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UNANTICIPATED TRANSIENTS DURING OPENING OF A MOTOR OPERATED VALVE

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ABSTRACT

Unanticipated pressure transients observed during the opening of a motor operated gate valve have been explored using a computer program SURGE. In the absence of air pockets or vapor cavities the cause of such pressure spikes is believed to be the cavitation phenomenon occurring at the valve during the initial phase of its opening. Computer predicted results compared well with the actual field test data.

INTRODUCTION

Pressure transients due to opening and closing of valves in a fluid system are well established phenomena. The USNRC's Generic Letter 89-10 requires adequate consideration of these phenomena in designing fluid systems of nuclear plants. Generally pressure transients generated by closing a valve are more severe than those due to valve opening. However, while the consequences of a valve closure can be minimized by choosing a large closing time (relative to the wave travel time), the transients caused by valve opening may not be reduced significantly by merely increasing the valve opening time, if the system has entrapped air pockets, vapor cavity or valve cavitation.

During a routine High Pressure Cooling System (HPCS) vessel injection test high pressure surges were observed due to opening of a motor operated gate valve. The transient pressure significantly exceeded the pump shut-off head and was accompanied by significant vibrations and noise. In contrast, for the same system a considerably less severe pressure transient was observed during the closing of the same valve.

The objective of this paper is to identify the potential causes of this unanticipated transient pressure surge observed during a valve operability test. Further, it is intended to compare the field test data with analytical results obtained from computer simulation of the valve opening transients.

BACKGROUND

HPCS in a nuclear plant is a part of the Engineered Safety Feature (ESF) systems. One of the main functions of the HPCS is to provide makeup water to the reactor in the event of a loss of reactor inventory. Consequently it is required to be functional and available for accident mitigation during the design basis event, e.g., loss of offsite power (LOOP) or a loss of coolant accident (LOCA).

A simplified diagram of the HPCS is shown in Figure 1. A high head pump takes suction from Condensate Storage Tank (CST) and supplies cooling water to the reactor vessel. Valve V1 is opened to initiate the flow to the vessel. However, since the reactor pressure may be high in the beginning, there may be little or no flow through valve V1, and in order to maintain certain minimum flow through the pump, valve V2, must be opened. After sufficient flow through valve V1 is established, valve V2, is closed. During a routine test to demonstrate the operability of valve V2, a significantly high pressure spike was observed, following the valve opening.

There are three potential causes of the pressure surge under investigation: entrapped air pocket, vapor cavity, and cavitation occurring at the valve orifice. The pressure rise resulting from entrapped air in a liquid pipeline has been demonstrated by Wylie and Streeter (1978). When entrapped air followed by liquid passes through an orifice (or any constriction in the flow path like throttled valve) the air-liquid interface accelerates. When the interface reaches the orifice, it decelerates resulting in pressure surge. Entrapped air may prove to be either detrimental or beneficial, depending upon the amount and location of the air as well as the pipeline configuration and the nature and cause of the transient (Martin, 1976).

Cavity formation (or column separation) and subsequent collapse (or re-joining) in a liquid piping system is a well documented phenomenon. Provoost (1976) calculated and experimentally verified the pressure surge due to column-separation at high points in a pipeline.

Cavitation at the orifice or a throttled valve is another source of pressure surges. Cavitation at an orifice is a well known phenomenon. Theoretical predictions of cavitation conditions are fairly accurate. The cavitation criteria for valves are normally provided by the manufacturers, since they are highly dependent on the valve geometry, especially the design of the nozzle. However, since some valves are designed for operation at the fully open position, the cavitation criteria do not apply or exist.

The pressure difference between the inlet to the valve and the minimum pressure just after the valve nozzle is often much greater than the total pressure drop. When the minimum static pressure drops to the vapor pressure the flow chokes at the valve. A condition of supercavitation may occur with a large vapor filled cavity after the valve. Cavitation downstream of a nearly closed valve occurs in the turbulent eddies of the jet issuing from the valve. Within the core of turbulent eddies and vortices, created just after the valve opening, the static pressure is further lowered by centrifugal forces.

Irrespective of the specific cause, the fluid flow under the circumstances discussed above is highly decelerated to the point it is practically stopped. This sudden stoppage of flow is the root cause of the pressure surge.

SIMULATION MODEL

In order to quantify the magnitude of transient pressure spikes observed in the test, a simulation model, as schematically shown in Figure 1, has been developed. The computer program SURGE (Wood and Funk, 1991) is used to solve basic water hammer equations for the transient flow of an incompressible fluid in a piping network.

The program initially calculates the steady state flow through the piping system. Subsequently, the steady state output file is updated with transient input data. For this analysis, opening and closing profiles of gate valves, discussed in the input parameter section, are incorporated. In order to obtain transient responses due to opening or closure of gate valves the modified output file from the steady state analysis is used.

During the reactor vessel injection test valve V2 is initially maintained in a closed position whereas valve V1 is kept open. Subsequent to the vessel injection, valve V1 is closed and the HPCS system is boxed-up, or in other words, the HPCS pump operates under shut-off condition for a short duration before valve V2 is opened which allows flow to the suppression pool. The opening/closing time (t_0) of valve V2 is 7 seconds.

Hydraulic Loss Parameters

Figure 1 shows the nodes used in the computer model. The piping between any two consecutive nodes is designated as a link. Table 1 presents node and link information used in the model. The overall hydraulic loss parameter ($\Delta H/Q^2$) for each link has been calculated from the experimentally measured head loss data, ΔH, for an associated flow. Wherever possible loss factors for valves and fittings obtained from manufacturer's data. Otherwise, generic data have been used. The basis for calculation of hydraulic loss parameter is as follows.

Hydraulic loss parameter, $\Delta H/Q^2$, is expressed as:

$$\Delta H/Q^2 = K/(2A^2 g)$$

where

K = fL/D for pipe
= $891\ d^4/C_v^2$ for valve
ΔH = head loss, feet
Q = flow, cfs
f = friction factor
A = cross-sectional area of pipe, sq. ft
L = length of pipe, feet
D = diameter of pipe, feet
d = diameter of pipe, inch
C_v = flow coefficient

Component Loss factors

Valve settings are based on the HPCS test conditions. The K-factor of fully open gate valve V1 is taken as 0.2 as a generic value (Streeter and Wylie, 1985). For valve V2 the hydraulic loss parameter, $\Delta H/Q^2$, is calculated from experimentally determined head loss ΔH and corresponding Q (Table 1). Other fully open valve and orifice Cvs are based on generic data from Miller (1990).

Generic opening/closing characteristics for a typical gate valve used in the analysis are as follows:

TIME(t/t_0)	AREA RATIO (A/A_0)
0.00	1.000
0.10	0.767
0.20	0.609
0.30	0.461
0.40	0.354
0.50	0.277
0.60	0.204
0.70	0.146
0.80	0.100
0.90	0.055
0.95	0.019
1.00	0.000

Speed of Sound

The speed of sound is calculated from the following formula [Wylie and Streeter,1978]:

$$a = \{(Kg/\rho)/[1+(K/E)(D/e)]\}^{0.5}$$

where

E = Modules of elasticity of steel, lb/sq. in
K = Bulk Modules of fluid, lb/sq. in.
ρ = density for water, lb/cu. ft
D = diameter of pipe, ft
e = wall thickness, ft

For 6" Sch. 40 pipe the velocity of sound is calculated to be 4354.5 ft/sec.

Pump and Motor Characteristics

The HPCS pump characteristics are obtained from manufacturer supplied data. The head vs. flow data for the pump are as follows:

Head, ft	3300	3150	2875
Flow, cfs	0.000	2.228	4.456

RESULTS

Experimental Data

Experimental data from an actual plant system were available to be compared with the theoretical predictions. Digital data for valve upstream pressure, valve stem position, thrust on the valve operator, and motor current for the valve operator were recorded among many other parameters. Figures 2A, 2B, 2C, and 2D show the time history plots of motor current, the thrust generated by the motor, the opening position of valve V2, and the transient pressure at the upstream of valve V2, respectively. Figure 2D shows that initially the pressure dropped to about 450 psi below the shut-off head of the pump within 200 msecs. After the initial drop in pressure a surge of pressure occurred within a short duration of approximately 150 msec. During this time the pressure increased to about 250 psi (17%) above the shut-off head of the pump. The pressure surge occurred when the opening of the valve V2 was between 2%-17%. Also, during the valve opening 'excessive noise' was heard for a short duration of time. The valve closing did not produce any appreciable pressure transient.

In the experiment the opening and closing of the valve were repeated several times and exactly the same transients were duplicated. This also eliminated the possibility of the existence of air pockets in the system.

Although, the elevation of the valve outlet is about 32 feet above the water surface in the suppression pool, the atmospheric pressure in the suppression pool should keep the entire discharge piping of valve V2 flooded, thus precluding the formation of any vapour cavity.

Simulation Results

Figure 3 shows the numerical results of the present analysis. Pressure transients due to normal closing of valve V2 is shown in Figure 3A and due to valve opening in Figure 3B. It is evident from Figures 3A and 3B that there is hardly any pressure transients in the HPCS system during opening or closing of valve V2, if cavitation phenomenon is ignored. During valve closing the transient pressure does not exceed more than 3% of the shut-off head whereas during valve opening the rise in pressure is insignificant.

Numerical experiments were conducted simulating postulated cavitation condition at the valve during opening by adjusting the opening/closing profile of valve V2. When valve V2 starts to open, the flow area of the valve is small which results in choking condition and hence, the valve cavitates. This, in turn, results in impeded flow through the valve for a short time when the initial opening area of the valve is small. In order to simulate the cavitation phenomenon, valve characteristics are created such that after opening valve V2 for 200 msec, similar to the experimental results, the valve is closed instantaneously which causes rapid deceleration in the flow. Subsequent to the closure, the valve is opened with a normal opening profile.

Figure 3C shows the pressure transient as predicted by the computer model when cavitation was postulated during opening of valve V2. The predicted pressure profile has remarkable similarity both in shape and magnitude with the actual test profile shown in Figure 2D. During the stoppage of flow the maximum transient pressure at the valve exceeds the pump shut-off head by more than 17%. It is to be noted that there is some difference between the theoretical shut-off head of the pump and the actual shut-off head observed in the field test. If this is adjusted the comparison becomes even closer.

CONCLUSION

The present investigation identifies the cause of a substantially high pressure spike observed in a field test following the opening of a gate valve. In the absence of an air pocket or a vapor cavity, the cause of such transients is believed to be the cavitation phenomenon occurring at the valve. The cavitation which is accompanied by choking of flow due to flashing at the gate is equivalent to drastically reducing the flow through the valve thereby causing compression wave of significant magnitudes. The magnitude of pressure waves would depend upon the severity of cavitation at the valve. Eventhough the phenomenon investigated here was experimentally observed in a gate valve it should also be applicable to other valves, if the potential for cavitation exists.

It is to be noted that these pressure surges observed in the actual test did not impede valve stem motion or the motor operation. The valve appeared to function as intended with the exception of high pressure surge which may have caused excessive loads on the pipe supports.

REFERENCES

Wylie, E. B., and Streeter, V. L., 1978, Fluid Transients, McGraw-Hill International Book Co., Chapter 8, pp 136-155.

Martin, C. S., 1976, Entrapped Air in Pipelines, Proc. 2nd Int. Conf. Pressure Surges, Bedford, England, BHRA.

Provoost, G. A., 1976, Investigation into Cavitation in a Prototype Pipeline Caused by Water Hammer, Proc. 2nd Int. Conf. Pressure Surges, Bedford, England, BHRA.

Miller, D. S., 1990, Cavitation, Chapter 6, Internal Flow Systems, BHRA Fluid Engineering, 2nd Edition, Gulf Publishing Company, Houston, TX.

Wood, D.J. and Funk, J.E., Computer Program SURGE, 1991, Version 4.3, University of Kentucky.

Streeer, V.L. and Wylie, E.B., Fluid Mechanics, Eighth Edition, McGraw Hill Book Company, Newyork, 1985

Baumeister, T. and Marks, L.S., Standard Book for Mechanical Engineers, 9th Ed., McGraw-Hill.

Table 1: Internodal Information for Computer Model

FROM NODE (#)	TO NODE (#)	LINK LENGTH (ft)	PIPE DIAMETER (in)	ΔH (psid) or L/D (*)	REFERENCE FLOW (gpm)	$\Delta H/Q^2$ (sec^2/ft^5)
CST	17	296.5	17.3	3.58	7800	0.0274
17	4	116.0	15.3	3.28	7800	0.0251
4	5	8.0	23.3	0.157	7800	0.0012
5	6	PUMP	-	-	-	-
6	7	8.0	13.9	0.41	6110	0.0051
7	10	32.0	13.9	12.2	6110	0.152
10	32	ORIFICE	-	62.65	6110	0.781
32	11	74.0	13.9	1.25	6110	0.0156
11	12	VALVE V1	-	-	775	0.0028
12	13	84.0	11.4	16.71	6110	0.2082
13	14	ORIFICE	-	96.58	6110	1.2037
14	REA	8.0	11.4	1.59	6110	0.0198
7	75	16.0	3.4	203 (*)	-	12.904
75	76	ORIFICE	-	1160	600	1499.3
76	15	101.0	3.4	488 (*)	-	31.02
15	16	VALVE V2	-	0.693	600	0.8956
16	181	43.0	11.3	2.66	7000	0.0253
181	18	ORIFICE	-	217.7	7000	2.0672
18	SUP	9.0	11.9	0.33	7000	0.0031

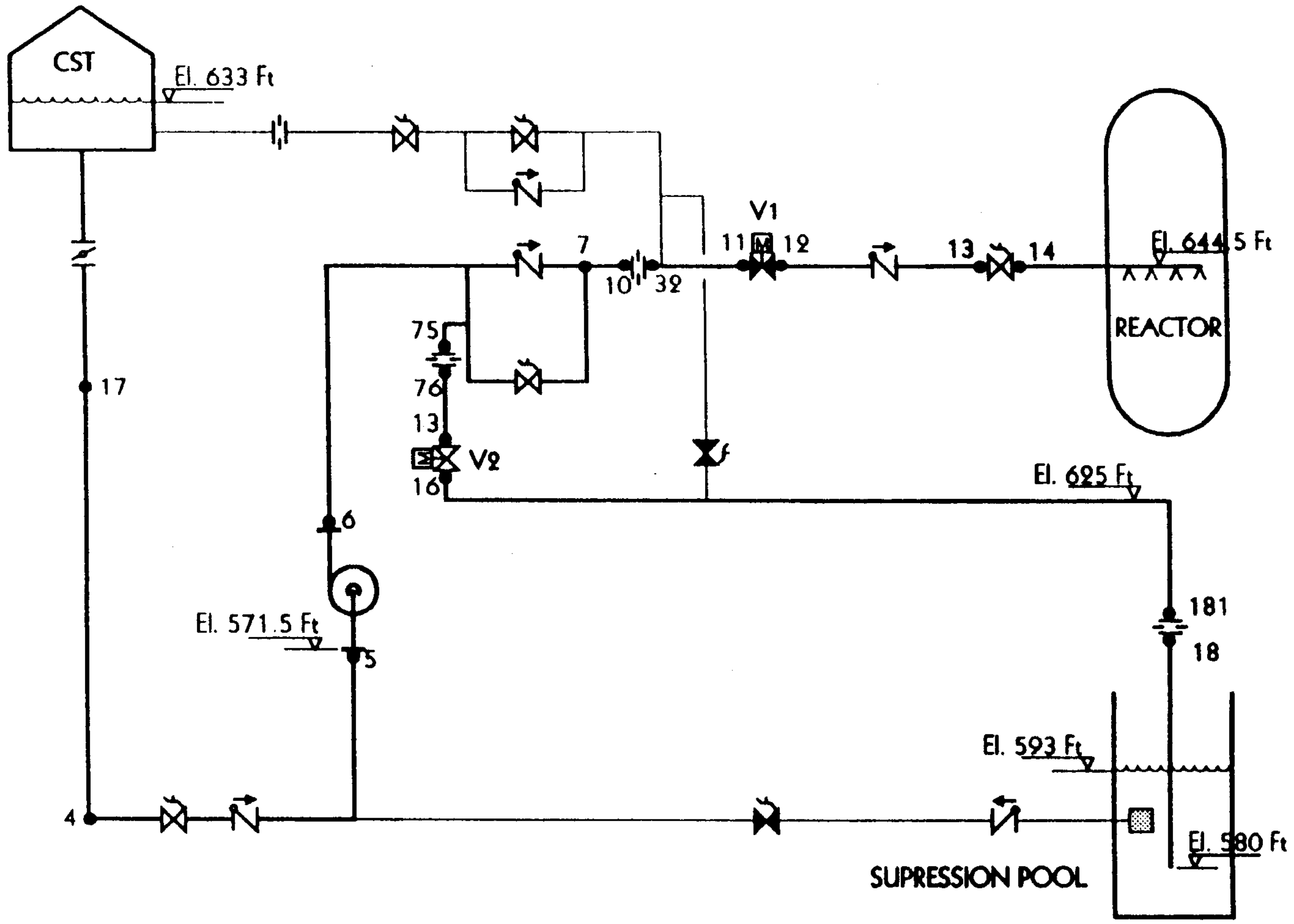
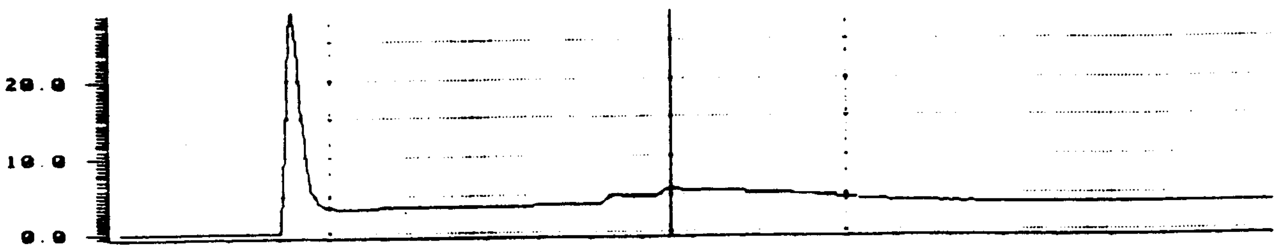
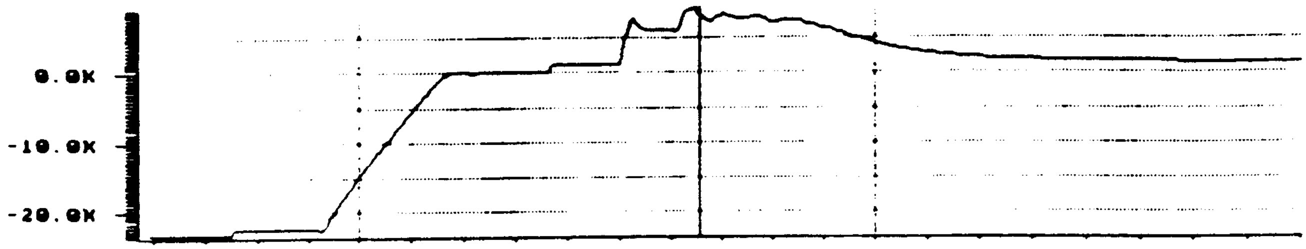


Figure 1: Schematic Diagram of High Pressure Cooling System (HPCS)

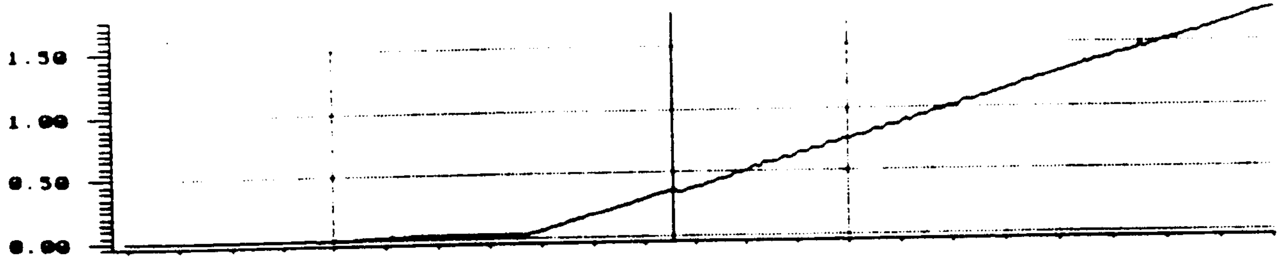
(A) Motor Current



(B) Thrust Generated by Motor



(C) Opening Position of Valve V2



(D) Transient Pressure Upstream of Valve V2

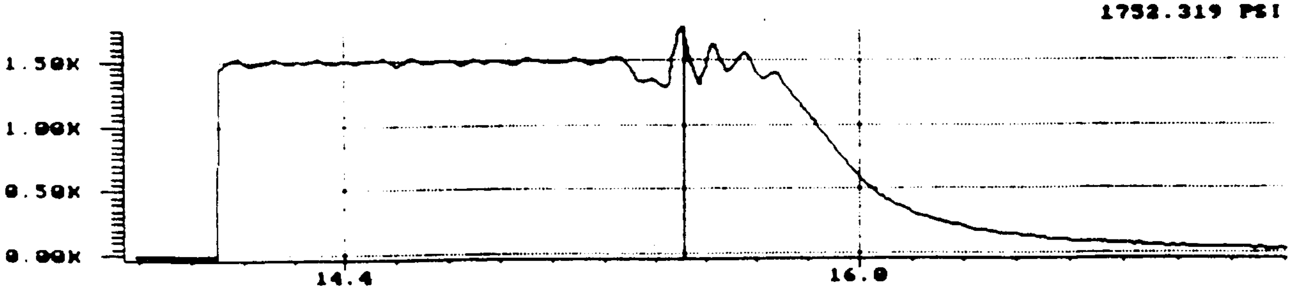


Figure 2: Experimental Field Data- (A) Motor Current (B) Thrust Generated by Motor (C) Opening Position of Valve V2 (D) Transient Pressure Upstream of Valve V2

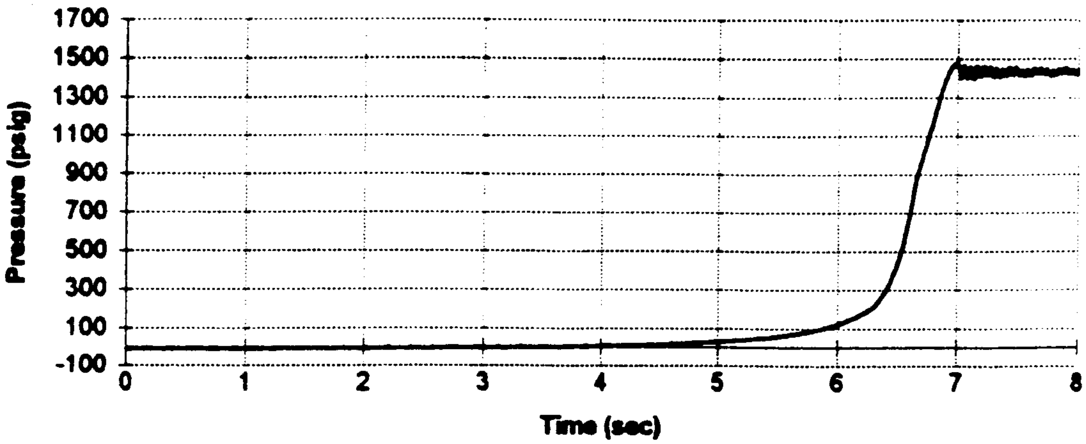


Figure 3A: Pressure transient due to closing of valve V2

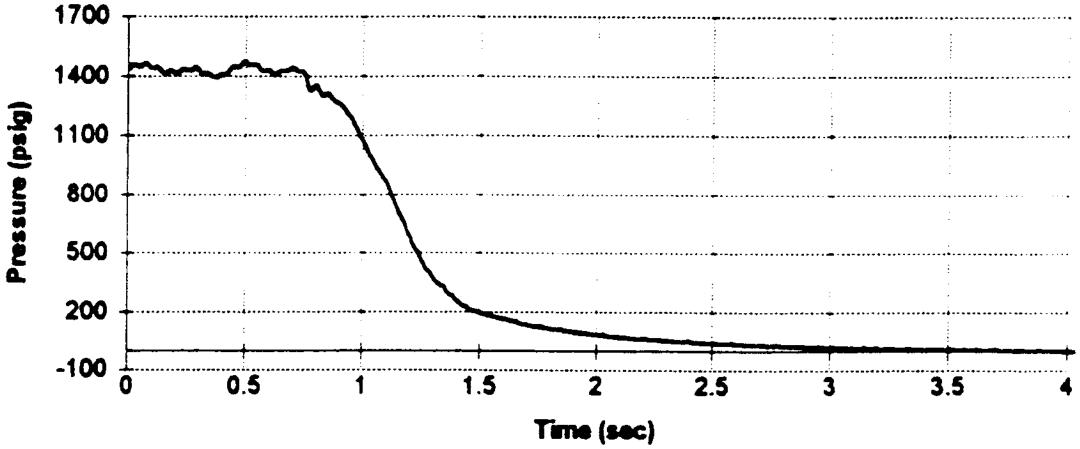


Figure 3B: Pressure transients due to opening of valve V2

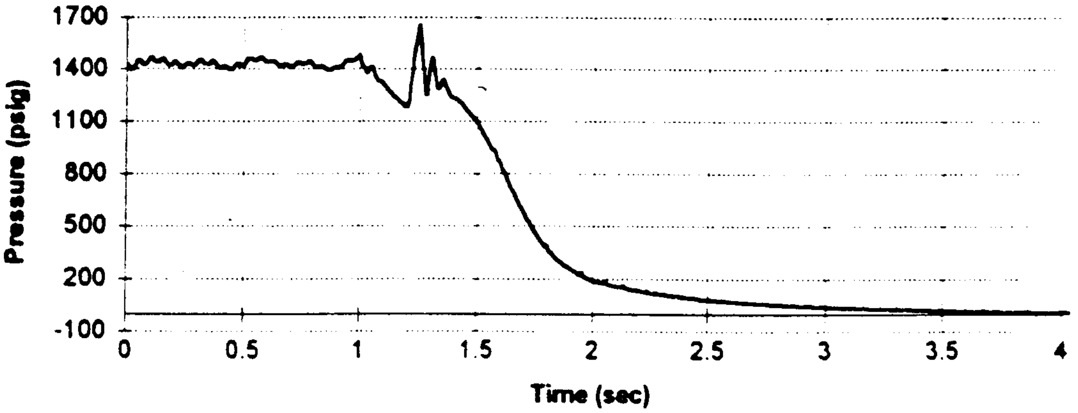


Figure 3C: Pressure transient due to opening of valve V2 having cavity formation