1. Therefore, the parameters of interest are time averaged values calculated over this time period.

The observed and calculated two-phase flow multipliers for the stage 1 piping sections containing an orifice or valve, averaged over the 15-25 second time period, are shown in Table 4-3 with other two-phase multipliers from all tests. These multipliers were calculated based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. Note that the theoretical calculated multiplier for the stage 1 piping section containing the orifice (location 7-8) is similar to the observed multiplier, indicating that no choking is occurring. However, the theoretical calculated multiplier for the stage 1 piping section containing the globe valve (location 8-9) is significantly less than the observed multiplier, which indicates that choking may be present. The presence of critical flow at the globe valve is confirmed by the static pressure ratio of 0.4 which also indicates that choking occurred in the ADS stage 1 valve. However, this is not confirmed by the assessment based on the Henry-Fauske/homogeneous equilibrium model (see Table 4-4).

#### Test A027212

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-2. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-2. Therefore, the parameters of interest are time averaged values calculated over this time period.

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The observed and calculated two-phase multipliers for the stage 1 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. Note that the theoretical calculated multiplier for the stage 1 piping containing the orifice (location 7-8) is similar to the observed multiplier. However, the theoretical calculated multiplier for the stage 1 piping section containing the globe valve (location 8-9) is significantly less than the observed multiplier, which indicates that choking may be present. This critical flow assessment is confirmed by the static pressure ratio of 0.41, which also indicates that choking occurred in the stage 1 globe valve. However, this is not confirmed by the assessment based on the Henry-Fauske/homogeneous equilibrium model (see Table 4-4).

### **Test A028221**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-3. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state is achieved is from about 15 to 25 seconds, as shown in Figure 4-3. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1 and 2 piping sections containing an orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. Note that the calculated multiplier for the stage 1 piping containing the orifice (location 7-8) is ~2 times higher than the observed multiplier, and the calculated multiplier for the stage 2 piping containing the gate valve (location 10-11) is also higher than the observed multiplier, indicating that choking is not occurring. However, the calculated multiplier for the stage 1 piping section containing the globe valve (location 8-9) and stage 2 piping section containing the orifice simulating a globe valve (location 11-12) are less than the observed multipliers, which indicates that choking may be present. This critical flow assessment is confirmed by the static pressure ratio of 0.56 for the stage piping with the globe valve while this ratio is 0.61 for the stage 2 piping section with the orifice. The indication for choked flow using homogeneous equilibrium choked flow model also show choking may be occurring with the stage 1 piping with the globe valve mass flow ratio just below 0.9, while the stage 2 piping with the orifice is 1.06, and indicating choked flow (see Table 4-4).

### **Test A029231**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-4. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 20 seconds, as shown in Figure 4-4. Therefore, the parameters of interest are time averaged values calculated during this time period.

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The observed and calculated two-phase multipliers for the stage 1 and 3 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. Note that the calculated multiplier for the stage 1 piping containing the orifice (location 7-8) is just slightly lower than the observed multiplier, while the calculated multiplier for the stage 3 piping containing the gate valve is slightly higher than the observed multiplier. However, the calculated multiplier for the stage 1 piping section containing the globe valve (location 8-9) and the stage 3 piping section containing the orifice are both significantly less than the observed multipliers, which indicates that choking is present. This critical flow assessment is confirmed by the static pressure ratios of 0.49 and 0.50 for stages 1 and 3 globe valve and orifice, respectively. The homogeneous equilibrium model also indicates choked flow, with stage 1 globe valve mass flow ratio being 0.94 and the stage 3 orifice mass flow ratio being 0.95 (see Table 4-4).

#### **Test A030220**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-5. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-5. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for stage 1 and 2 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. Note that the calculated multiplier for the stage 1 piping containing the orifice (location 7-8) is almost 2 times higher than the observed multiplier, and the calculated multiplier for the stage 2 piping containing the gate valve (location 10-11) is also higher than the observed multiplier. This indicates that the flow in these piping sections is not choked. Also, the calculated multiplier for the stage 1 piping section containing the globe valve (location 8-9) is less than the observed multiplier, which indicates that choking may be occurring. The calculated multiplier for the stage 2 piping section containing the orifice (location 11-12) is almost equal to the observed multipliers, which indicates that choking is not present. This critical flow assessment is confirmed by the static pressure ratios of 0.58 and 0.63 for stages 1 and 2, respectively. The Henry-Fauske/homogeneous equilibrium model indicates choked flow at both locations, with stage 1 globe valve mass flow ratio being 1.0 and the stage 2 orifice mass flow ratio being 1.2 (see Table 4-4).

#### **Test A031230**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-6. The flow quality, as calculated from Equation 3-1, and the measured pressure at six locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-6. Therefore, the parameters of interest are time averaged values calculated during this time period.

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The observed and calculated two-phase multipliers for the stage 1 and 3 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. Note that the calculated multiplier for the stage 1 piping containing the orifice (location 7-8) and for the Stage 3 piping containing the gate valve (location 13-14) are similar to the observed multipliers. Also, the calculated multipliers for the stage 1 piping section containing the globe valve (location 8-9) and the stage 3 piping section containing the orifice (location 14-15) are both less than the observed multipliers, which indicates that choking is present. This critical flow assessment is confirmed by the static pressure ratios of 0.52 and 0.50 for stages 1 and 3, respectively. The Henry-Fauske/homogeneous equilibrium model predicts choked flow at both locations, with the stage 1 globe valve mass flow ratio being 1.10 and the stage 3 orifice mass flow ratio being 1.11 (see Table 4-4).

#### **Test A033241**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-7. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-7. Therefore, the parameters of interest are averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the stage 1, 2, and 3 piping sections are higher than the observed multipliers, which indicates that choking is not occurring. This critical flow assessment is confirmed by the static pressure ratios, which are all greater than 0.6 for each piping section. The Henry-Fauske/homogeneous equilibrium model however, shows that the critical mass flow of just 0.9 is achieved in the downstream, high  $\Delta P$  piping section for each stage (see Table 4-4). This disagreement between the observed multipliers and  $\Delta P$  ratios with the Henry-Fauske/homogeneous equilibrium model suggests that the calculated fluid qualities may be higher than actually occurs.

#### **Test A034242**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-8. The flow quality, as calculated from Equation 3-1, and the measured pressures at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-8. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated

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multipliers for all the stage 1, 2, and 3 piping sections are higher than the observed multipliers, which indicates that choking is not occurring. This critical flow assessment is confirmed by the static pressure ratios which are all greater than 0.6 for each piping section. The Henry-Fauske/homogeneous equilibrium model however, shows that the critical mass flow is achieved in the downstream, high delta-P piping section for each stage (see Table 4-4). This disagreement between the observed multipliers and delta-P ratios with the choked mass flow ratio suggest that the calculated fluid qualities may be higher than actually occurs.

#### **Test A035240**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-9. The flow quality, as calculated from Equation 3-1, and the measured pressures at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state is achieved is from about 15 to 25 seconds, as shown in Figure 4-9. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the stage 1, 2, and 3 piping sections are higher than the observed multipliers, which indicates that choking is not occurring with the exception of the upstream portion of stage 1 containing the low  $\Delta P$  orifice. This critical flow assessment is confirmed by the static pressure ratios, which are all greater than 0.6 for each piping section. The Henry-Fauske/homogeneous equilibrium model also indicates no choking since the critical mass flow ratio is  $<0.9$  in the downstream, high  $\Delta P$  piping section for each stage (see Table 4-4).

#### **Test A036250**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-10. The flow quality, as calculated from Equation 3-1, and the measured pressures at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-10. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 2 piping section containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for the stage 2 upstream piping section containing the gate valve is higher than the observed multiplier, which indicates that choking is not occurring. However, the calculated multiplier for the stage 2 downstream piping section containing the orifice is much larger than the observed multiplier, which indicates that choking is occurring. This critical flow assessment is confirmed by both the static pressure ratios for each piping section and the Henry-Fauske/homogeneous equilibrium model critical mass flow calculation (see Table 4-4).

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-11. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 12 to 22 seconds, as shown in Figure 4-11. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1 piping section containing the orifice or valve, averaged over the 12 to 22 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for the stage 1 upstream piping section containing the orifice simulating a gate valve is slightly smaller than the observed multiplier, which indicates that choking may be occurring. However, the calculated multiplier for the stage 1 downstream piping section containing the globe valve (location 8-9) is significantly less than the observed multiplier, which indicates that choking is occurring. This critical flow assessment is confirmed by the static pressure ratios for each piping section, however the Henry-Fauske/ homogeneous equilibrium model critical mass flow calculation indicates that the critical flow ratio of the globe valve is 0.86, i.e., less than 0.90. (see Table 4-4)

#### 4.2 300-Series Cold Quench Tank Tests

The 300-series cold quench tank tests were performed with only one valve in each ADS path. The orifice was replaced with a full bore spool piece to simulate ADS flow paths with minimum resistance, full bore gate valves. The quench tank was maintained at a temperature of < 140°F for these 300 Series tests. There were eight acceptable tests performed in this series.

##### Test A002311

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-12. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-12. Therefore, the parameters of interest are time average values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the stage 1, 2, and 3 piping sections, with the exception of the Stage 1 full bore pipe section, are higher than the observed multipliers; which indicates that choking is not occurring. This critical flow assessment is confirmed by the static pressure ratios and the Henry-Fauske/homogeneous equilibrium model critical flow calculation (see Table 4-4).

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### Test A003331

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-13. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-13. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1 and 2 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the stage 1 and 2 piping sections are higher than the observed multipliers, which indicates that these piping section is not choked. This critical flow assessment is confirmed by both the static pressure ratios and by the choked mass flow ratios predicted by the Henry-Fauske/homogeneous equilibrium model (see Table 4-4).

### Test A004330

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-14. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. Experienced pressure drops in the various valves and sparger. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-14. Therefore, the parameters of interest are time average values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1 and 2 piping sections containing the orifice or valve, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the stage 1 and 2 piping sections are higher than the observed multipliers, indicating that the flow in these piping sections is not choked. This critical flow assessment is confirmed by the static pressure ratios and by the choked flow ratios predicted by the Henry-Fauske/ homogeneous equilibrium model (see Table 4-4).

### Test A006340

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-15. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-15. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 2 piping sections averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the

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tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multiplier for the upstream stage 2 piping section containing the gate valve is lower than the observed multiplier, which indicates that choking is occurring. This critical flow assessment is not confirmed by the static pressure ratios and the Henry-Fauske/homogeneous equilibrium model critical flow calculation. In addition, the critical flow model does indicate that the mass flow in the downstream full bore piping section is 0.94 of the critical mass flow (see Table 4-2).

#### **Test A042312**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-16. The flow quality, as calculated from Equation 3-1, and the measured pressure at locations in the flow path is listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-16. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for the stage 2 full bore pipe and stage 3 gate value piping sections were lower than the observed multipliers, indicating that the flow in these piping sections is choked. This critical flow assessment is not confirmed by the static pressure ratios and by the Henry-Fauske/homogeneous equilibrium model (see Table 4-4).

#### **Test A043331**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-17. The flow quality, as calculated from Equation 3-1, and measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-17. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1 and 2 piping sections averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the stage 1 and 2 piping sections were higher than the observed multipliers, indicating that the flow in these piping sections is not choked. This critical flow assessment is confirmed by the static pressure ratios and by the Henry-Fauske/homogeneous equilibrium model (see Table 4-4).

#### **Test A044310**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-18. The flow quality, as calculated from Equation 3-1, and measured pressure at locations in

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the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 12-22 seconds, as shown in Figure 4-18. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections, averaged over the 12 to 22 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the stage 1 and 2 piping sections and for the downstream portion of stage 3 were equal to or higher than the observed multipliers, indicating that the flow in these piping sections is not choked. The calculated multiplier for the portion of stage 3 containing the gate valve was lower than observed. However, non-choked flow in all stages is consistently indicated by the static pressure ratios and by the Henry-Fauske/homogeneous equilibrium model (see Table 4-4).

#### **Test A046340**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-19. The flow quality, as calculated from Equation 3-1, and measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state is achieved was from about 12 to 22 seconds, as shown in Figure 4-19. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 2 piping sections, averaged over the 12 to 22 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multiplier for the stage 2 piping section containing the gate valve is lower than the observed multiplier, which indicates that choking is occurring. This critical flow assessment is not confirmed by the static pressure ratio and the Henry-Fauske/homogeneous equilibrium model critical flow calculation (see Table 4-4 which do not indicate choked flow.). Note that pressure transducer PE-12W was not operational for this test run so that an observed multiplier could not be calculated for the downstream piping section. However, the single observed multiplier and the calculated multipliers are similar to those obtained in test run A006340 discussed above.

### **4.3 300-Series Hot Quench Tank Tests**

The 300-series hot quench tank tests were performed with only one valve in each ADS path. The orifice was replaced with a full bore spool piece to simulate the ADS valves with minimum resistance. The quench tank was maintained at a temperature of about 212°F for all tests. There were five matrix tests performed in this series.

#### **Test A047322**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-20. The flow quality, as calculated from Equation 3-1, and measured pressures at locations

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in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-20. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for the stage 2 and 3 piping sections containing gate valves were lower than the observed multipliers, indicating that the flow in these piping sections was choked. This critical flow assessment is not confirmed by the static pressure ratios on the Henry-Fauske/homogeneous equilibrium model critical flow comparison (see Table 4-4).

#### **Test A048321**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-21. The flow quality, as calculated from Equation 3-1, and measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 15 to 25 seconds, as shown in Figure 4-21. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections, averaged over the 15 to 25 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the piping sections, with the exception of the stage 3 gate valve, were higher than the observed multipliers, indicating that the flow in these piping sections is not choked. Both the static pressure ratios and the Henry-Fauske/homogeneous equilibrium model critical flow ratios indicate no choking (see Table 4-4).

#### **Test A049351**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-22. The flow quality, as calculated from Equation 3-1, and measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 12 to 22 seconds, as shown in Figure 4-22. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1 and 2 piping sections, averaged over the 12 to 22 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for all the piping sections were higher than the observed multipliers, indicating that the flow in these piping sections is not choked. This critical flow assessment is confirmed by the static pressure ratios and the Henry-Fauske/homogeneous equilibrium model (see Table 4-4). Note that pressure transducer PE-12W was

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not operational for this test run and the Martinelli-Nelson two-phase flow  $\Delta P$  multiplier was not determined.

#### **Test A050350**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-23. The flow quality, as calculated from Equation 3-1, and measured pressure at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 12 to 22 seconds, as shown in Figure 4-23. Therefore, the parameters of interest are time averaged values calculated at this time.

The observed and calculated two-phase multipliers for the stage 1 and 2 piping sections, averaged over the 12 to 22 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. All calculated multipliers for the piping sections were higher than the observed multipliers, indicating that the flow in these piping sections is not choked. This critical flow assessment is confirmed by the static pressure ratios and the Henry-Fauske/homogeneous equilibrium model except that the stage 2 downstream pipe static pressure ratio is 0.59. However, this ratio may not be accurate since PE-12W was not operational, and therefore was based on PE-16W (see Table 4-4).

#### **Test A051320**

The mixture mass flow, as calculated from the pressurizer level measurement (LT1B), is shown in Figure 4-24. The flow quality, as calculated from Equation 3-1, and measured pressures at locations in the flow path are listed in Tables 4-1 and 4-2. The time period when a quasi-steady state was achieved was from about 12 to 22 seconds, as shown in Figure 4-24. Therefore, the parameters of interest are time averaged values calculated during this time period.

The observed and calculated two-phase multipliers for the stage 1, 2, and 3 piping sections, averaged over the 12 to 22 second time period, are shown in Table 4-3 with the other two-phase multipliers from all the tests. These calculated multipliers were determined based on the Martinelli-Nelson correlation (Reference 2) assuming that the flow is not choked. The calculated multipliers for the Stage 1 globe valve and Stage 3 gate valve piping sections, were lower than the observed multipliers; indicating that the flow in these piping sections is choked. Non-critical flow through all piping sections is indicated both by the static pressure ratios and the Henry-Fauske/ homogeneous equilibrium model (see Table 4-4).

#### **4.4 Test Evaluation**

The test analysis results are interpreted and evaluated to confirm that they are consistent with engineering principles and are compared with the Martinelli-Nelson two-phase flow-multipliers.

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#### 4.4.1 Flow Quality

The flow qualities for the 200 and 300 series two-phase flow test were calculated just upstream of each ADS valve package component using equation 3-1, i.e.;

$$x \text{ (fraction)} = \frac{H_{L-TK} - H_L}{H_{fg}}$$

where  $H_{L-TK}$ ,  $H_L$  and  $H_{fg}$  were based on the static measured pressure. No correction for the kinetic energy of the fluid was made in order to make comparisons with the methodology used in the NOTRUMP safety analysis model. This section evaluates the impact of kinetic energy on the fluid conditions and other parameters evaluated in this report.

The energy equation which considers kinetic energy is

$$H_{L-TK} + \frac{U_{L-TK}^2}{2J_c} = H_i + \frac{U_i^2}{2J_c} \quad (4-1)$$

where  $U_{L-TK}$  = the fluid velocity in the supply tank discharge piping  
 $U_i$  = the velocity of the two-phase fluid at location  $i$   
 $H_i$  = the total enthalpy of the two-phase fluid at location  $i$   
 $J_c$  = Joule's coefficient X  $g_c$

assuming that  $U_{L-TK} \ll U_i$ , Equation 4-1 can be simplified to

$$H_{L-TK} = H_i + \frac{U_i^2}{2J_c} \quad (4-2)$$

Since,

$$H_i = H_L(P_i) + x_i H_{fg}(P_i) \quad (4-3)$$

and

$$U_i = \frac{Wv_i}{A_i} = \frac{W}{A_i} (v_L(P_i) + x_i v_{fg}(P_i)) \quad (4-4)$$

substitution into Equation 4-2, results in the following for any location i

$$H_{L-TK} = H_L + xH_{fg} + \frac{W^2(v_L + xv_{fg})^2}{2A^2J_c} \quad (4-5)$$

and

$$x^2 - \frac{x(2Cv_L v_{fg} + H_{fg})}{Cv_{fg}^2} + \frac{Cv_L^2 + H_L - H_{L-TK}}{Cv_{fg}^2} = 0 \quad (4-6)$$

where  $C = W^2/2J_cA^2$

This quadratic equation was solved for the quality  $x$  for six tests to assess the impact of the fluid kinetic energy and are compared to the qualities determined using Equation 3-1 in Table 4-5.

The quality change impacts the results of this analysis in the following manner:

- The calculated effective flow area of the Stage 1 globe valve is reduced by 5%, from 4.7 in<sup>2</sup> to 4.5 in<sup>2</sup>.
- The effective flow areas of the Stage 2 and 3 orifices that simulate globe valves are not significantly affected.
- The mass flow ratios presented in Table 3-4 of test flow rate/(critical flow X area) change slightly, for example, Test A027212 mass flow ratio for the downstream globe valve increase by ~4%.
- The Martinelli-Nelson 2 phase flow  $\Delta P$  multipliers change slightly, for example:
  - Test A027212 M-N multipliers decrease from 1.69 and 1.97, for the upstream and downstream Stage 1 piping sections; to 1.39 and 1.59, respectively.
  - Test A033241 M-N multipliers for the Stage 1 globe valve and Stage 2 and 3 orifice piping sections decrease from 32.03, 31.83, and 32.30; to 28.82, 27.85, and 27.93, respectively.

In summary, the effect of kinetic energy on the factors evaluated in this report are sufficiently small, so as to not invalidate the observations and conclusions. It is noted that the NOTRUMP analysis methodology, which does not specifically consider the effect of fluid kinetic energy, properly determines mass flow at choked conditions with the effective flow areas as determined in this report.

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#### 4.4.2 Two-Phase Multipliers

A summary of the theoretical calculated and observed two-phase flow  $\Delta P$  multipliers for the ADS valve/piping package piping sections for each stage, is provided in Table 4-3 for all the matrix tests. The calculated two-phase multipliers were determined using the Martinelli-Nelson correlation (Reference 2), illustrated in Figure 4-25. Figures 4-26, 4-27, and 4-28 show the calculated theoretical multiplier divided by the observed multiplier for each piping section in ADS stages 1, 2, and 3; respectively. These theoretical/observed multiplier ratios are plotted versus the fluid quality at the upstream end of each piping section.

These figures show that for the most part, the calculated/observed multiplier ratios range from 1 to 2.5 and are consistent over the entire range of fluid quality experienced in the test. Higher calculated/observed multiplier ratios are observed to occur principally in piping sections that have a small pressure drop, and therefore don't contribute significantly to the overall pressure drop.

Figure 4-29 shows the  $\Delta P$  weighted average theoretical/observed multiplier ratios, where each ratio includes both sections of pipe in each stage (the low pressure drop upstream piping section containing no orifice, a gate valve, or a low- $\Delta P$  orifice; and the high pressure drop downstream piping section containing a globe valve or a high- $\Delta P$  orifice). With the exception of one stage 1 multiplier ratio for test run A042312, all the theoretical/observed multiplier ratios for an entire ADS stage range from 1.0 to 2.0.

- 1 NOTRUMP and non-choked, two-phase WCOBRA/TRAC utilize Martinelli-Nelson two-phase flow pressure drop multipliers to determine the ADS flow in the AP600 S&SR LOCA analyses. These test results confirm that the codes will calculate two-phase flows through the AP600 ADS valve/piping
- 1 package that are less than or equal to the actual flows obtained in the 200- and 300-series ADS Phase
- 1 B1 test, over the entire fluid quality range achieved.

#### 4.4.3 Critical Flow Assessment

The critical flow assessment results obtained for the ADS valve/piping package piping sections for each of the three ADS stages, using the three methods outlined in Section 3.4, are in most cases in agreement. The only consistent contradiction between the three methods occurs when only Stage 1 was open in the 200-series tests: namely tests A037210, A026211, A027212.

- 1 In the Stage 1 only tests, the observed flow multipliers for the piping section containing the globe valve were two times greater than the calculated Martinelli-Nelson flow multipliers. In addition, the ratio of downstream pressure over upstream pressure was  $\sim 0.4$ . Both these facts are strong indications
- 1 of choked flow. However, the mass flow ratio (observed test flow rate/(critical mass flux X area) through the globe valve was just less than 0.9 in all three tests. It is noted that all three of these tests had very low quality fluid.

In addition, two of the three 200 Series tests performed with all three stages open indicated disagreement between the mass flow ratio and the other two choked flow indicators. The test A033241 mass flow ratios for the downstream piping section in each stage were just 0.9; while the  $\Delta P$

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ratios were ~0.8 and the calculated flow multipliers were 1.25 to 2 times greater than observed. In test A034242, performed at a similar fluid quality and higher mass flow rate, the mass flow ratios were ~1.0 while the  $\Delta P$  ratios and flow multipliers do not indicate choking. As in the case of the Stage 1 only tests discussed above, these tests are at low fluid quality. The third 200 Series test with all three stages open, A035240, was conducted at higher fluid quality and higher mass flow rate. In this test, all three indicators; mass flow ratio,  $\Delta P$  ratio, and the flow multipliers consistently indicate no choking.

#### 4.4.4 Comparison of ADS Test Flow Rates and Fluid Qualities to NOTRUMP Results

Figures 4-30, 4-31, 4-32, and 4-33 illustrate the total mass flow rate and fluid quality of the ADS 1, 2, and 3 discharge calculated by the NOTRUMP analysis for the following postulated events:

- Inadvertent ADS actuation at full pressure
- 0.5-in. CL Break
- 2-in. CL Break
- DEDVI Break

Table 4-6 summarizes the range of these flow rates and fluid qualities for each ADS flow path combination (i.e.; Stage 1 only operating, Stages 1 and 2 operating, and Stages 1, 2 and 3 operating). Also the corresponding range of flow and quality achieved in the ADS Phase B1 testing is compared to the NOTRUMP results. Note that the NOTRUMP mass flow rates shown in the above figures represent the flow through both the two ADS flowpaths in the AP600, and therefore are divided by two for comparison with the test flow rates. Also, the NOTRUMP results show the fluid quality that occurs just upstream of the ADS valve/piping package, and therefore the ADS test fluid qualities were determined for Location 6 (PT6W) shown in Figure 3-1.

Table 4-6, clearly shows that the ADS Phase B1 tests flow rate and fluid quality range corresponds well with the NOTRUMP ranges for all the ADS flowpath combinations.

**TABLE 4-1  
FLUID QUALITY FRACTION THROUGH FACILITY\***

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A037210								
A026211								
A027212								
A028221								
A029231								
A030220								
A031230								
A036250								

a,b,c

\*All values are averaged over quasi-steady state period.

**TABLE 4-1 (cont)  
FLUID QUALITY FRACTION THROUGH FACILITY\***

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A033241								
A034242								
A035240								
A002311								
A003331								
A004330								

a,b,c

\*All values are averaged over quasi-steady state values.

**TABLE 4-1 (cont)  
FLUID QUALITY FRACTION THROUGH FACILITY\***

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A042312								
A043331								
A044310								
A046340								
A047322								
A048321								
A049351								

a,b,c

\*All values are averaged over quasi-steady state period.  
\*\*PE12W was not operational.

**TABLE 4-1 (cont)  
FLUID QUALITY FRACTION THROUGH FACILITY\***

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A050350	[							
A051320	[							
A006340	[							

a,b,c

\* All values averaged over quasi-steady state period.  
 \*\* PE12W was not operational.

**TABLE 4-2  
PRESSURE (PSIA) VARIATION THROUGH FACILITY\***

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A037210	[							
A026211								
A027212								
A028221								
A029231								
A030220								
A031230								
A036250								
A033241								

a,b,c

\*All values are averaged over quasi-steady state period.

**TABLE 4-2 (cont)  
PRESSURE (PSIA) VARIATION THROUGH FACILITY\***

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A034242								
A035240								
A002311								
A003331								
A004330								
A042312								

a,b,c

\*All valves are averaged over quasi-steady state period.

**TABLE 4-2 (cont)  
PRESSURE (PSIA) VARIATION THROUGH FACILITY\***

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A043331								
A044310								
A046340								
A047322								
A048321								
A049351								
A050350								

a,b,c

\*All values are averaged over quasi-steady state period.

\*\* PE12W was not operational.

TABLE 4-2 (cont)  
PRESSURE (PSIA) VARIATION THROUGH FACILITY\*

Test No.	Total Flow (lb/S)	Upstream of ADS Package Location 6	Upstream/Downstream of ADS Valves			Downstream of ADS Package Location 16	Sparger Body	Sparger Arms
			Location 7/10/13	Location 8/11/14	Location 9/12/15			
A051320								
A006340								

a,b,c

\*All values are averaged over quasi-steady state period.

\*\* PE12W was not operational.

**TABLE 4-3  
OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS (Flow Splits used Assume Non-Choked Flow)**

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier		Theoretical Flow Multiplier	
						Individ. Section	Avg for Stage	Individ. Section	Avg for Stage
A037210									
A026211									
A027212									
A028221									

**TABLE 4-3 (cont.)  
OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS**

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier	Theoretical Flow Multiplier	Individ. Section	Avg. for Stage	Individ. Section	Avg. for Stage
A029231											
A030220											
A031230											
A036250											

TABLE 4-3 (cont.)  
 OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
 FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier		Theoretical Flow Multiplier	
						Individ. Section	Avg. for Stage	Individ. Section	Avg. for Stage
A033241									
A034242									

TABLE 4-3 (cont.)  
OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier		Theoretical Flow Multiplier	
						Individ. Section	Avg. for Stage	Individ. Section	Avg. for Stage
A035240									
A002311									
A003331									

**TABLE 4-3 (cont.)  
OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS**

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier		Theoretical Flow Multiplier	
						Individ. Section	Avg. for Stage	Individ. Section	Avg. for Stage
A004330									
A042312									
A043331									

**TABLE 4-3 (cont.)  
OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS**

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier		Theoretical Flow Multiplier	
						Individ. Section	Avg. for Stage	Individ. Section	Avg. for Stage
A044310									
A046340									
A047322									

**TABLE 4-3 (cont.)  
OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS**

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier		Theoretical Flow Multiplier	
						Individ. Section	Avg. for Stage	Individ. Section	Avg. for Stage
A048321									
A049351									
A050350									

**TABLE 4-3 (cont.)  
OBSERVED VS. CALCULATED TWO-PHASE FLOW MULTIPLIERS  
FOR THE ADS PIPING/VALVE PACKAGE COMPONENTS**

Test No.	Total ADS Flow (lbs/sec)	Open ADS Paths	Piping Section/Component	Upstream Pressure (psia)	Upstream Quality (Fraction)	Observed Flow Multiplier		Theoretical Flow Multiplier	
						Individ. Section	Avg. for Stage	Individ. Section	Avg. for Stage
A051320									
A006340									

TABLE 4  
CRITICAL FLOW ASSESSMENT FOR

Test Number	Stage 1 Orifice/Pipe				Stage 1 Valve - VAD1				Stage 2 Valve - VAD2			
	Press. Ratio	Choke (press. ratio <0.6)	Mass Flow Ratio	Choke (mass flow ratio >0.9)	Press. Ratio	Choke (press. ratio <0.6)	Mass Flow Ratio	Choke (mass flow ratio >0.9)	Press. Ratio	Choke (press. ratio <0.6)	Mass Flow Ratio	Choke (mass flow ratio >0.9)
A037210												
A026211												
A027212												
A030220												
A031230												
A029231												
A035240												
A033241												
A034242												
A036250												
A044310												
A002311												
A042312												
A004330												
A003331												
A043331												
A006340												
A046340												
A051320												
A048321												
A047322												
A050350												
A049351												

\* PE12W failed in these tests; values estimated using PE16W data as downstream pressure.



**TABLE 4-5  
EFFECT OF FLUID VELOCITIES AT ADS VALVE PACKAGE  
COMPONENTS ON THE FLOW QUALITY FOR SELECTED TESTS\***

Test No.	Supply Tank Pressure (psia)	Stages Open	i Location See Fig. 3-1	Eq. 3-1 Quality	Eq. 4-6 Quality (with KE Considered)	% Difference in Calc. Quality
A027212						
A028221						
A033241						
A036250						
A051320						
A044310						

a,b,c

\*All values are time averaged over quasi-steady state time period.

**TABLE 4-6  
COMPARISON OF ADS TEST FLOW RATE AND FLUID QUALITY TO NOTRUMP ANALYSIS RESULTS**

ADS Stages Open	NO-TRUMP Flow and Quality Range		ADS Test Flow and Quality Range		
	Postulated Event Description	(lbs/s)	Quality	(lbs/s)	Quality
Stage 1	Inadvertent ADS Actuation 0.5-in. CL Break 2.0-in. CL Break DVI DEG Break				
Stage 1 & 2	Inadvertent ADS Actuation 0.5-in. CL Break 2.0-in. CL Break DVI DEG Break				
Stage 1, 2 & 3	Inadvertent ADS Actuation 0.5-in. CL Break 2.0-in. CL Break DVI DEG Break				

a,b,c

\*Phase B 300 Series Test Runs

**Figure 4-1 Test A026211  
Total Mass Flow Rate**

**Figure 4-2 Test A027212  
Total Mass Flow Rate**

**Figure 4-3 Test A028221  
Total Mass Flow Rate**

**Figure 4-4 Test A029231  
Total Mass Flow Rate**

a.b.c

**Figure 4-5 Test A030220  
Total Mass Flow Rate**

**Figure 4-6 Test A031230  
Total Mass Flow Rate**

**Figure 4-7 Test A033241  
Total Mass Flow Rate**

a.b.c

Figure 4-8 Test A034242  
Total Mass Flow Rate

a.b.c

**Figure 4-9 Test A035240  
Total Mass Flow Rate**

**Figure 4-10 Test A036250  
Total Mass Flow Rate**

a.b.c

**Figure 4-11 Test A037210  
Total Mass Flow Rate**

a.b.c

Figure 4-12 Test A002311  
Total Mass Flow Rate

a.b.c

**Figure 4-13 Test A003331  
Total Mass Flow Rate**

a.b.c

**Figure 4-14 Test A004330  
Total Mass Flow Rate**

a.b.c

**Figure 4-15 Test A006340**  
**Total Mass Flow Rate**

a.b.c

**Figure 4-16 Test A042312  
Total Mass Flow Rate**

a.b.c

**Figure 4-17 Test A043331**  
**Total Mass Flow Rate**

a.b.c

**Figure 4-18 Test A044310  
Total Mass Flow Rate**

a.b.c

**Figure 4-19 Test A046340  
Total Mass Flow Rate**

a.b.c

**Figure 4-20 Test A047322**  
**Total Mass Flow Rate**

a.b.c

**Figure 4-21 Test A048321  
Total Mass Flow Rate**

a.b.c

**Figure 4-22 Test A049351  
Total Mass Flow Rate**

a.b.c

**Figure 4-23 Test A050350  
Total Mass Flow Rate**

**Figure 4-24 Test A051320  
Total Mass Flow Rate**

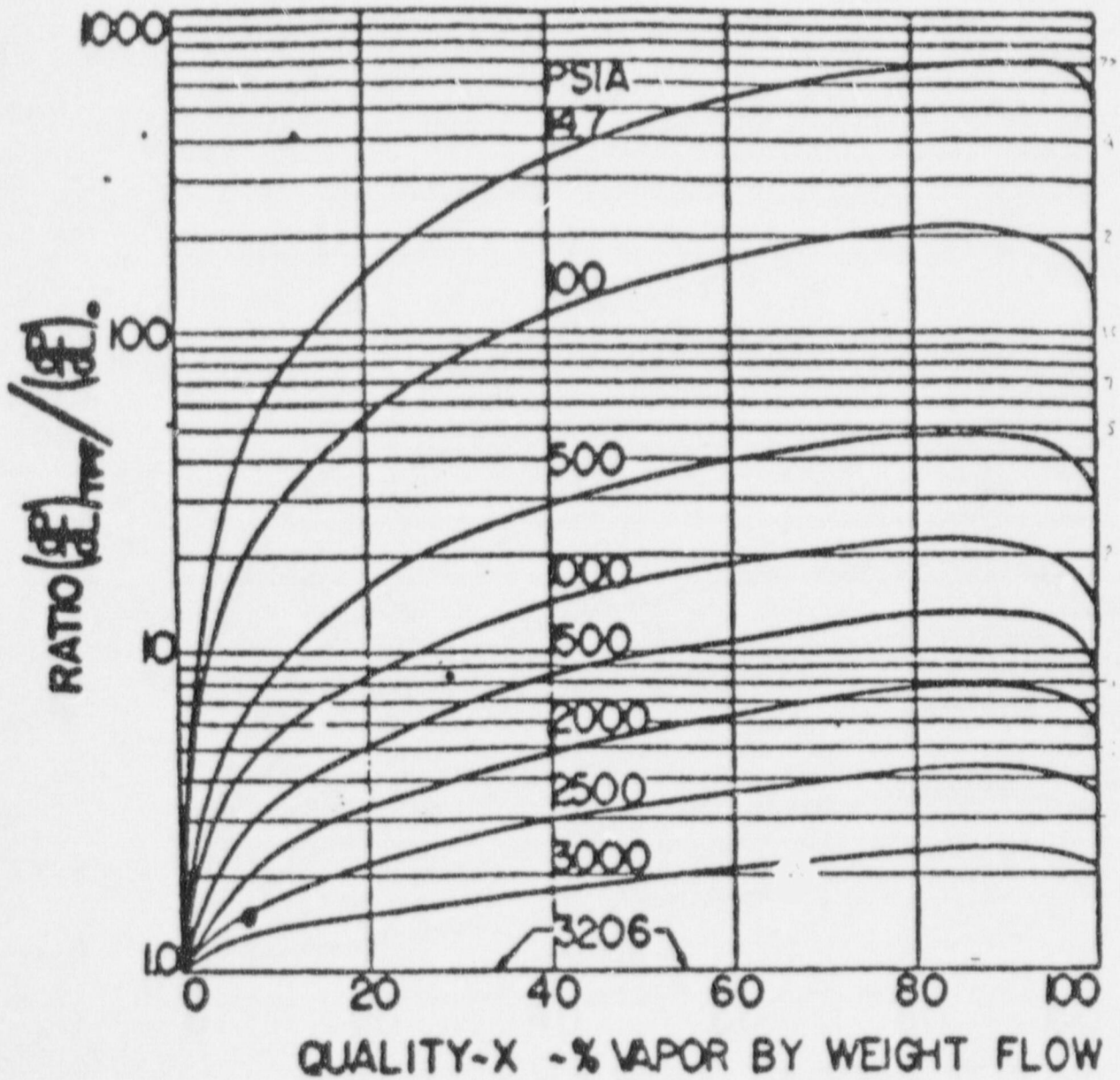


Figure 4-25 The Martinelli-Nelson Correlation Ratio of Local Two-Phase Pressure Gradient to Pressure Gradient for 100 Percent Liquid Flow as a Function of Quality and Pressure

**Figure 4-26 ADS Stage 1, Theoretical/Observed  
2-Phase Flow Pressure Drop Multipliers (for Each of Two Piping Sections)**

**Figure 4-27 ADS Stage 2, Theoretical/Observed  
2-Phase Flow Pressure Drop Multipliers (for Each of Two Piping Sections)**

**Figure 4-28 ADS Stage 3, Theoretical/Observed  
2-Phase Flow Pressure Drop Multipliers (for Each of Two Piping Sections)**

**Figure 4-29 All ADS Stages, Theoretical/Observed 2-Phase Flow Pressure Drop Multipliers (Weighted Average Multiplier for both Piping Sections in Each Stage)**

**Figure 4-30**  
**NOTRUMP Analysis ADS 1, 2, 3 Total Mass Flow and Fluid Quality**  
**for AP600 Inadvertent ADS Actuation**

**Figure 4-31 NOTRUMP Analysis ADS 1, 2, 3 Total Mass  
Flow and Fluid Quality for AP600 0.5-inch CL Break**

**Figure 4-32 NOTRUMP Analysis ADS 1, 2, 3 Total Mass  
Flow and Fluid Quality for AP600 2-inch CL Break**

**Figure 4-33 NOTRUMP Analysis ADS 1, 2, 3 Total Mass Flow and Fluid Quality for AP600 DEDVI Break**

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## 5.0 CONCLUSIONS

This report provides the analysis and methodology to calculate the pressure loss coefficients, effective flow areas, choked and non-choked flow splits, flow quality, and two-phase flow multipliers for locations throughout the facility for the ADS Phase B1 matrix tests.

The pressure loss coefficients for the ADS package valves, orifices, and piping were calculated using the four 100-series single-phase steam flow tests. These loss coefficients were found to be consistent when compared to the loss coefficients obtained from tests performed with cold water (Reference 1). The loss coefficients obtained when all three-stages were open resulted in an overall resistance for the ADS valve and pipe package that was ~35% higher than the overall loss calculated using Crane Technical Paper 410 methodology. This underprediction has been considered in the AP600 safety analysis. In addition, these pressure loss coefficients were used to estimate the flow split across the ADS package to calculate two-phase flow  $\Delta P$  multipliers that occurred in the two-phase flow tests (200-series and 300-series).

The 100-series test data were also used to determine the effective flow area of the stage 1 globe valve, and to confirm the flow area of the orifices used to simulate globe valves in stages 2 and 3. These effective flow areas were used to establish the flow splits through the ADS stages to compare the critical mass flow through components with the measured test mass flow rate.

The two-phase flow multipliers for the ADS valve/piping package piping sections were calculated using the Martinelli-Nelson correlation, and found to range from 1 to ~2 times greater than the observed flow multipliers obtained using the non-choked flow splits derived from the 100-series tests loss coefficients. This agreement was found for all ADS flow path combinations and was consistent over the entire range of pressures, flow rates, and fluid qualities tested. Since the Martinelli-Nelson correlation is used in NOTRUMP and WCOBRA/TRAC, these test results confirm that these codes will calculate conservatively low non-choked, two-phase ADS flow rates.

Critical or choked flow in the ADS package was evaluated in several different manners which included downstream versus upstream pressure ratios, comparison of observed versus calculated two-phase flow delta-P multipliers, and comparison of the observed flow versus critical flow calculated with Henry-Fauske/homogeneous equilibrium critical flow model. The assessment showed consistent results as to whether critical flow occurred in the ADS.

The ADS tests demonstrated consistent ADS behavior, pressure drops, quality, flows, and two-phase flow multipliers; identified as important in the PIRT. The data and associated analysis are used to validate the ADS flow and pressure drop models used in the NOTRUMP and WCOBRA/TRAC codes.

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## 6.0 REFERENCES

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