BYRON/BRAIDWOOD UNIT 1 RHR/SI PIPING

WATER HAMMER ACOUSTIC ANALYSIS

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Illinois Department of Nuclear Safety

ABSTRACT

The water hammer acoustic analysis described in this report was conducted to determine whether an unanalyzed safety significant condition could exist by implementation of the requested license amendment. The analysis was conducted using thermal hydraulic and hydrodynamic analysis codes available at the Illinois Department of Nuclear Safety (IDNS). A peer review of the early analysis was conducted by the Idaho National Engineering Laboratory (INEL) and their work is reported in Reference (9). The analysis shows that over a wide range of non-condensible gas volumes pressure spikes are present which exceed normal operating system pressures.

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1.0 INTRODUCTION

Commonwealth Edison Company (CECO) has submitted to the U. S. Nuclear Regulatory Commission (USNRC) an amendment application to the Facility Operating Licenses for the Byron and Braidwood Nuclear Stations. The proposed amendment requests a change to Technical Specification 4.5.2 modifying the existing surveillance requirements for venting of ECCS discharge piping (Reference 1). The Illinois Department of Nuclear Safety (IDNS) was notified of this license amendment application by receipt of Reference 1 in accordance with 10 CFR 50.91.

A number of water hammer conditions have been reported by the USNRC. These are documented in References 3 through 7. The cited references evaluate water hammer phenomena and provide mitigating fixes and actions including the installation of high point vent valves, installation of instrumentation to detect entrapment of non-condensibles in the piping, and venting surveillances. Water hammer events in RHR systems are attributed to condensation of steam bubbles in the RHR/SI system following flow startup and inadvertantly voided pump discharge lines. One water hammer event resulted from an air bubble inadvertantly collected and trapped during a maintenance operation (Reference 5). Other events occurred when a RHR flow entered a voided line, which may have been caused by an incorrect valve lineup prior to pump start, inadequate design and/or filling and venting procedures, and poor testing procedures (Reference 3).

The IDNS began a series of studies to evaluate the effects of the proposed license amendment on the safe operation of the Byron and Braidwood plants. The underlying concern is the formation of high acoustic pressures resulting from compression of potential entrapped air in the high points of the piping system. The studies conducted utilized the hydrodynamic computer code AWHAM (Reference 11) and the thermalhydraulic code RELAP 5. The results from AWHAM were compared with the results from RELAP 5 analyses. The comparisons show good agreement. A peer review of the analyses was performed by the Idaho National Engineering Laboratory using the code WHAM-6B.

The pipe model previously discussed with NRC (Reference 15) for the water hammer analysis included only that portion of the Safety Injection (SI) piping injecting into the Loop 1 Cold Leg. Due to the potential impact of the IDNS analysis on the approval of the license amendment, and the results of the 5/9/91 NRC/CECo meeting, a refined model was developed which included the SI piping injecting into both Loop 1 and Loop 4 cold legs, and less conservative, more realistic Darcy-Weisbach friction coefficents were used. Additionally, the RHR pump minimum recirculation flow was modeled.

2.0 PLANT MODEL DESCRIPTION

The piping system analyzed for potential water hammer condition consists of that section of the Residual Heat Removal (RHR) system piping which is connected to the Safety Injection (SI) piping for cold leg injection into the Reactor Coolant System (RCS). The RHR/SI water source is from either the Refueling Water Storage Tank (RWST) or the RCS hot leg. Figure 1 is a schematic representation of the analyzed piping system (Reference 13). Figure 2 shows the horizontal and vertical positions of the pipe run (Reference 1).

The Advanced Water Hammer Analysis Model (AWHAM) was utilized for the analysis. AWHAM is a water hammer code that simulates a variety of transient problems in liquid systems using the method of characteristics (Reference 11).

2.1 NORMAL PLANT TRANSIENT MODEL

Prior to analyzing the abnormal plant transient conditions with air pockets, a model of the piping system was developed to verify AWHAM's capability to accurately predict the steady state flows and pressures under normal plant transient conditions (e.g. pump start-up, valve opening). This analysis was benchmarked to the FSAR process flow diagram (Reference 8). The AWHAM model nodalization is presented in Figure 3.

The RHR pump was modeled using the radial pump characteristics found in AWHAM. The rated pump head and flow was extracted from the process flow diagram provided in the FSAR (Reference 8) and the licensee supplied pump data (Reference 14).

The model consists of twenty (20) pipe segments and twenty-one (21) nodes. Nodes are generally represented by junctions (JUNCT) where two or more pipes meet. The butterfly valve RH0606 is represented by MVALVE at node 7. The minimum flow recirculation valve RHR0610 is represented by a gate valve (MVALVE) at node 5. The check valves SI8948A and SI8948D were represented as gate valves (RVALVE) at nodes 16 and 21. AWHAM does not directly model check valves. Other valves in the piping system were not explicitly modeled. A discussion on the assumptions is presented in section 3.0.

A five second baseline run verified AWHAM reproduces the steady state process flow data provided in the FSAR (Reference 8). The results from the steady state analysis are reported in Section 5.1.

2.2 ABNORMAL PLANT TRANSIENT MODEL

The normal plant transient model described in the previous section was converted to abnormal plant transient model by changing nodes 14 and 15 to VACBR. This allows examination of air pockets present in pipe segments 13 and 14 which are located at the high point of the piping system. The total volumes of pipe segments 13 and 14 are 21.67 ft^3 and 6.05 ft^3 respectively. The range of air pocket sizes analyzed were from 0 ft^3 to 26 ft^3. Transient results are discussed in Section 5.2; air pocket sensitivity, Section 4.0.

3.0 ANALYSIS ASSUMPTIONS AND INITIAL CONDITIONS

The FSAR process flow diagram (Reference 8) was used to establish the initial pressures and flows in the piping system. The initial conditions used in the normal plant transient analysis are listed in Table 1. The abnormal plant transient analysis with air pockets utilized the initial conditions listed in Table 1 with differences specific to modeling the air pockets. These differences are listed in Table 2.

The following assumptions and approximations were made in the development of the analytical model:

1. The minimum recirculation flow through valve RH0610 is diverted to a constant reservoir represented by RRES. This flow is normally recirculated to the pump suction. Since AWHAM cannot have a JUNCT as a left boundary condition, a simplification was made which diverts the flow to a right reservoir (RRES).

2. Due to modeling limitations of AWHAM, check valves SI8948A and SI8948D are modeled as gate valves. In the analyzed case, this valve functions to prohibit flow from the RCS cold leg into the Safety Injection (SI) piping.

   To simulate check valve characteristics, several trial runs were made to determine the time at which the upstream pressure exceeds the downstream (RCS cold leg) pressure by 0.5 psi. This differential pressure is the assumed minimum required to open the check valve. The opening of the gate valve was set to coincide with this time step. Table 1 & 2 list the opening times. 0.1 seconds was assumed for check valve stroke time. It is further assumed that once the check valve opens it remains open during the rest of the transient.

3. Valves which do not open or close during the transient are not modeled and are assumed to be in the normal operating position.

4. The transient initiator is butterfly valve RH0606 failing open in one second.

5. AWHAM does not have the capability to model relief valves. Therefore, the actual peak calculated pressure would be somewhat lower.

6. High point vent valves are not modeled and are assumed closed at all times.

7. Drain valves are not modeled and assumed closed.

8. Valve opening and closing characteristics are modeled by AWHAM.

4.0 PEAK PRESSURE SENSITIVITY STUDIES

The study examined the sensitivity of the peak pressures to the volume of entrapped air. Air volumes in pipes 13 and 14 were varied from the case of no air entrapment to a maximum of 26.0 ft^3. This sensitivity study confirmed the theory that when the amount of entrapped air is relatively small (approaching zero in the limit) the peak pressures are limited to those caused by the sudden opening of valves, pump startups, etc. Large air pockets tend to act as kinetic energy absorber (shock absorber) thus reducing the effects of accelerating water slugs. Between those two bounds lies a worst case volume of air which produces large pressure spikes of short duration. The sensitivity study revealed that peak pressure occurs for approximately 12 ft^3 of entrapped air. The calculated peak pressure as a function of entrapped air volume is presented in Figure 5.

5.0 RESULTS

5.1 NORMAL PLANT TRANSIENT

The normal plant transient analyzed the condition when the RHR system is entering shutdown cooling mode, RHR pump suction aligned to the RCS hot leg and no air in the system. The RHR pump is running delivering an initial 550 gpm flow through the minimum flow valve RH0610. The butterfly valve (RH 0606) opens and flow is established to the RCS cold leg. Pressure downstream is due to the static head of water (34 feet).

As the butterfly valve RH0606 opens, flow is established in pipe 7. Flow oscillations are initially expected but should damp out as the flow is fully established. The results of this transient are included in Appendix A. Figure A-1 is the speed of the RHR pump as a function of time, which was assumed to be at 100% at all times. Figure A-2 is the fluid torque exerted on the pump. As flow is established, the fluid torque rises gradually to 100%. Figure A-3 is a plot of the head in pipe 1 (the discharge of the RHR pump). As the flow is established through the RHR system, the pump discharge head stabilizes at approximately 1400 feet of water (541.8 psig). This matches the process flow data in Figure 4 (542 psig).

Figure A-3 is a plot of the fluid velocity in pipe 1. The initial value of 3.5 ft/sec corresponds to the velocity at the minimum flow of 550 gpm. Once the flow is established in the RHR system, the velocity gradually rises to the steady state value of 19.2 ft/sec which corresponds to the 3000 gpm flow from the process flow diagram (Figure 4).

Figure A-4 is the head in pipe 7 (downstream of the butterfly valve RH0606). As the butterfly valve is opened, head in pipe 7 builds up and gradually stabilizes to the steady state value of 1281 ft (495.7 psig). This agrees with the 496 psig from the process flow diagram (Figure 4).

Figure A-5 is the fluid velocity profile in pipe 7. The velocity is initially zero and as the butterfly valve is opened, flow is established in pipe 7 and the velocity gradually builds up to the steady state value of 19.2 ft/sec.

These results agree well with the process flow data obtained from the FSAR. These results also establish confidence in the use of AWHAM for fluid transient analyses in piping systems.

5.2 ABNORMAL PLANT TRANSIENT

The abnormal plant transient analyzed is for the same condition as for the normal plant transient described in the previous section. However, it is assumed that an abnormal condition in the piping system leads to the formation of air pockets at the high points of the pipe network.

The worst case air pocket of 12 ft^3 was used for this analysis. Ten (10) second runs were made for this transient to observe the steady state conditions in each pipe as the transient oscillations are eventually damped out. Pump speed was maintained at 100% throughout the transient.

The results are included in Appendix B. Figure B-1 is the plot of head in pipe 8. Figure B-2 is the plot of head in pipe 9. These two pipes approximate the location of the relief valve SI8856A.

6.0 CONCLUSIONS

The transient analyzed in the study was conservatively selected to bound worst case plant conditions in an effort to determine the potential safety significant consequences of voids in the RHR/SI piping system. The results of the study yielded three important conclusions. First, peak pressures are void volume sensitive and, for the system analyzed, correspond to the curve in Figure 5. One of those volumes (i.e., 12 ft^3) produced higher peak pressures than those analyzed by the licensee. Second, for a void volume of 12 ft^3 peak pressures exceed the set point of relief valve SI8856A. Finally, the transient analyzed credibly describes a safety significant plant condition that was not analyzed in the license amendment application.

Industry experience confirms that piping system voids and beyond design basis water hammer loads are credible events. The results of this study and industry experience combine to reaffirm the risk potential of piping system voids. Therefore, IDNS recommends that NRC review this analysis to determine whether elimination of the high point venting requirement will reduce plant safety margins.

7.0 REFERENCES

1. Letter S.C. Hunsader (CECO) to Dr. Thomas E. Murley (ONRR/USNRC) dated March 12, 1990, "Byron Station Units 1 & 2, Braidwood Station Units 1 and 2 Supplement to Application for Amendment to Facility Operating Licenses."

2. RELAP 5/MOD 3 analysis code.

3. NUREG/CR-2781, Quad-1-82-018, EGG-2203, Evaluation of Water Hammer Events In Light Water Reactor Plants, July 1982.

4. NUREG-0993, Revision 1, Regulatory Analysis for USI A-1, "Water Hammer", March 1984.

5. NUREG-0582, Water Hammer in Nuclear Power Plants, July 1979.

6. NUREG-0927, Evaluation of Water Hammer Occurrence in Nuclear Power Plants, March 1984.

7. NUREG-1990, Loss of Power and Water Hammer Event at San Onofre, Unit 1, on November 21, 1985. Published January 1986.

8. Braidwood station Updated Final Safety Analysis Report, Revision 2, Figure 5.4-4.

9. Acoustic Analysis of the Braidwood Unit 1 RHR/SI piping, INEL report dated January 30, 1991.

10. Representation of Pump Characteristics for Transient Analysis, Professor C.S. Martin, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia. (ASME Transaction)

11. Water Hammer Program AWHAM for IBM Personal Computer, C.S. Martin, Atlanta, Georgia.

12. Marks' Standard Handbook for Mechanical Engineers, Eighth Edition.

13. Plant Process and Instrumentation drawings M61-3 Rev. AL, M61-4, Rev. AS, M61-6, Rev. Y, M62, Rev. BC.

14. 28 Feb 91 CECo/IDNS meeting.

15. 09 May 91 NRC/IDNS meeting.

APPENDIX A

<u>Normal Plant Transient Curves</u>

<u>Pump start up and flow establishment</u>

List of Figures

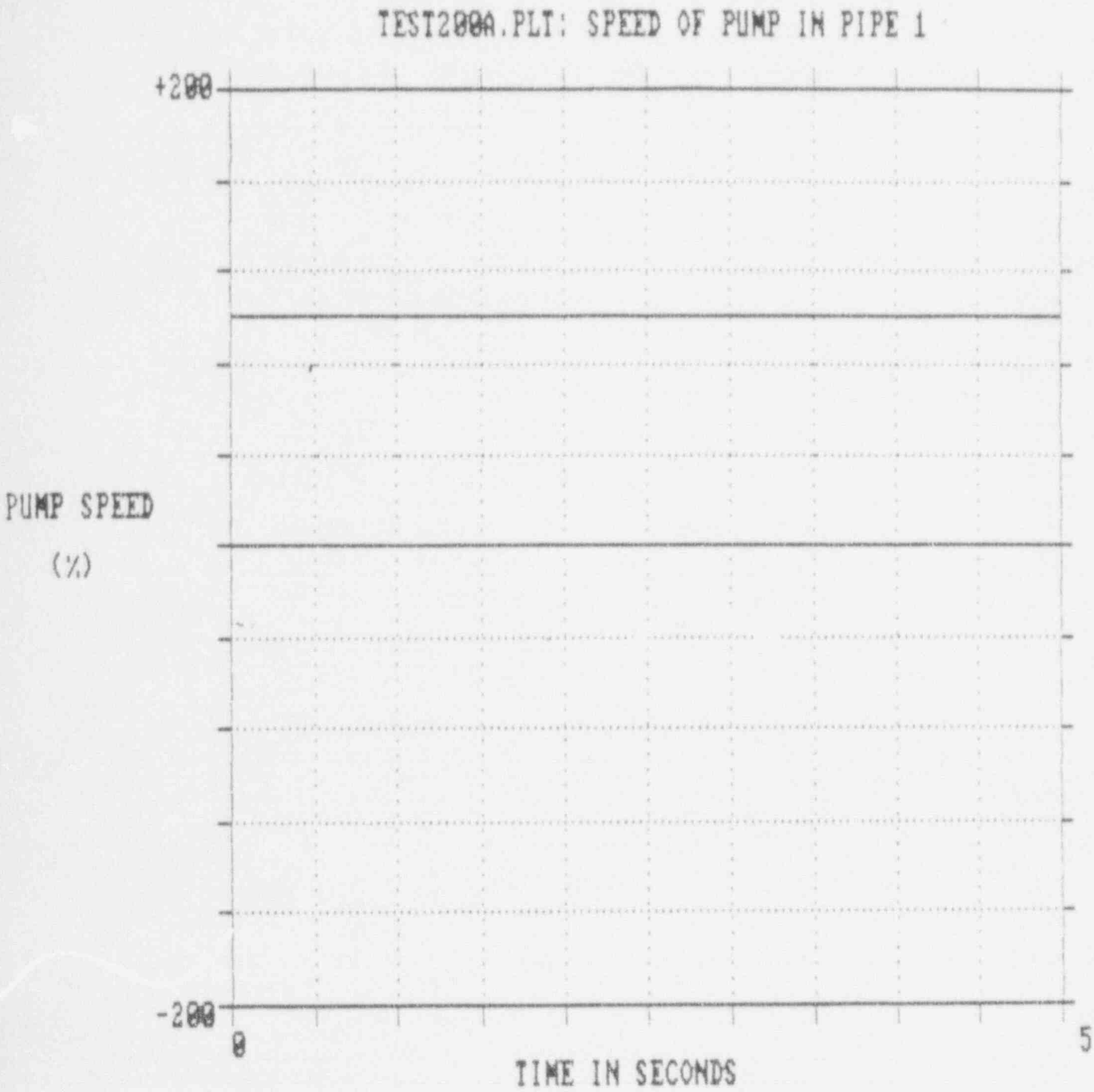

TEST200A.PLT: SPEED OF PUMP IN PIPE 1
+200
-200
PUMP SPEED
(%)
0
5
TIME IN SECONDS

Figure A-1

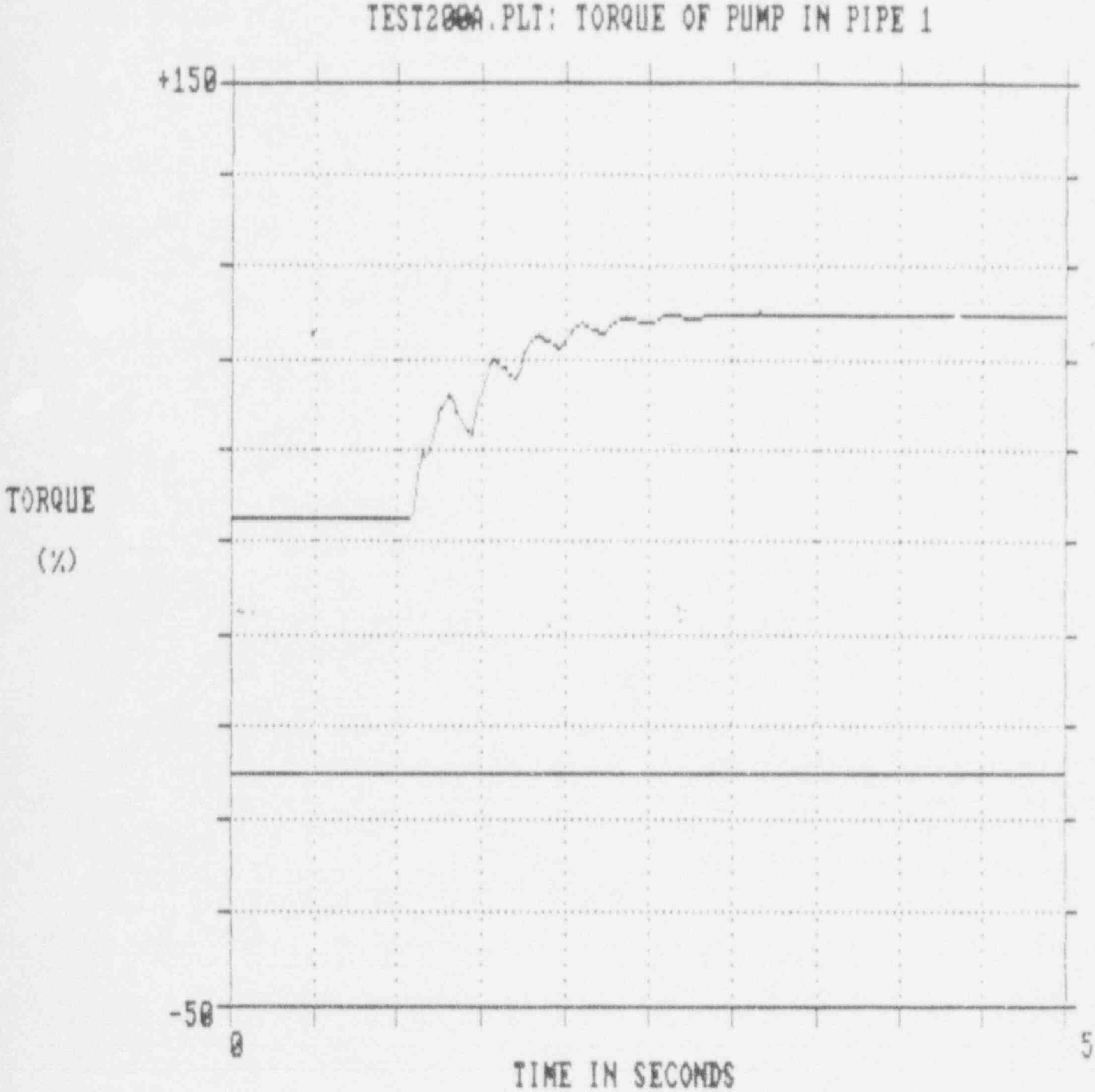

TEST200A.PLT: TORQUE OF PUMP IN PIPE 1
+150
-50
TORQUE
(%)
0
5
TIME IN SECONDS

Figure A-2

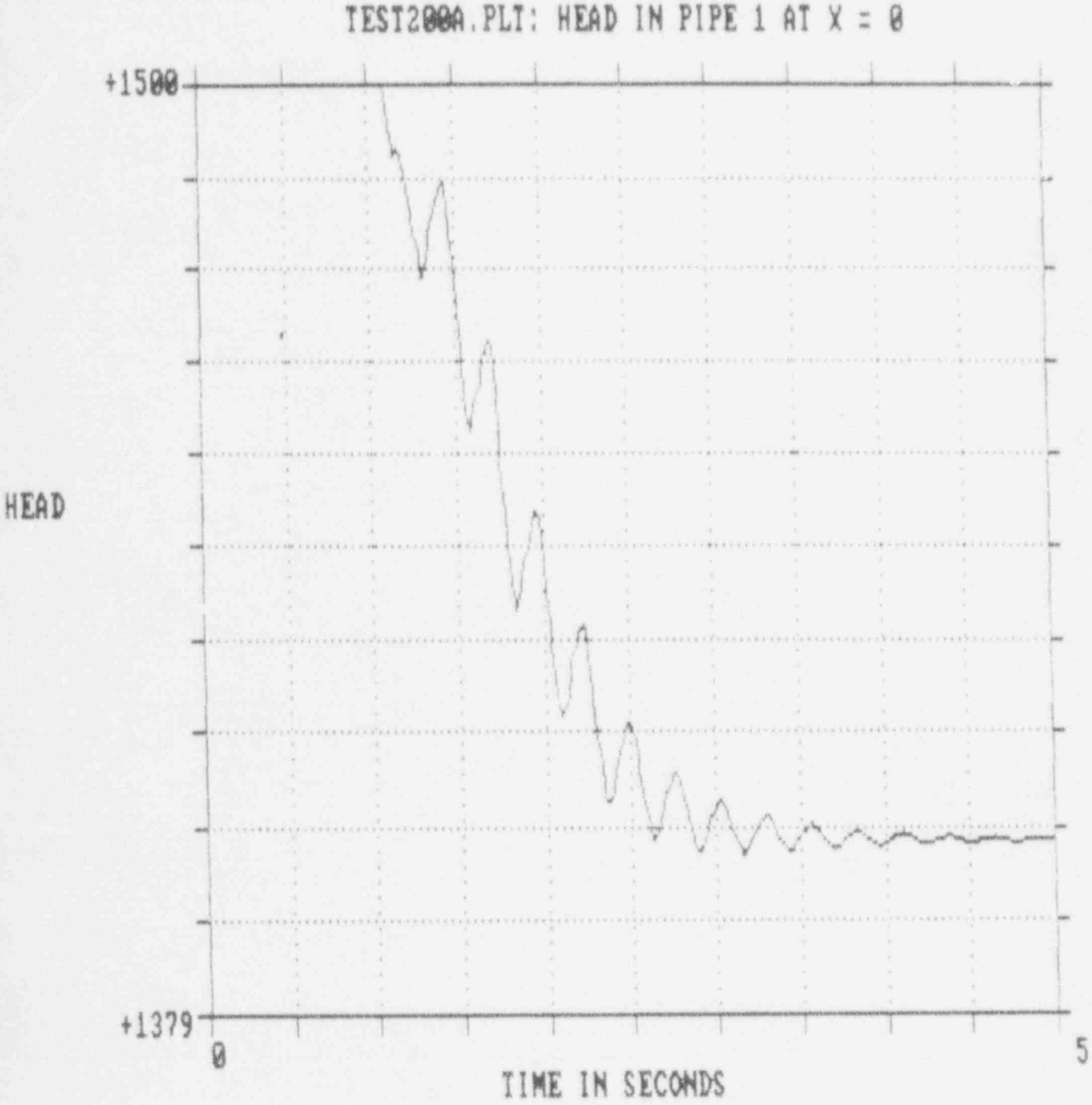

TEST200A.PLT: HEAD IN PIPE 1 AT X = 0
+1500
HEAD
+1379
0
5
TIME IN SECONDS

Figure A-3

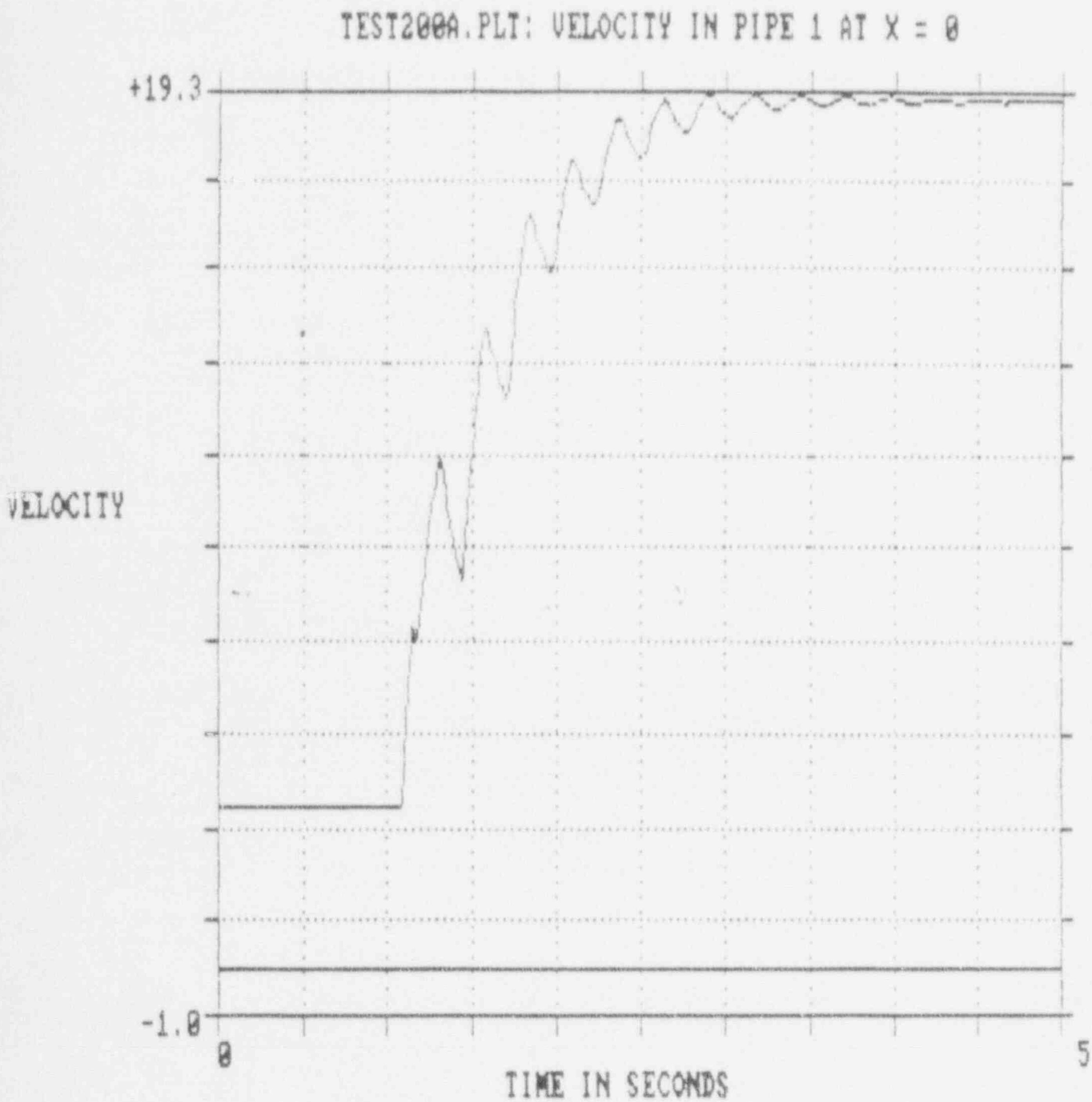
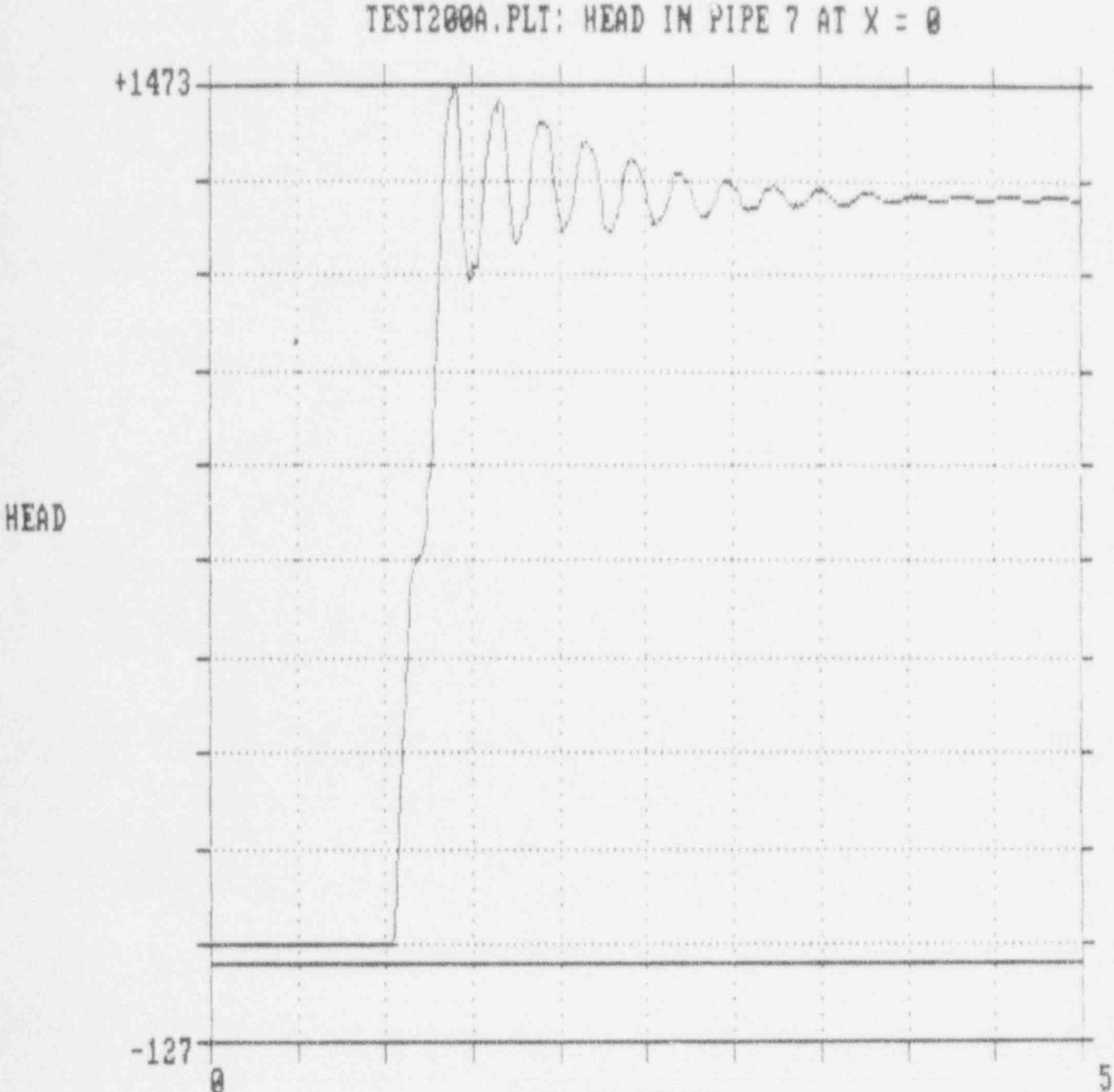

TEST200A.PLT: VELOCITY IN PIPE 1 AT X = 0
+19.3
-1.0
VELOCITY
0
5
TIME IN SECONDS

Figure A-4



TEST200A.PLT: HEAD IN PIPE 7 AT X = 0
+1473
HEAD
-127
0
5
TIME IN SECONDS

Figure A-5

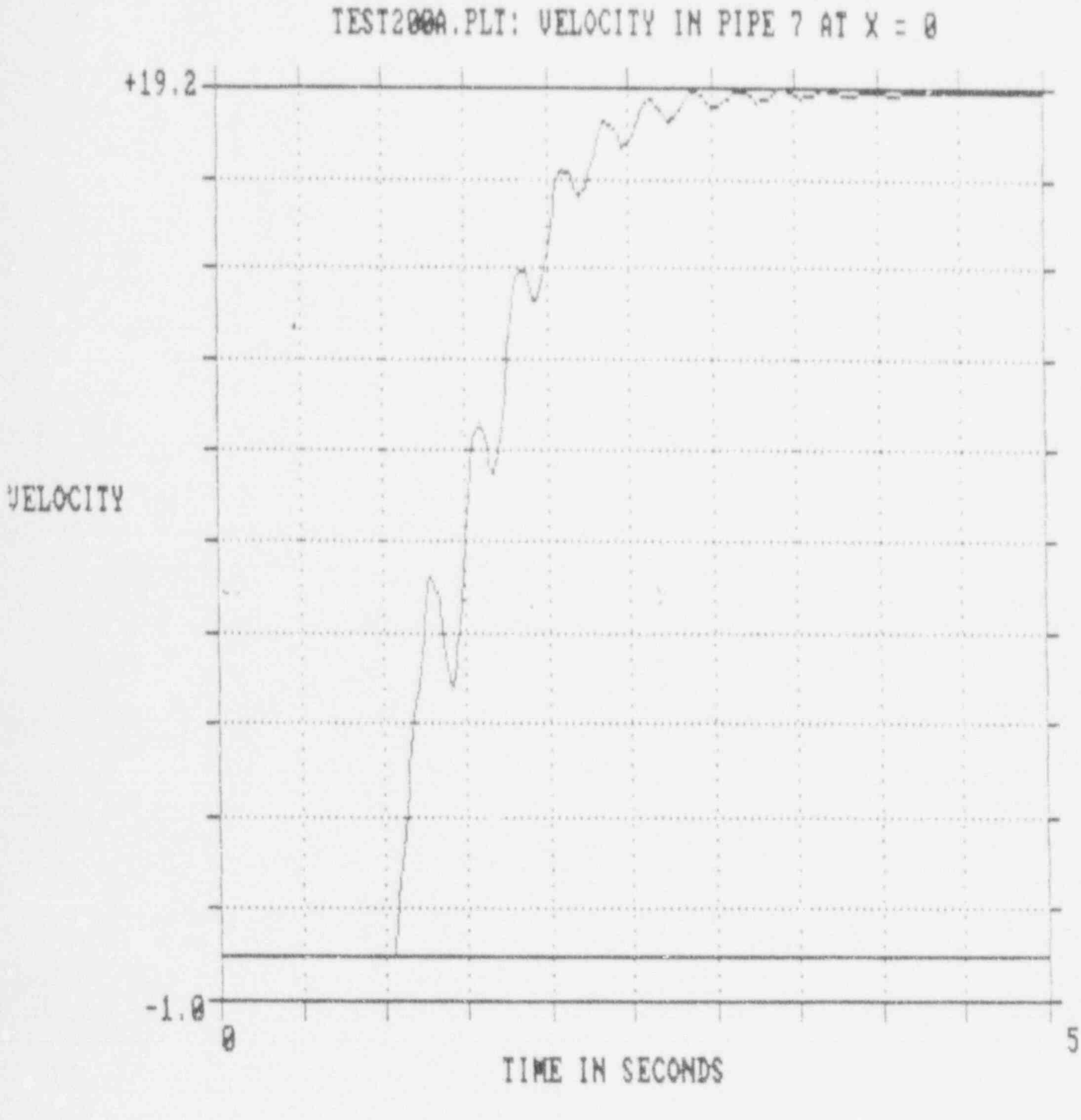

TEST200A.PLT: VELOCITY IN PIPE 7 AT X = 0
+19.2
-1.0
VELOCITY
0
5
TIME IN SECONDS

Figure A-6

APPENDIX B

Abnormal Plant Transient

Head Profiles

Worse case analysis

(12 ft^3 air pocket)

List of Figures

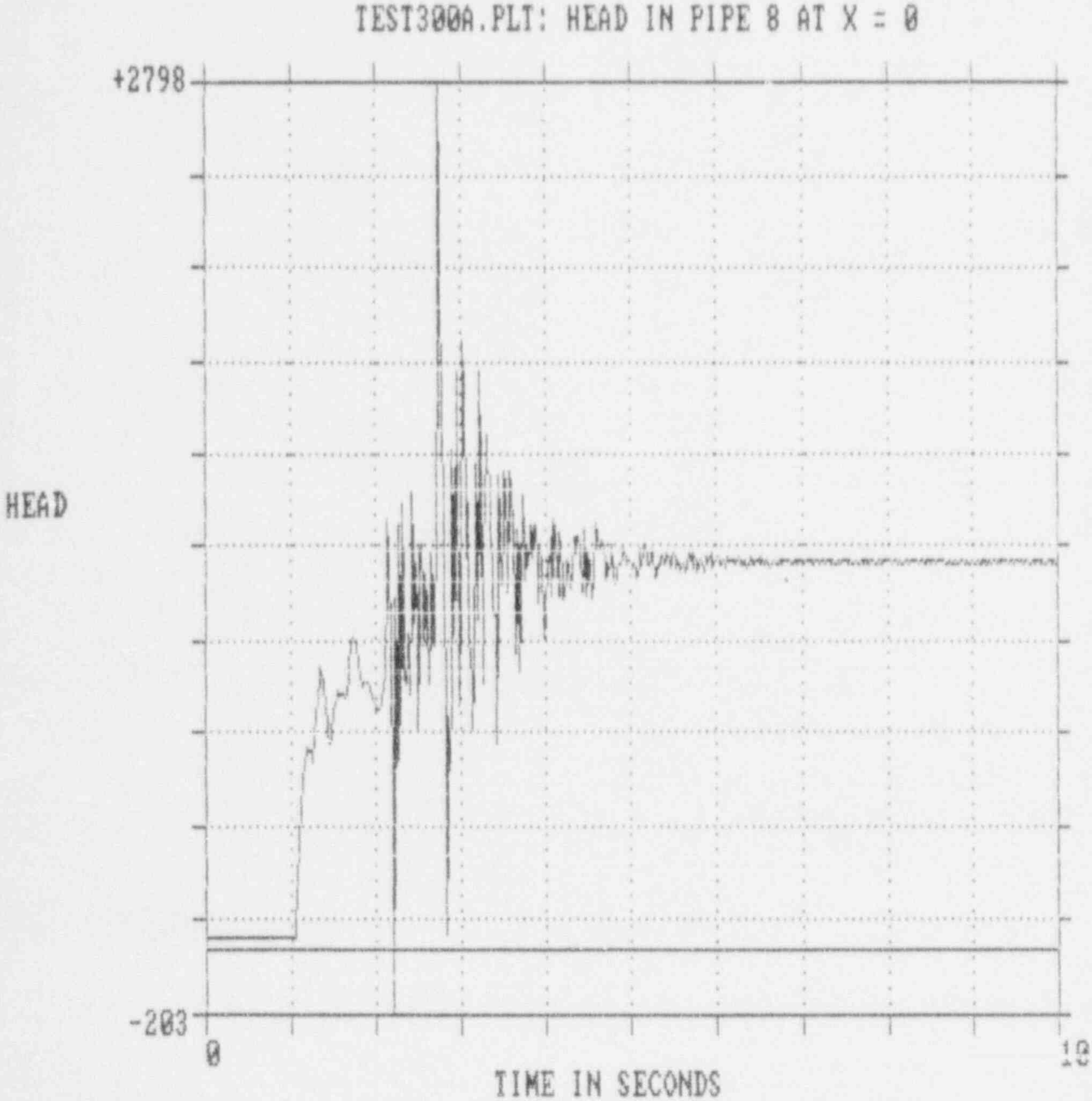

TEST300A.PLT: HEAD IN PIPE 8 AT X = 0
+2798
HEAD
-203
0
10
TIME IN SECONDS

Figure B-1

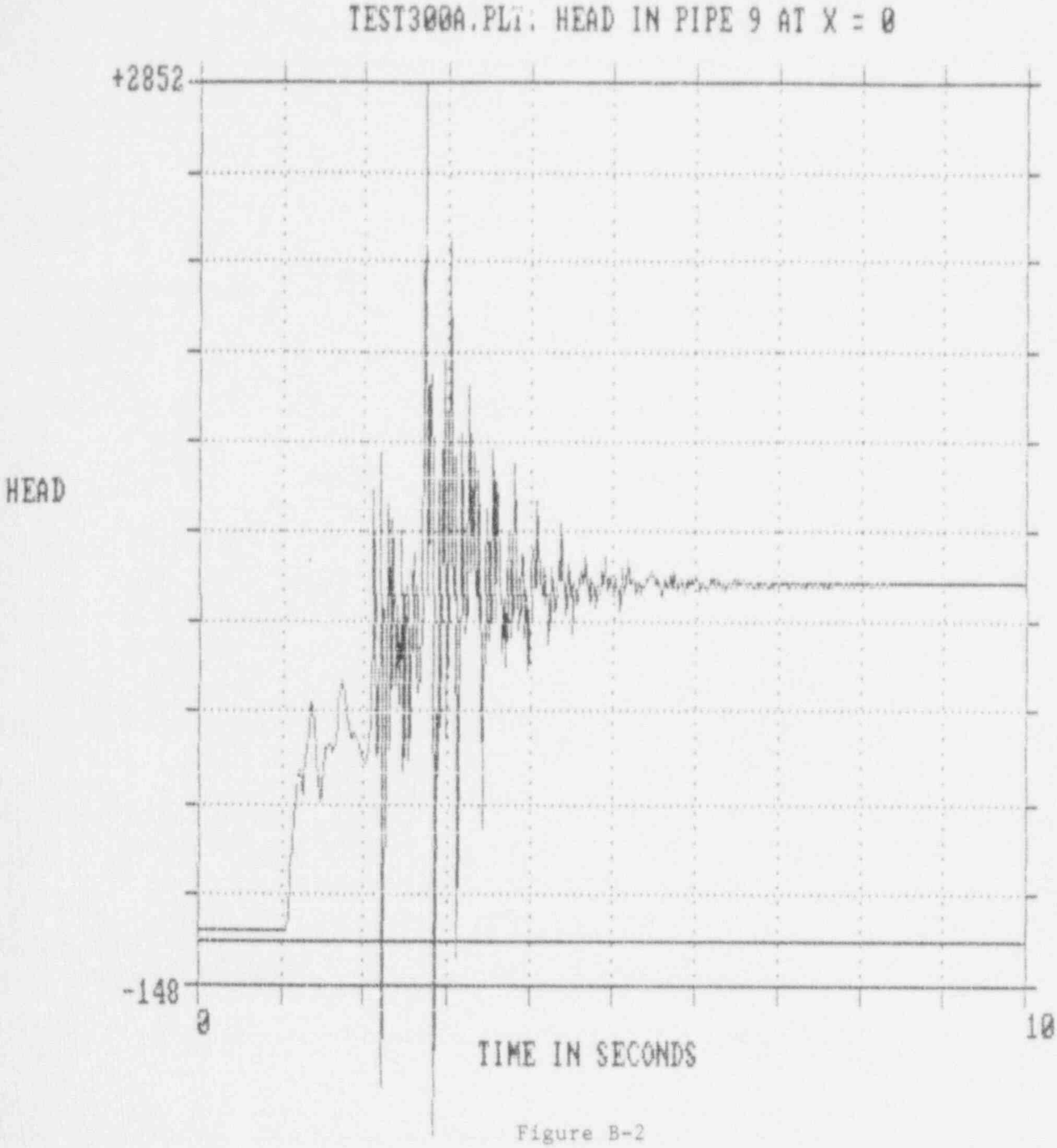

TEST300A.PLT: HEAD IN PIPE 9 AT X = 0
+2852
-148
HEAD
0
10
TIME IN SECONDS

Figure B-2

Appendix C

TABLE 1

INITIAL CONDITIONS
(Normal Plant Transient Analysis)

1. Water in pipe volumes 1-6 is at 350°F; all other volumes are 120°F.

2. Water density at 350°F is 55.55 lbm/ft^3; at 120°F, 61.67 lbm/ft^3.

3. Barometric head corrected to 120°F = 34.4 ft of water.

4. Conversion factor from pressure (psig) to head (ft) at 350°F is 0.387 psi/foot of water; at 120°F, 0.427 psi/foot of water.

5. Pump suction pressure is 407 psig which is equivalent to 1051.7 feet of water.

6. Rated head across pump obtained from process flow diagram is 135 psig (542 psig - 407 psig). In feet of water this is equal to 348.83 feet of water.

7. Head downstream of initially closed butterfly valve (RH0606) is at 0 psig + 34 feet of water column = 34 ft.

8. Head downstream of SI check valves (SI8948A and SI8948D) is at 404 psig (1043.9 feet of water).

9. Rated flow from process flow diagram:

   Q = 3000 gal/min = 6.684 ft^3/sec

10. Pump discharge head = 1,400.53 ft.

11. Volume of air pocket is zero.

12. Valve stroke times are as follows:

Valve	Initial Position	Starts Opening/ Closing at (sec)	Fully Open/ Closed at (sec)	Stroke time (sec)
RH0606	Closed	1.05	2.05	1.0
RH0610	Open	1.10	2.10	1.0
SI8948A	Closed	1.298	1.398	0.1
SI8948D	Closed	1.298	1.398	0.1

13. Pump is running at all times with initial flow equal to the minimum recirculation flow of 1.227 ft^3/sec (550 gpm).

TABLE 2

INITIAL CONDITIONS
(Abnormal Plant Transient Analysis Differences)

1. Air pockets in volumes 13 and 14 are at 14.7 psia (0 psig).

2. Approximate pipe elevation where air pocket is formed is 68 feet above the pump discharge elevation.

3. Check valve opening times for the case of 12 ft^3 air pocket are as follows:

Check Valve	Starts Opening at (sec)	Fully Open at (sec)
SI8948A	2.632	2.732
SI8948D	2.142	2.242

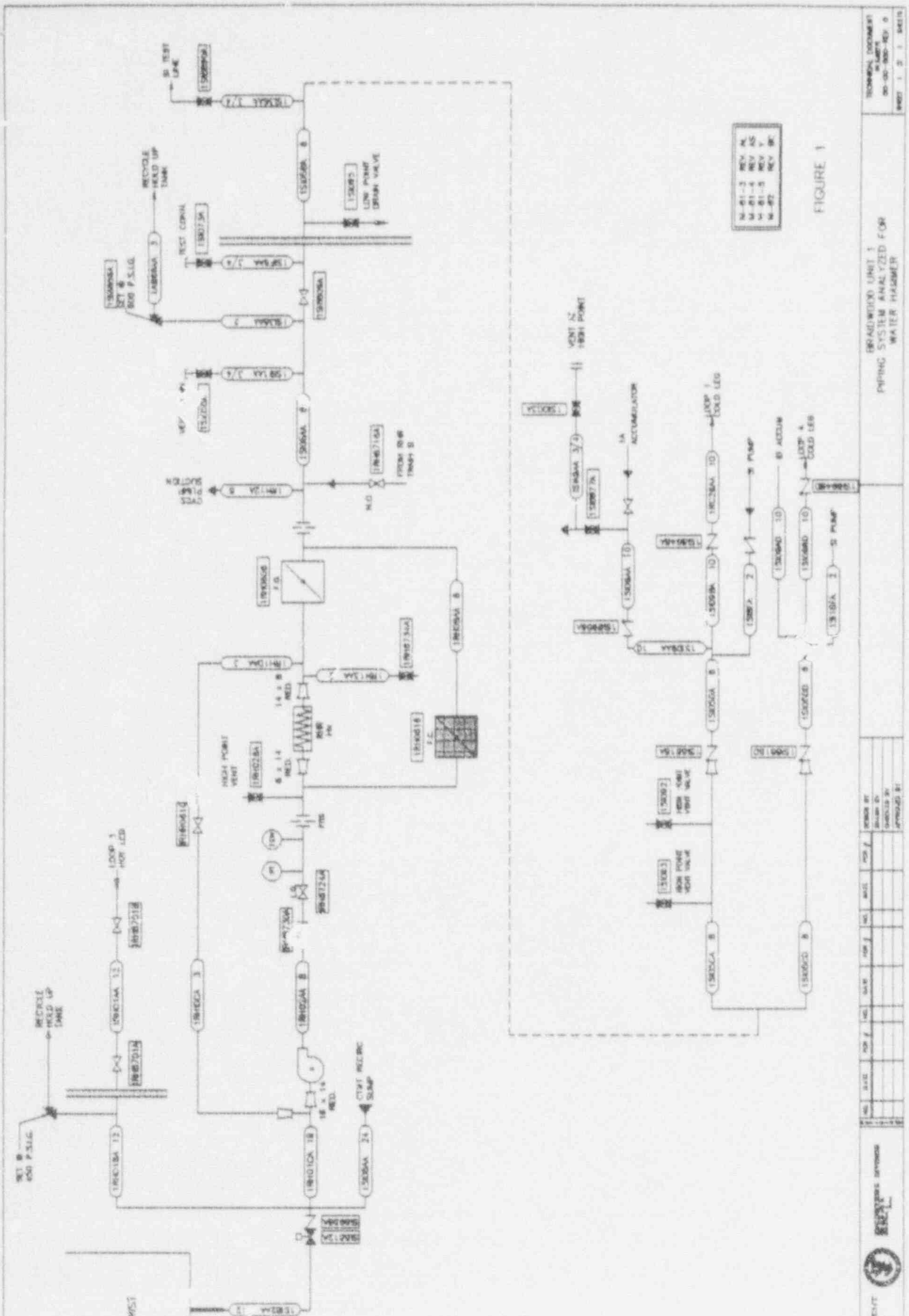

BRAIDWOOD UNIT 1
PIPING SYSTEM ANALYZED FOR
WATER HAMMER
FIGURE 1
ILLINOIS
DEPARTMENT
OF
NUCLEAR
SAFETY

Figure 1

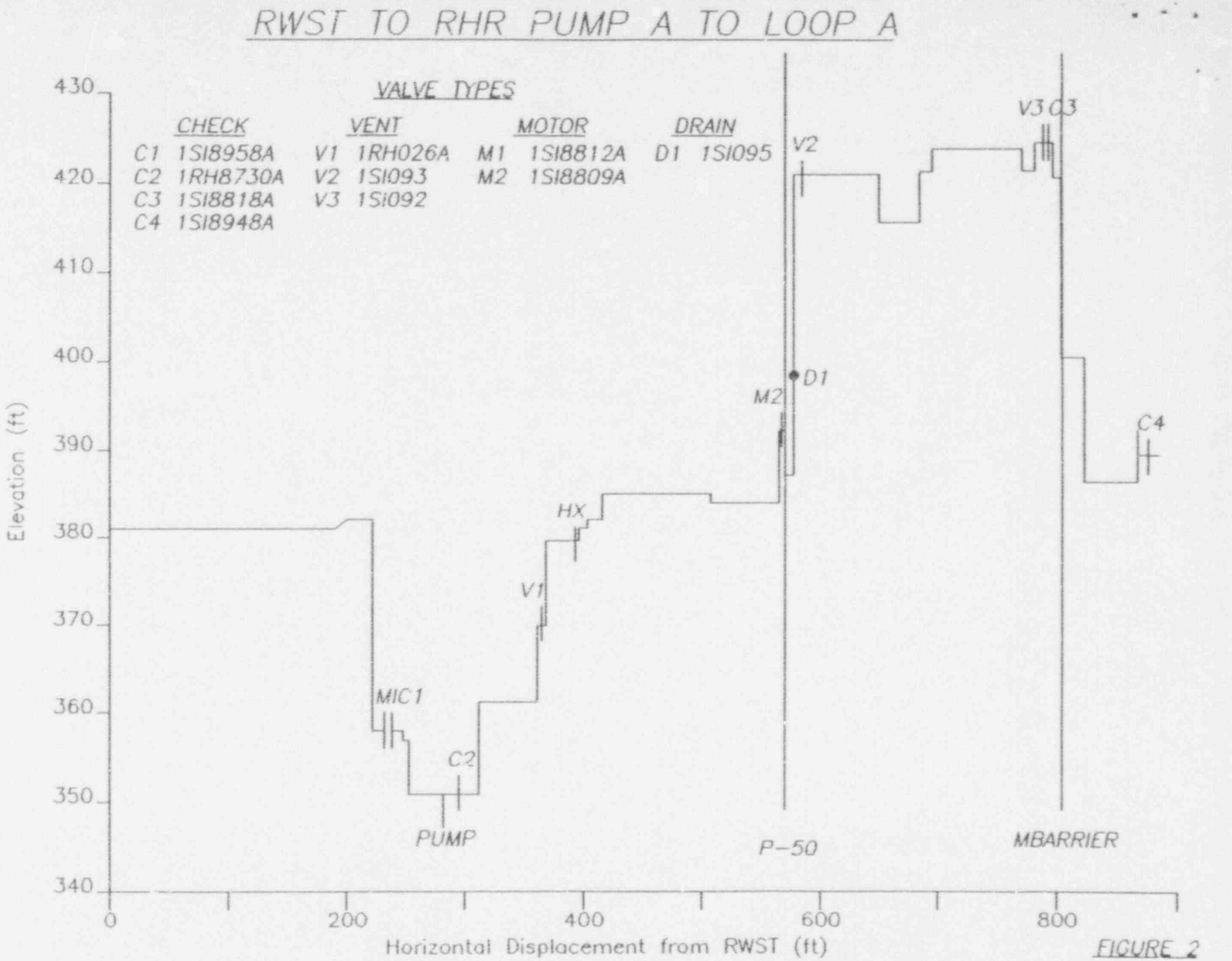


FIGURE 2

Figure 2

BRAIDWOOD UNIT 1 PI EM
WATER HAMMER AN
AWHAM MODEL

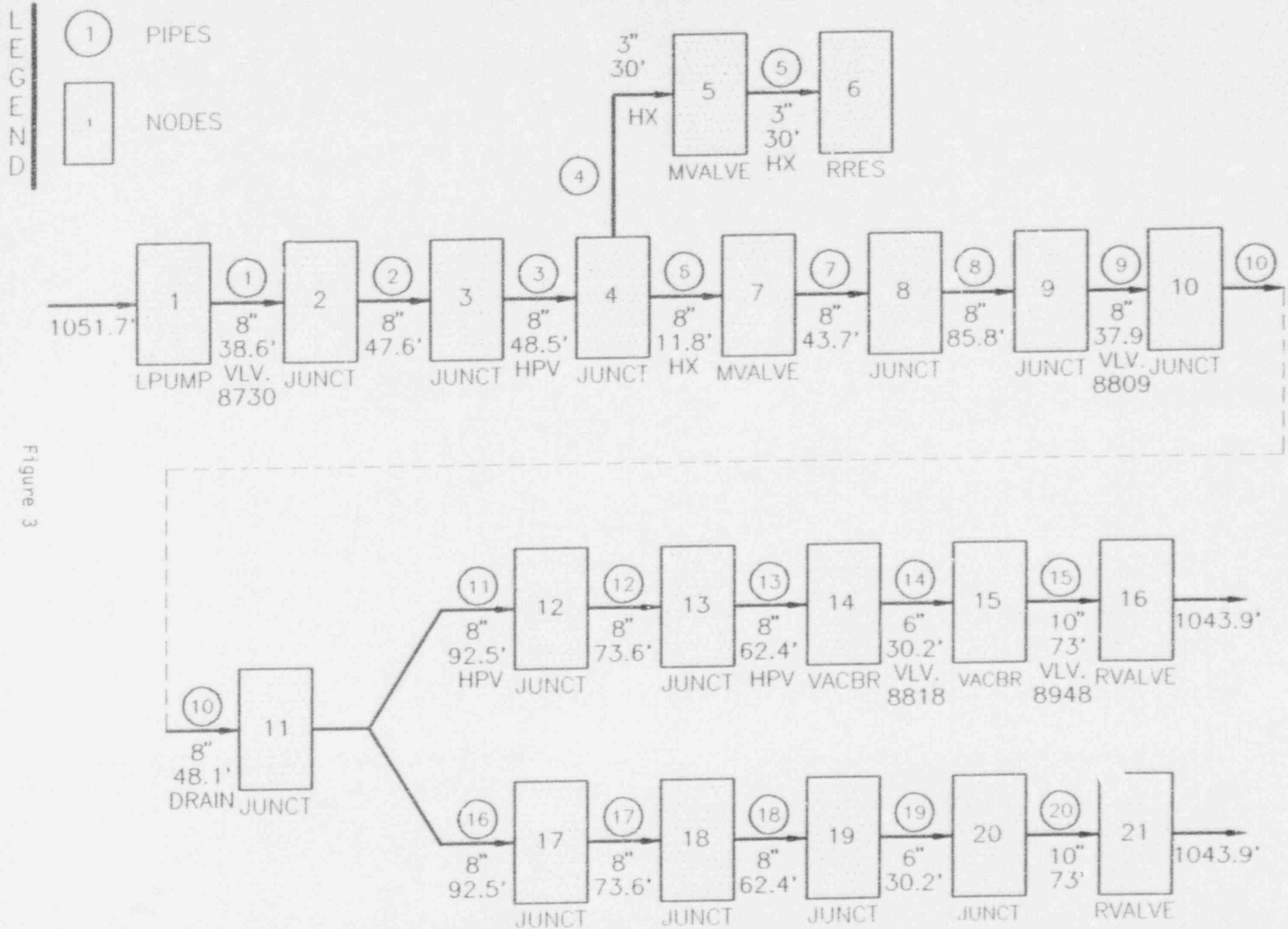


Figure 3

LOCATION	PRESSURE (PSIG)	TEMPERATURE (°F)	FLOW (GPM)	LOCATION	PRESSURE (PSIG)	TEMPERATURE (°F)	FLOW (GPM)
20	404	280	1555	36	542	350	3000
21	–	–	–	37	541	350	1259
22	–	–	–	38	479	280	3110
23	–	–	–	39	496	350	1741
28	480	280	2890	40	–	–	–
32	498	280	3000	41	539	140	1259
34	400	350	3000	42	496	280	3000
35	407	350	3000				

(REFERENCE: BYRON/BRAIDWOOD UPDATED FSAR FIGURE 5.4-4)

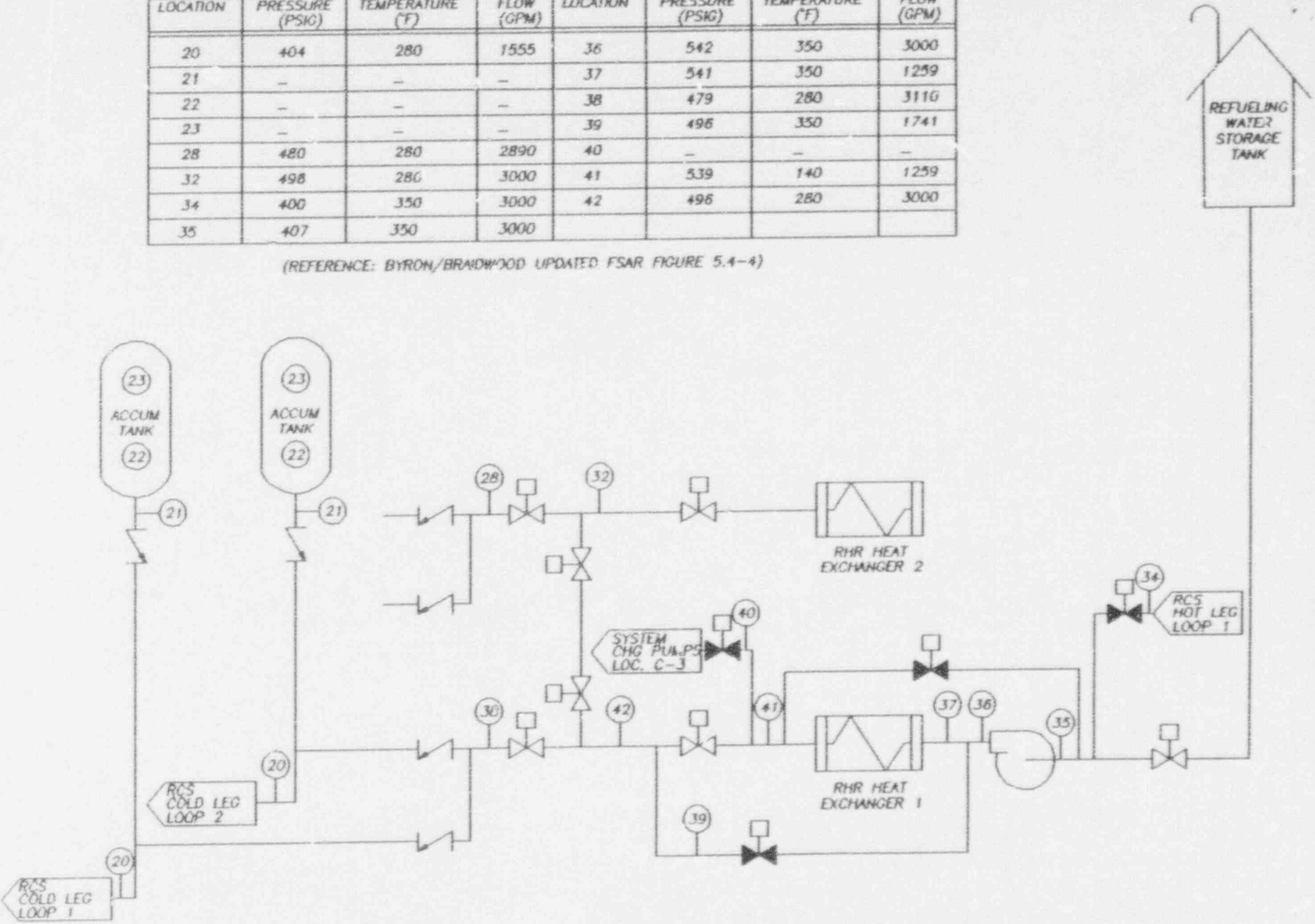
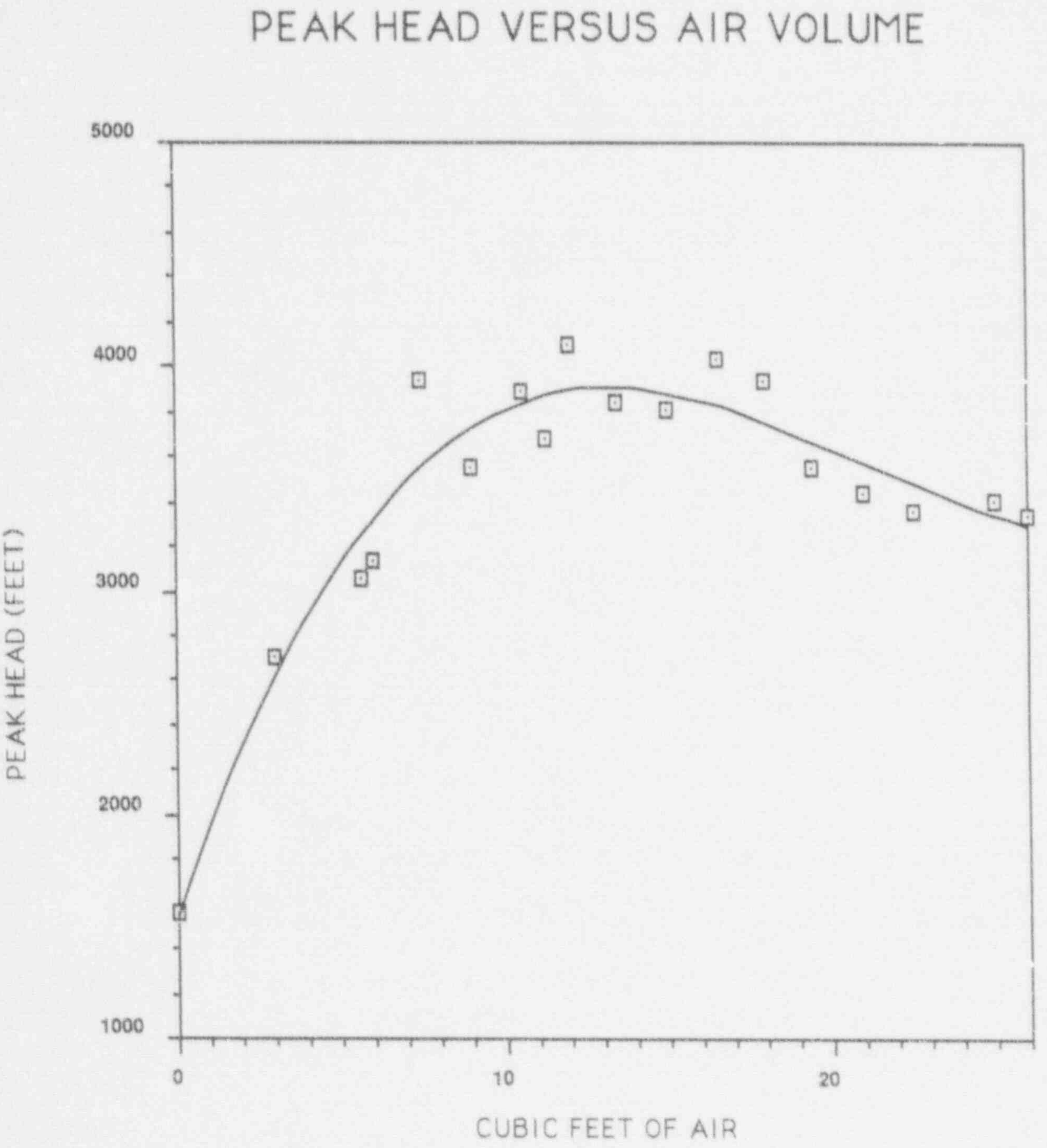


Figure 4



PEAK HEAD VERSUS AIR VOLUME
5000
4000
3000
2000
1000
PEAK HEAD (FEET)
0
10
20
CUBIC FEET OF AIR

Figure 5