Attachment C

FAI/96-75

EVALUATION OF POSSIBLE WATER-HAMMER LOADS IN THE SERVICE WATER SYSTEM FOR DBA CONDITIONS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

For the conditions assumed for a Design Basis Accident (DBA), a large break is postulated in the Reactor Coolant System (RCS) along with a Loss of Off-Site Power (LOOP) causing the on-site diesels to start and supply power to the safety systems. Given this event sequence, systems such as the service water would trip following the LOOP. These would subsequently receive power as they would be loaded back onto the busses after the diesels start. This may result in a 20 to 30 second delay in establishing the flow through the service water circuit, including the containment fan coolers (CFCs) which would simultaneously experience a high steam partial pressure and heat input on the containment side of the cooling coils.

2.0 EXPERIMENTAL INVESTIGATION

2.1 Scaling Considerations

For an experiment to provide meaningful results, the apparatus (unless it is full scale) needs to be scaled with respect to the controlling physical processes. A format for developing the appropriate scaling was presented by the Nuclear Regulatory Commission (NRC, 1991) and the first major step is to develop a Phenómena Importance Ranking Table (PIRT). For waterhammer evaluations in this part of the service water system, the set of physical processes of interest are:

1) column separation,
2) net steam generation in the fan coolers,
3) the configuration of the service water piping including loop seals,
4) steam condensation due to the discharge pipe heat sink and
5) the cold water refill rate when the service water flow is established.

Since the fan coolers are located at different elevations, the potential for column separation will be different for each elevation. Nevertheless, an experiment should have the capability to represent the potential for significant column separation.

As discussed above, the high steam partial pressure in the containment resulting from the LOCA causes substantial energy transfer to the fan cooler coils and the service water inside. However, if the steam is generated too rapidly, the steam outflow would "flood" the water in the tubes and force the service water out of the coils. Therefore, consideration should be given to the maximum steam generation rate that would enable water to remain within the fan cooler tubes and support further vaporization. If the vaporization rate becomes sufficient to displace the water from the fan cooler tubes, the vaporization would cease and the final location of the water in the discharge piping would essentially be determined by column separation. Conversely, if the vaporization process is sustained, the net steam generation could continue to

displace the water inventory in the discharge piping well beyond that location representing the equilibrium limit for column separation.

Typically, the velocity necessary to "flood" liquid in a horizontal configuration is taken to be the same velocity for "flooding" vertically downward flow. This velocity can be expressed as

$$U_g = \frac{3 \sqrt[4]{g\sigma(\rho_w - \rho_g)}}{\sqrt{\rho_g}} \qquad (2\text{-}1)$$

where g is the acceleration of gravity, σ is the steam-water surface tension, ρ_w is the water density and ρ_g is the steam density. For a saturated steam-water mixture at 1 atm, this is a velocity of 59 ft/sec (18 m/sec). Translating this into an effective heat load that would be removed in the fan coolers corresponds to a removal rate of approximately 1 MW, or about 1/10th of the design heat load for the fan cooler units. This is important when considering the extent of steam generation since the heat removal that the fan coolers could produce in terms of net steam generation within each unit is only about 1/10th of the design load without disrupting the capabilities for sustaining the steam generation. This steam production rate of 1 MW net steam generation at 1 atm corresponds to a velocity (without considering condensation losses) of 79 ft/sec (24 m/sec) in the 8-inch discharge piping. Since the Froude number characterizes the two-phase flow pattern, it is important that the experiment has a similar steam supply velocity. For a pressure of 1 atm this corresponds to a flow rate of 0.016 lbm/sec (7×10^{-3} kg/sec) in a 1 in. pipe.

The steam flow was determined in the experiment by the single-phase critical flow of steam through an orifice plate. The orifice plate was sized to deliver approximately 79 ft/sec (24 m/sec) in the 1-inch pipe test apparatus since this represents the upper limit of steam generation within the fan coolers that would enable liquid to remain in the fan cooler coils. For an upstream pressure of 15 psig (2 bars absolute) an orifice plate of 1/4″ would be sufficient to deliver this steam flow. Obviously, higher pressures in the steam generator would cause higher flows into the test apparatus. Orifice sizes of 1/8″ and 3/16″ were also used to investigate the influence of small vaporization rates.

Many of the issues related to the formation of significant waterhammer loads are related to the specific configuration of the piping layout. In particular, loop seals are places where stratified steam-water configurations could develop, thereby leading to the formation of water slugs that could be accelerated through the piping. These geometrical features were included and will be discussed in the section on the experimental configuration.

The final scaling issue relates to the water refill rate since this dictates the means whereby the steam void would be condensed and fluid transients (including water hammer) are experienced that ultimately lead to the return of the service water flow to the steady-state conditions. The most important element of this refill rate is the Froude number given by

$$Fr = \frac{U_w}{\sqrt{gD}} \tag{2-2}$$

where U_w is the refill velocity and D is the pipe inner diameter. If this Froude number approaches or exceeds unity, the horizontal pipe will run filled with water (Wallis et al., 1977) and significant condensation induced waterhammer would not occur during this refilling transient (Bjorge and Griffith, 1984; Izenson et al., 1988). If this is the case, the dynamic loads on the piping system and the piping supports would be those related to the refilling velocity and the pressure associated with this is given by the waterhammer equation

$$\Delta P = \rho_w \, a_w \, U_w \tag{2-3}$$

where a_w is the speed of sound and water. As will be discussed, the Froude number for the refilling of the fan cooler discharge piping is substantially greater than 1. Therefore, this is another key scaling element to be represented in an experimental investigation.

Another aspect of the refilling rate is the behavior of the vertical piping with the water being added at the top of the piping configuration. In this regard, the drainage behavior of the piping segment can be related to the refilling rate to determine if the vertical piping can run full in the downward direction or whether it is determined by the drainage of film and/or rivulets as well as water falling through the central region of the pipe. For this we need to consider film

drainage and the bubble rise velocity for slug flow.

Figure 2-1 illustrates the laminar film draining process represented in Nusselt's analysis for a condensing film (Kreith, 1960). For this particular assessment, we are only concerned with the drainage rate and not the tension distribution through the film. Table 2-1 outlines a calculation that examines the steady-state film thickness needed to drain the imposed liquid flow rate for the 8-inch discharge piping at an assumed refilling rate of 1000 gpm. An indicated by this calculation, the 8-inch pipe would not run full of water. However, this calculation shown in Table 2-1 only represents the steady-state drainage rate and the liquid must accelerate, by gravity, to this condition. Table 2-2 approximates this acceleration and shows that after 3 ft (.9 m) the average film drainage rate would be approximately 10 ft/sec (3 m/sec) and the film thickness would be somewhat larger than one inch.

This approximate representation for the water drainage illustrates two important aspects which control the two-phase flow pattern. First, once a liquid film is formed and accelerates, the drainage rate for modest film thicknesses is more than sufficient to drain the incoming flow rate. Conversely, the accumulated water at the top of the vertical segment has no significant downward velocity, hence, water would accumulate and tend to be pushed downward at the refill velocity. This would form a steam bubble (Figure 2-2) which would tend to rise against the incoming water flow rate. Wallis (1969) characterizes the rise velocity of such inertially dominated steam bubbles as

$$U_\infty = 0.345 \left\{ \frac{gD(\rho_w - \rho_g)}{\rho_w} \right\}^{1/2} \tag{2-4}$$

where the constant 0.345 has been deduced experimentally but is quite close to that derived analytically by Davies and Taylor (1950) and others. Since the water density is far greater than that of steam, this essentially reduces to

$$U_\infty = 0.345 \sqrt{gD} \tag{2-5}$$

For the 8-inch discharge piping, this rise velocity is about 1.6 ft/sec (0.5 m/sec), which is

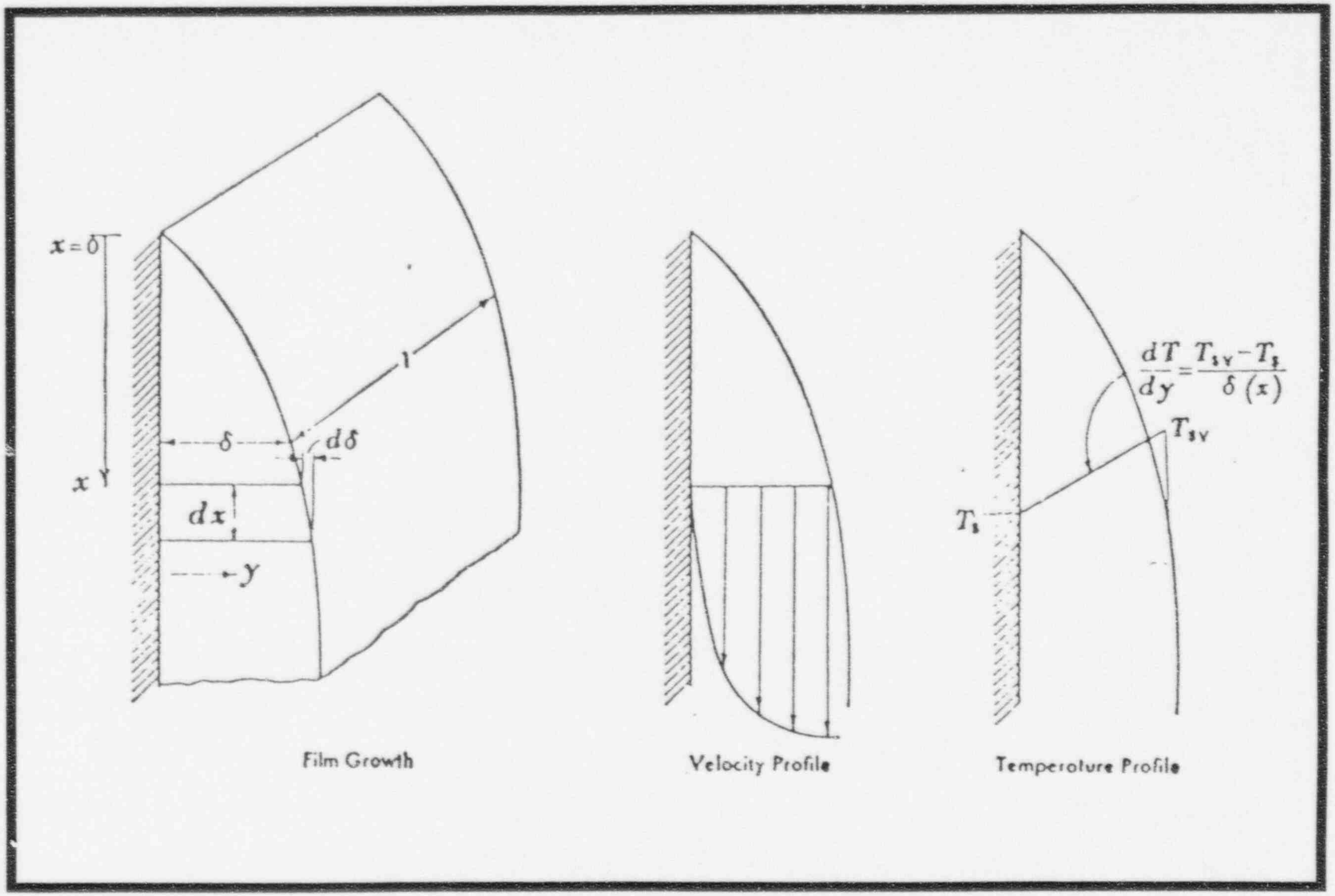

Figure 2-1 Filmwise condensation on a vertical surface - film growth, temperature distribution, and velocity profile (taken from Kreith, 1960).

Table 2-1
Drainage Calculation for a Vertical Pipe

Assume Nusselt's analysis for laminar film flow

Flow Rate per Unit of Wall Length

$$\Gamma \text{ (kg/sec/m)} = \frac{\rho^2 \, g \, \delta^3}{3\mu}$$

$$\delta = \left\{\frac{3\mu \, \Gamma}{\rho^2 \, g}\right\}^{1/3}$$

$$\Gamma = \frac{61 \text{ kg/sec}}{\pi \, (0.2) \text{ m}} = 97 \text{ kg/sec/m}$$

ρ = 100 kg/m^3
μ = 5 x 10^{-4} N•sec/m^2
g = 9.8 m/sec^2
δ = 2.5 mm (0.1 in)

This is much less than a thickness that would fill a pipe, i.e. the 8-inch discharge would not run full.

Flow Rate Per Unit Length
for the 2-1/2" Discharge Pipe

$$\Gamma = 12.1 \text{ kg/sec/m}$$

$$\delta = 1.2 \text{ mm (0.05 in)}$$

The 2-1/2" outlet piping from each coil unit will not run full.

Table 2-2
Approximate Representation of the Transient Water Film Development

$$u_{max} = gt$$
$$\bar{u} = 2/3 \, u_{max} = 2/3 \, gt$$
$$t \sim \sqrt{2 \, x/g}$$
$$\bar{u} = 2/3 \, \sqrt{2gx}$$

x (m)[ft]	$\bar{u}$ (m/sec)[ft/sec]	δ (mm)[in]
1 [3.3]	3 [9.8]	33 [1.3]
4 [13.1]	6 [19.7]	16 [0.63]
8 [26.2]	8.4 [27.5]	12 [0.47]

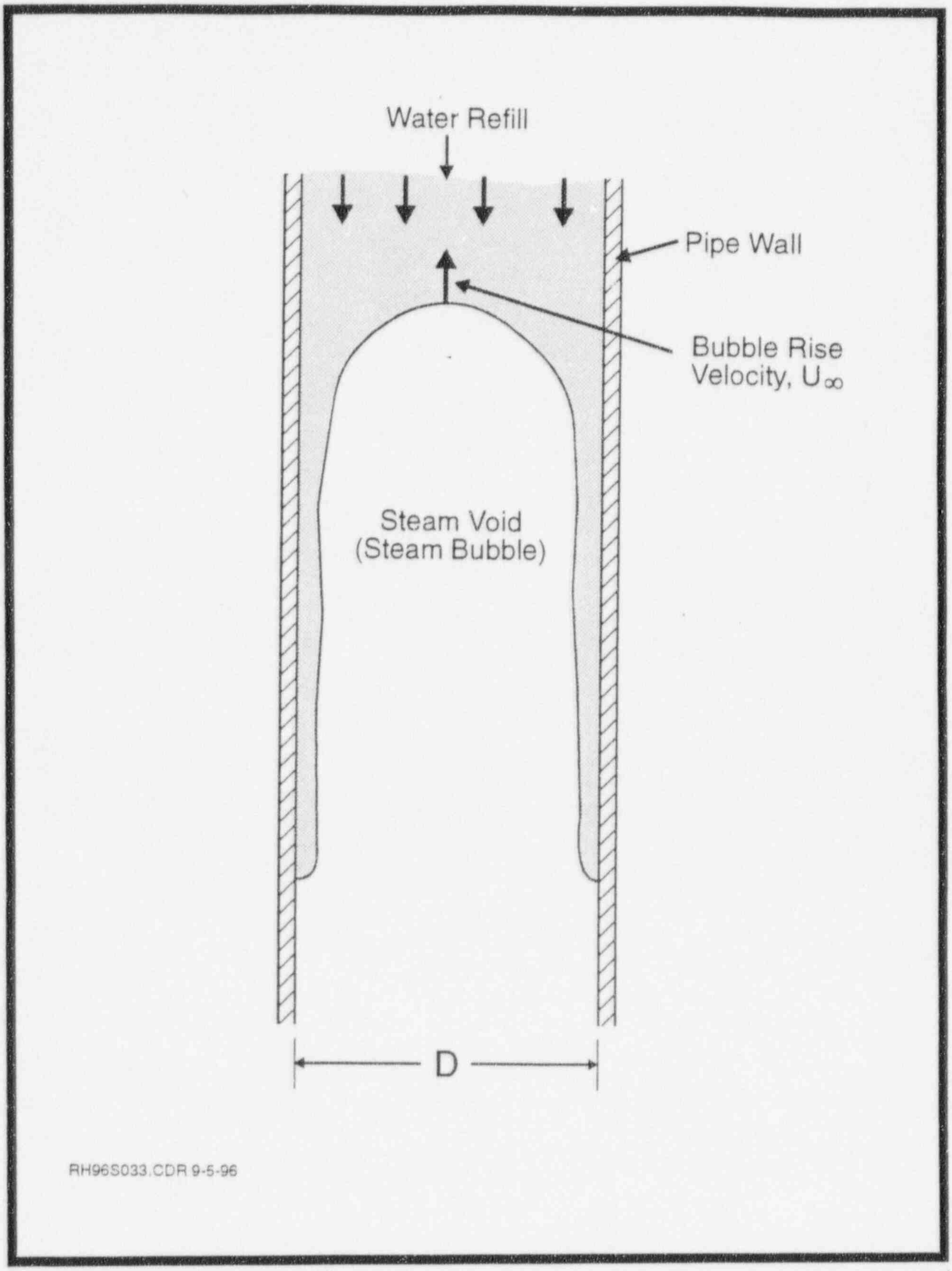

Figure 2-2 Representation of the bubble rise for a steam void during refill.

much less than the refill velocity. Consequently, while the film drainage rate is sufficient to drain away the water after the film has accelerated, the steam bubble rise velocity is too small compared to the water refill rate to enable a steam void to remain in place. Thus, from hydrodynamic considerations alone, the steam void would be "pushed" ahead of the water refill region. As will be discussed in Section 3, those thermocouples inserted into the central region of the vertical and horizontal pipes indicate that the regions are "quenched" sequentially at a rate that is in excellent agreement with the refill velocity.

With these considerations for the two-phase flow behavior in the horizontal and vertical components of the piping configuration, the general two-phase flow behavior in the discharge piping during refill is illustrated in Figure 2-3. Since there is some potential for either film drainage or free fall of water droplets through the central region of the pipe, there is a strong likelihood that a two-phase front would be developed at the leading edge, particularly in the horizontal part of the piping. This two-phase region would certainly tend to "cushion" any impacts associated with the refill at sharp turns in the piping configuration or at an impact on partially open valves. The influence of such behavior is discussed further with respect to the experiments in Section 3.

2.2 Experimental Apparatus

To address the phenomena identified in Section 2.1, an experimental apparatus was constructed to create a situation in which:

a) column separation could occur once the imposed flow rate was removed (decayed),

b) steam generation would be added to the piping configuration,

c) a significant size loop seal exists at the bottom of the piping and

d) water refill rates would be imposed on the system for Froude numbers typical of those of interest in the Point Beach service water system.

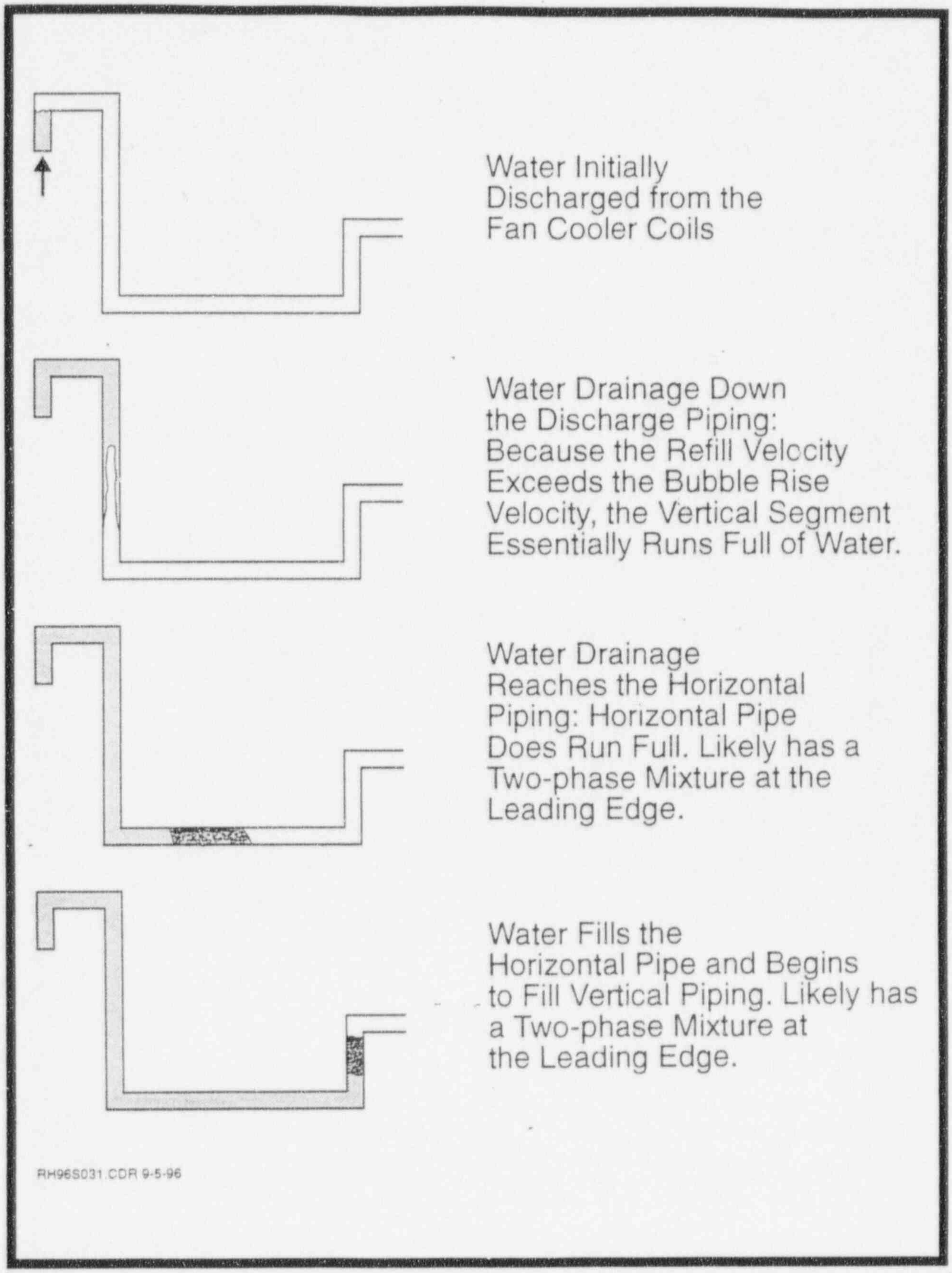

Figure 2-3 Two-phase flow patterns during refill of the discharge piping.

Figure 2-3 illustrates the general configuration used for these experiments and also indicates the relative elevation differences in the piping configuration. This experiment was assembled with 1-inch piping in the region of interest from the mixing zone immediately downstream of the two solenoid driven ball valves, through the 19.4 ft (5.9 m) vertical down leg and the remainder of the piping into the large evacuated received vessel.

As illustrated in Figure 2-4, the instrumentation consisted of pressure transducers located at the major changes in flow direction and thermocouples along the pipe. There were two different configurations used in this set of experiments. Figures 2-4 and 2-5 illustrate configurations #1 and #2, respectively. Both configurations used a gate valve to set the water flow rate through the piping, and this valve was responsible for virtually all of the pressure loss between the water supply vessel and the evaluated received vessel. Typically, this control valve was set by conducting isothermal experiments to establish a water flow rate through the test configuration which was representative of the conditions of interest in the Point Beach system. Once this control valve setting was achieved, this was not varied for a given set of experiments.

The major differences between the configurations are (a) how the flow was controlled and (b) the measurements of temperatures in the voided regions. Note the principle differences are that (a) in configuration #2 an additional gate valve was used in the water supply system to control the water flow to be more representative of the restart transient for the Point Beach service water pumps, and that (b) the thermocouples in the vertical and loop seal sections were installed in the central region of the pipe instead of being surface mounted. With this modification of the thermocouple location, the extent of void growth and collapse in the piping system is easy to determine.

To set up the test conditions, isothermal experiments were performed to obtain the settings for the gate valves used to control the flow from the test apparatus in the first configuration as well as the flow into and from the test apparatus in the second configuration. Typically these were set up to achieve the desired Froude number in the experiment. In particular, considering that the experiment was performed in 1-inch piping (ID = 1.049 in/0.0266 m) and the service water system has 8-inch piping (8.071 in/0.205 m), the refill velocity decreases as the square root of the pipe diameter. Hence, the water velocity in the

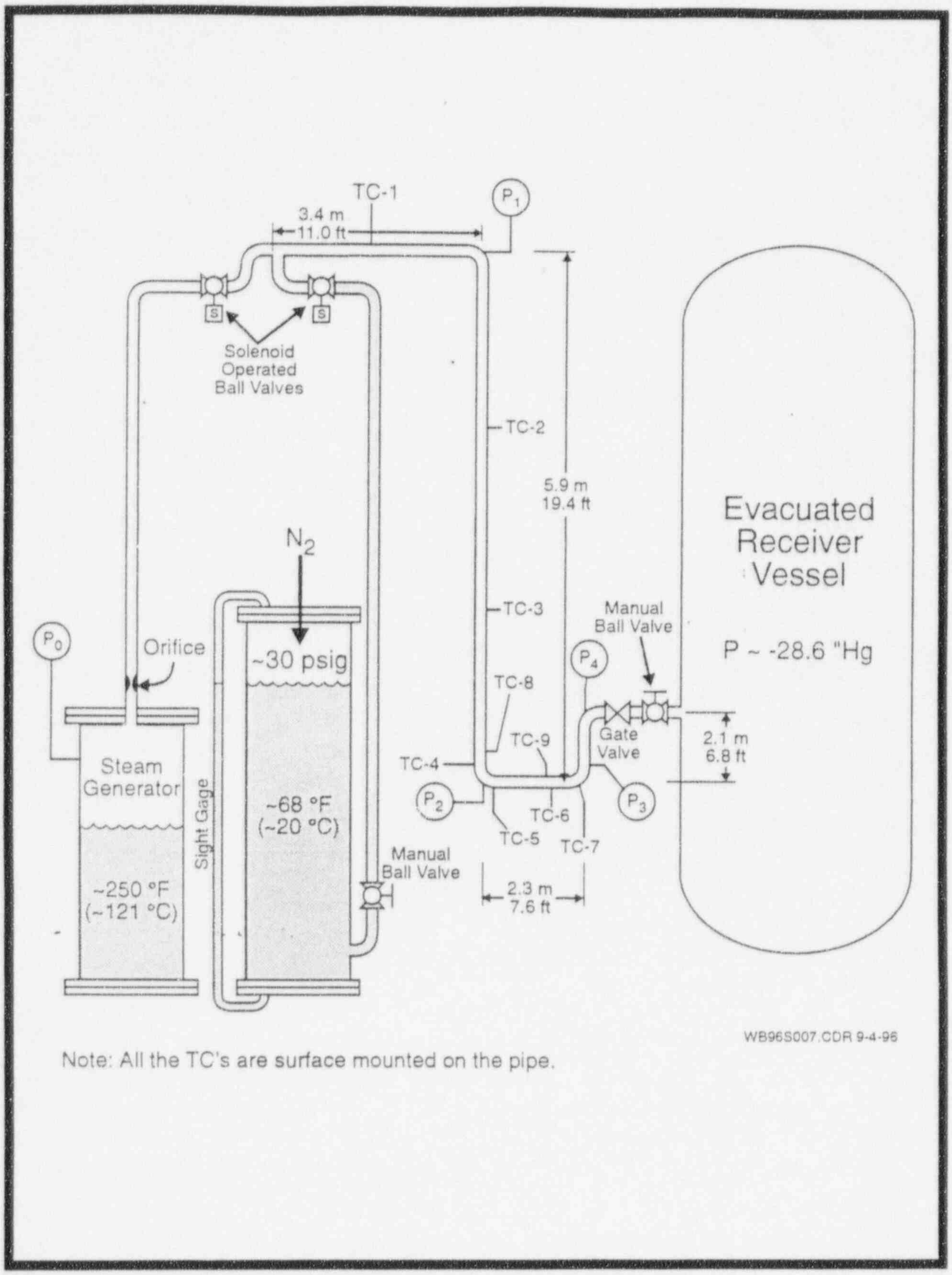

Figure 2-4 Waterhammer experiment (configuration #1).

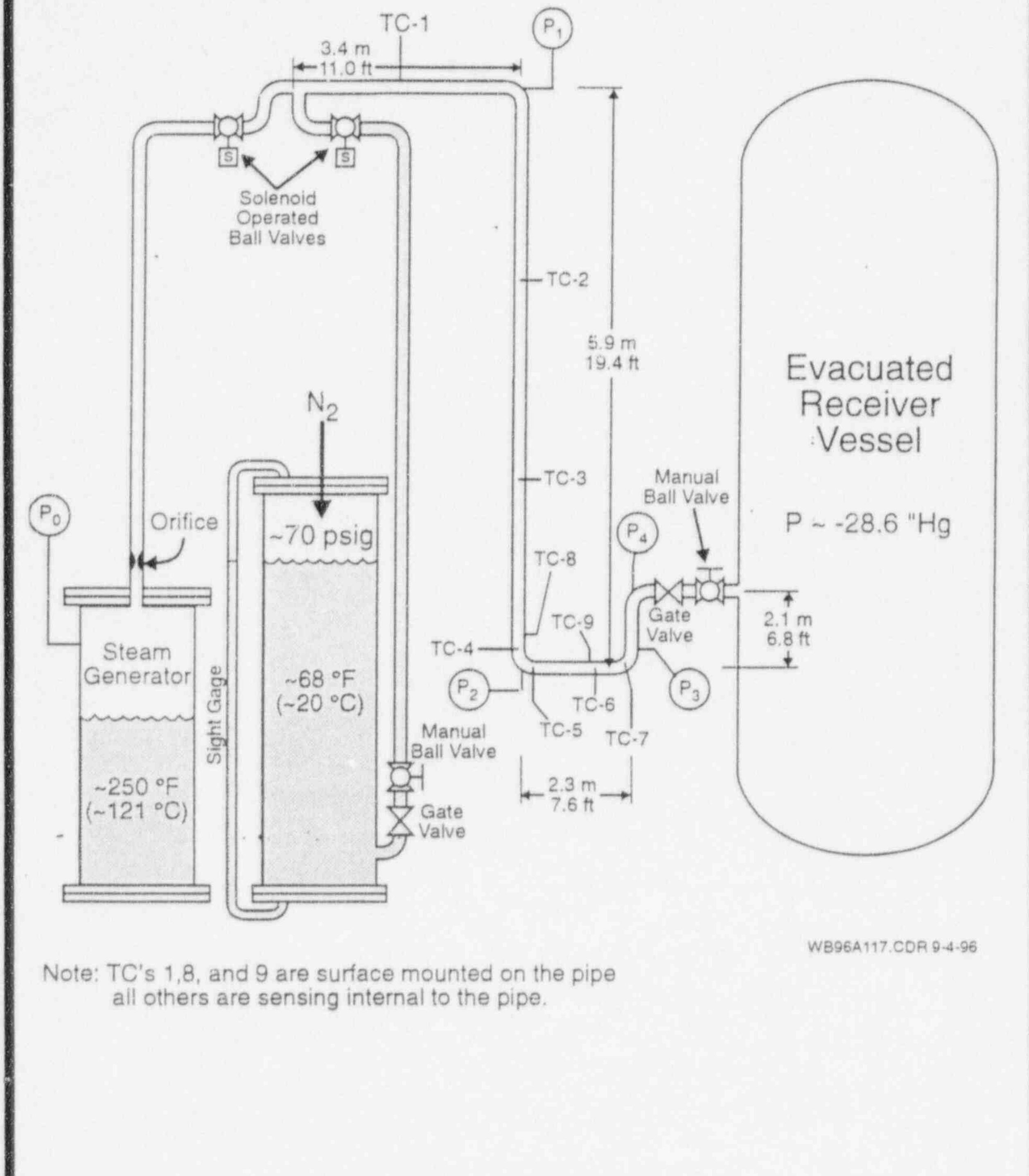

Figure 2-5 Waterhammer experiment (configuration #2).

experiment should be about 36% of the velocity in the service water system. For 1000 gpm flow rate, which is typical of the Point Beach case, the experimental flow rate should be about 2.5 ft/sec (0.76 m/sec).

A given test was typically run by establishing cold water flow through the entire flow circuit in approximately 10 seconds, simultaneously closing the ball valve for the water supply and opening the ball valve for the steam flow into the piping configuration. The steam flow was maintained for a pre-determined interval then the steam supply ball valve was closed and the water ball valve opened again to introduce cold water into the steam void.

One of the uncertainties to be addressed for the service water system is whether the evaluation is sensitive to a) the time at which off-site AC power is lost to the service water system and to b) the interval between when the AC power is lost and re-established by starting of the diesels. To address this in the experimental investigations, the interval for steam addition was varied from approximately 20 seconds to 1 minute to examine the influence of the magnitude of the initial steam bubble. Table 2-3 shows the variations in the parameters considered in the test program. Note also that the steam addition rate was varied by using three different orifices to control the steam line flow. Since most of the attention was to be directed at formation of a steam void and subsequently refilling of the horizontal loop seal, the largest steam orifice was used for most of the experiments.

One of the important parameters in setting up the condition for a given experiment is the pressure in the test section during the water flow conditions prior to initiating flow decay. To provide a situation similar to that in the Point Beach fan cooler discharge, the control valve at the discharge and at the test apparatus was adjusted such that the pressure in the test apparatus was approximately 30 psig (a total of approximately 3 bars). This provides a reasonable representation of the pressure within the test assembly under nominal flow conditions and therefore provides a good characterization of the steam pressure that could be created by vaporization within the fan cooler coils.

Typically a run was initiated by opening the ball valve at the entrance to the evacuated receiver vessel then opening the solenoid operated ball valve initiating water flow into the test apparatus. Through this set of conditions, the processes of column separation and column

Table 2-3
Waterhammer Test Data

Test	Steam Orifice Size (in)	Initial Water Temp (°F)	Water Reservoir Pressure (psig)	Initial Steam Temperature (°F)	Receiver Vessel Pressure (in Hg)	Initial Water Flow Interval (secs)	Steam Flow Interval (sec)
1	1/8	68	30	256	-28.8″	10	15
2	1/8	68	30	253	-28″	10	30
3	3/16	68	30	258	-28.6″	10	20
4	3/16	68	30	258	-28.6″	10	30
5	3/16	68	30	254	-28.6″	10	40
6	3/16	68	30	248	-28.6″	10	50
7	1/4	68	30	283	-28.6″	10	30
8	1/4	68	30	279	-28.6″	10	40
9	1/4	68	30	272	-28.6″	10	50

Table 2-3 (Continued) Waterhammer Test Data							
Test	Steam Orifice Size (in)	Initial Water Temp (°F)	Water Reservoir Pressure (psig)	Initial Steam Temperature (°F)	Receiver Vessel Pressure (in Hg)	Initial Water Flow Interval (secs)	Steam Flow Interval (sec)
10	1/4	68	67	271	-28.6	10	40
11	1/4	68	68	271	-28.6	10	50
12	1/4	68	69	279	-28.6	10	60
13	1/4	68	68	277	-28.5	10	30
14	1/4	68	68	277	-28.5	10	20
15	1/4	68	68	266	-28.5	20	40
16	1/4	68	68	268	-28.5	20	~120

rejoining could be observed in the experiment. Once water flow was initiated it was sustained for a few seconds to establish the initial conditions, then the water supply solenoid driven ball valve was closed and the ball valve for the steam flow was opened. This enabled steam to enter into the upper horizontal leg of the test apparatus and, depending upon the orifice size and the duration of the steam flow, the void propagated into the down leg and loop seal components of the test section. After the steam had flowed into the test apparatus for a pre-determined interval, the steam valve was closed and the water valve re-opened to permit water flow to the test apparatus as dictated by the driving pressure and the specific configuration, with configuration #2 being more representative of the plant behavior resulting from restart of the service water pumps.

2.3 Experimental Results

While the experiment was capable of recording the fluid transients associated with column separation, rejoining, steam addition, water refill and finally closing of the manual ball valve immediately upstream of the evacuated received vessel, the elements of primary interest were the pressures recorded as the water refilled the steam space and re-established the nominal flow rate from the water supply vessel to the evacuated received vessel. This was the configuration of interest for waterhammer in the test configuration including the loop seal formed at the bottom of the test apparatus. Thus, the element of principle interest was the dynamic pressure associated with this part of the complete pressure history recorded by the various transducers. Table 2-4 shows the peak pressures measured for the various experiments as well as the estimated refill velocity as indicated by the time interval necessary to fill the void within the test apparatus. As indicated in the table, there is a substantial difference between configuration #1 and configuration #2 which results from the control water flow in configuration #2. This will be discussed further in Section 3.0.

Table 2-4
Waterhammer Data

Test Configuration	Test	Estimated Water Refill Velocity (ft/sec)	Peak Pressure Experienced During Refill (psig)	Peak Pressure at Other Times (psig)
1	1	cannot be resolved	40	84 flow start
1	2	cannot be resolved	28	74 flow start
1	3	cannot be resolved	40	58 column rejoining
1	4	10	60	280 flow initiation
1	5	15	60	120 flow initiation
1	6	15	76	64 flow stop
1	7	19	170	none
1	8	22	260	180 flow stop
1	9	22	160	none
2	10	3.5	35	38 at switch from water to steam
2	11	4.0	33	35 at switch from water to steam
2	12	3.5	35	40 at switch from water to steam
2	13	3.7	30	160 flow stop
2	14	4.0	28	40 at switch from water to steam
2	15	< < 1	32	62 (voiding)
2	16	< < 1	33	48 (voiding)

3.0 DISCUSSION OF EXPERIMENTAL RESULTS

As shown in Table 2-4 there is a substantial difference in the waterhammer pressures arising from the two different configurations. This is due to the presence of the upstream control valve in the second configuration that limits the refill rate to a value typical of the Point Beach service water system when scaled according to the Froude number. In particular, for the same Froude number value, a 1-inch pipe should have a velocity that is about 35% of that an 8-inch pipe. Hence, for the condition in which the velocity in the service water system is 7 ft/sec (2.1 m/sec), the 1-inch pipe should be approximately 2.5 ft/sec (.76 m/sec). This was the original velocity set up in the second configuration and was represented by the pressure difference between the water vessel and the test apparatus of 30 psig (60 psig minus 30 psig). The refill velocity itself can be assessed by the changes in the thermocouples as cooling water is added. Consider the information shown in Figure 3-1 in which the thermocouple information (TCs 2, 3, 4, 5, 6 and 7 are embedded in the central region of the pipe) are shown along with the pressure measurements from pressure transducers (P1, P2, P3 and P4). Approximately 10 seconds of normal flow were established with the pressure at about 20 psig and flow decay was initiated at about 15 seconds into the experiment. The interval for steam flow was 60 seconds and examination of the embedded thermocouples show all reaching the saturation pressure as indicated by the essentially linear increase in temperature when the pressure increases linearly. This indicates that the void formation was virtually through the entire test apparatus. Cold water was added at approximately 75 seconds and required about 13 seconds to refill (as indicated by the rapid increase in the test apparatus pressure) which corresponds to an average refill rate of 3.4 ft/sec (1.03 m/sec). Figures 3-2 and 3-3 are expanded views of the thermocouples in the vertical section (Figure 3-2) and the horizontal part of the loop seal (Figure 3-3). It is clear from these measurements that the water flow rate essentially moved through the test apparatus at an average velocity of about 3.5 ft/sec (1.07 m/sec). The interval between TC-2 and TC-3 and that between TC-3 and TC-4 is 8.7 ft (2.8 m).

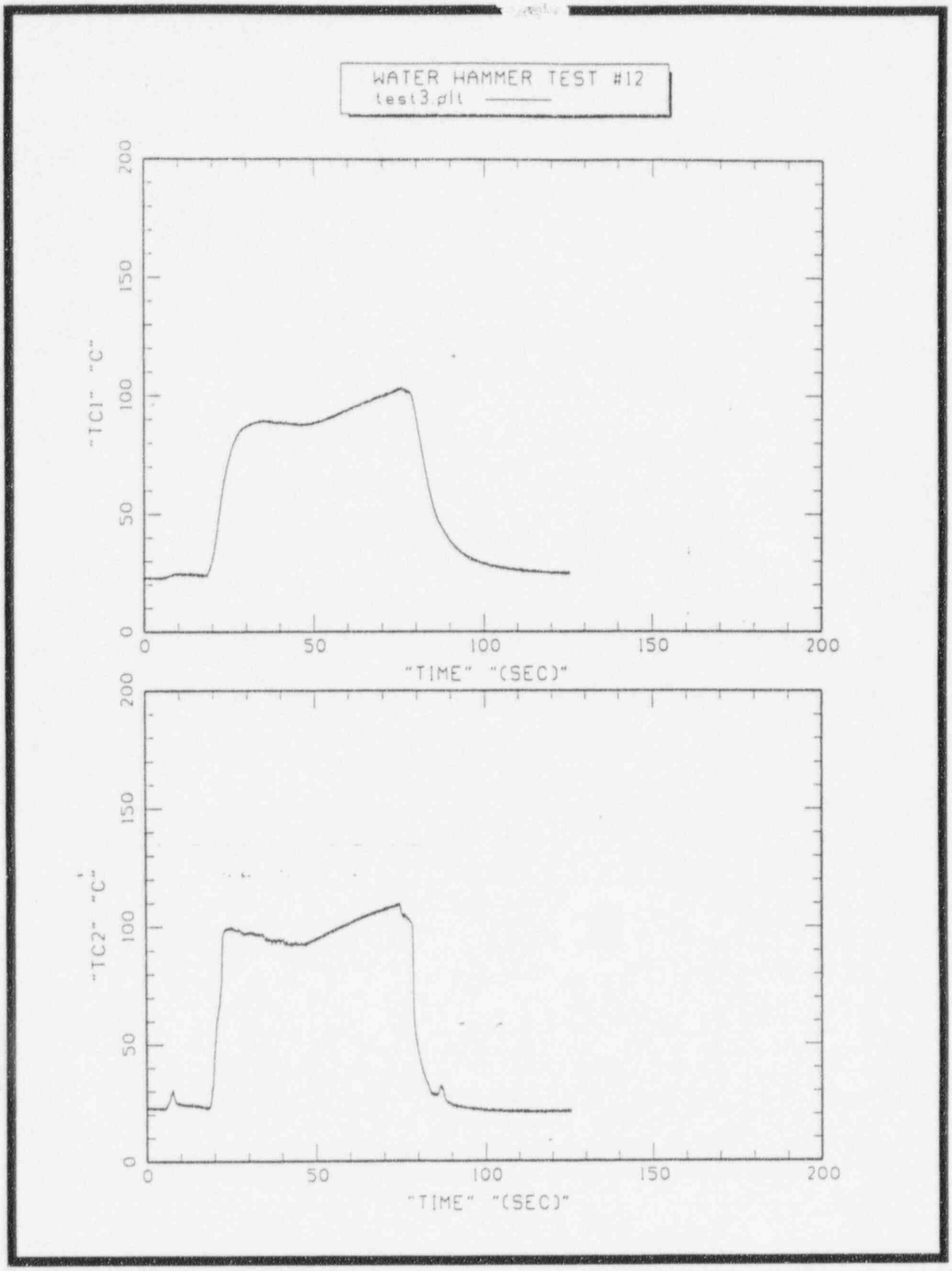
WATER HAMMER TEST #12
test3.plt
"TC1" "C"
0
50
100
150
200
"TIME" "(SEC)"
"TC2" "C"

Figure 3-1

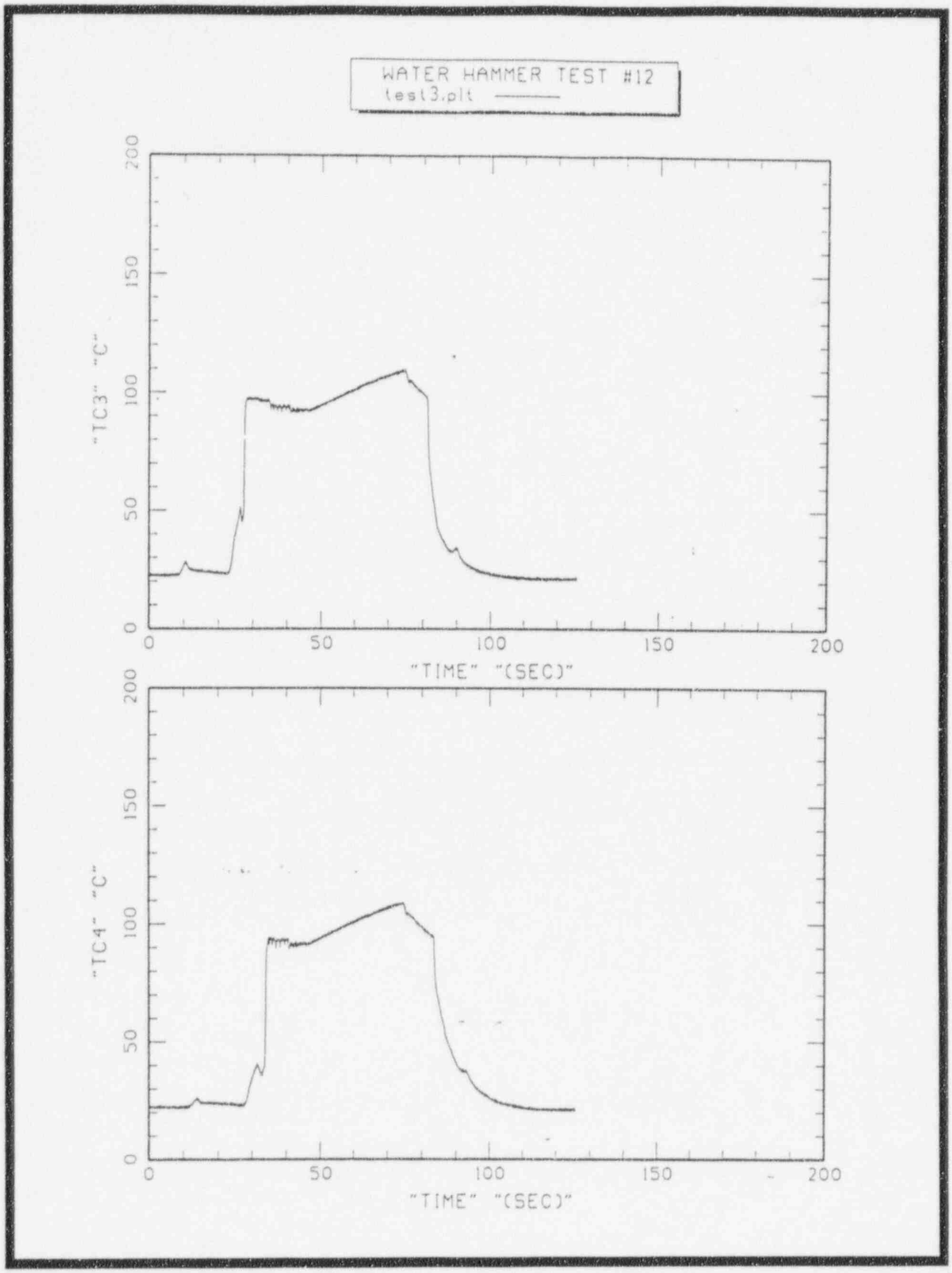

Figure 3-1 (Cont'd)

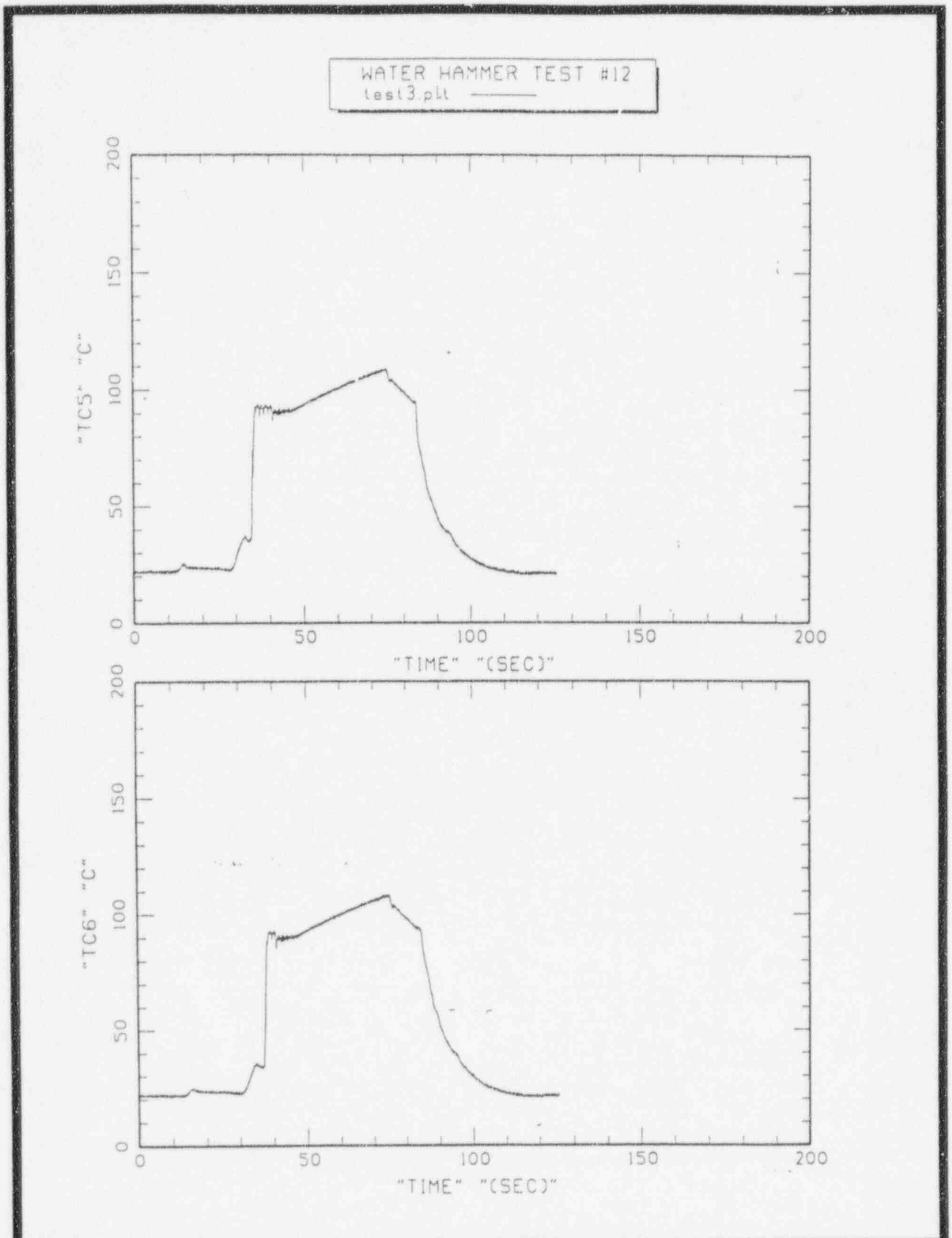

Figure 3-1 (Cont'd)

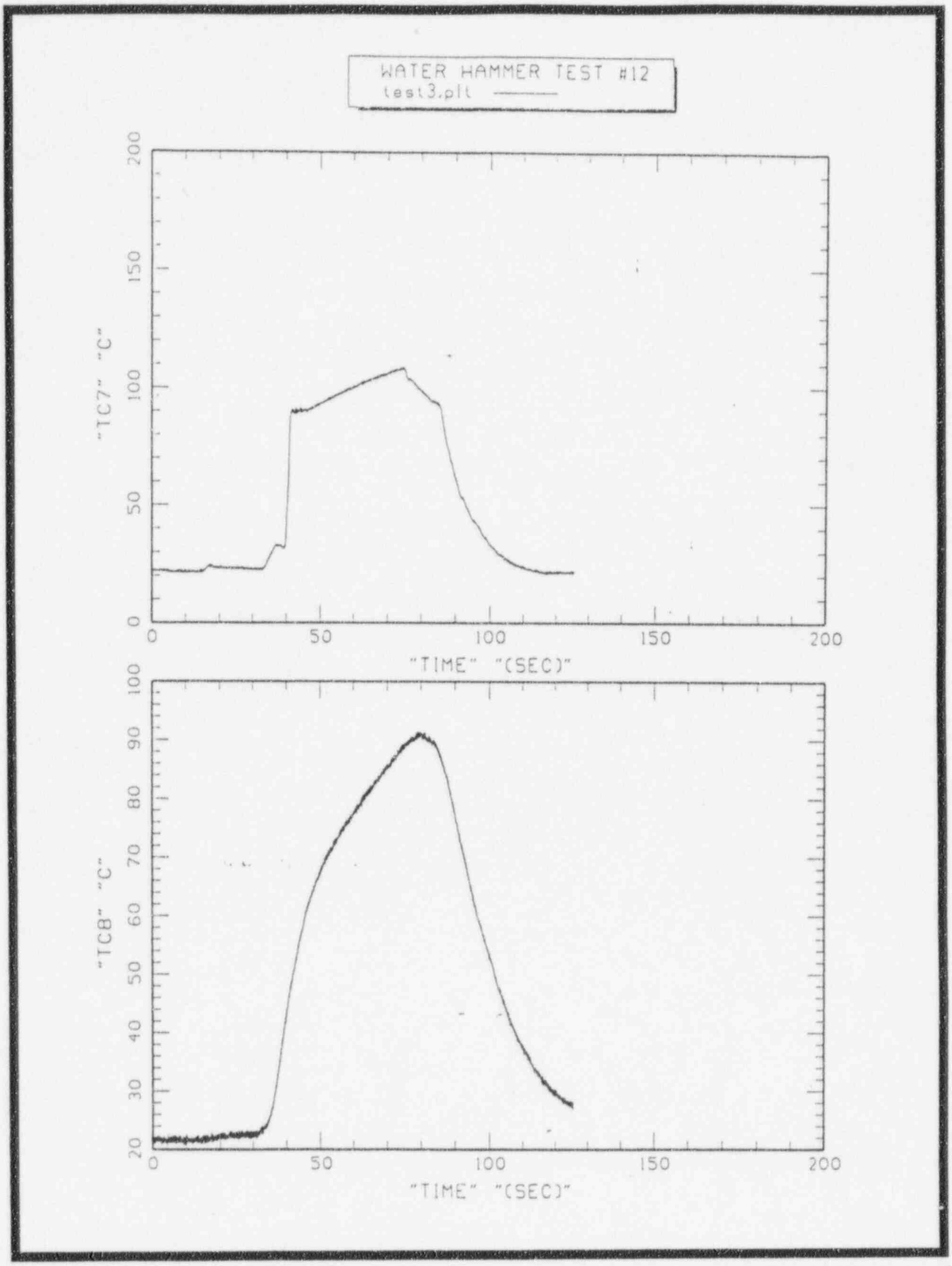

Figure 3-1 (Cont'd)

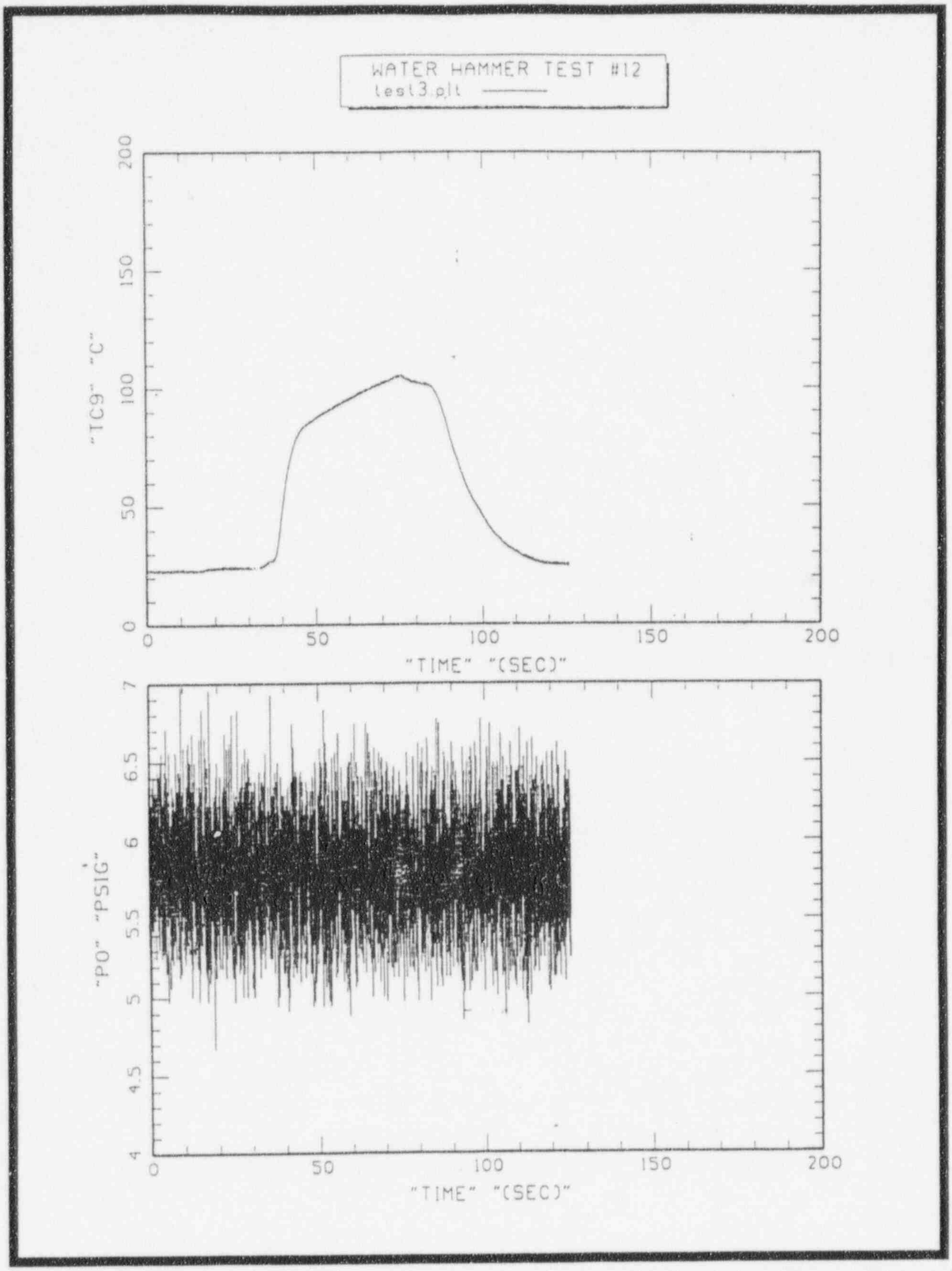

Figure 3-1 (Cont'd)

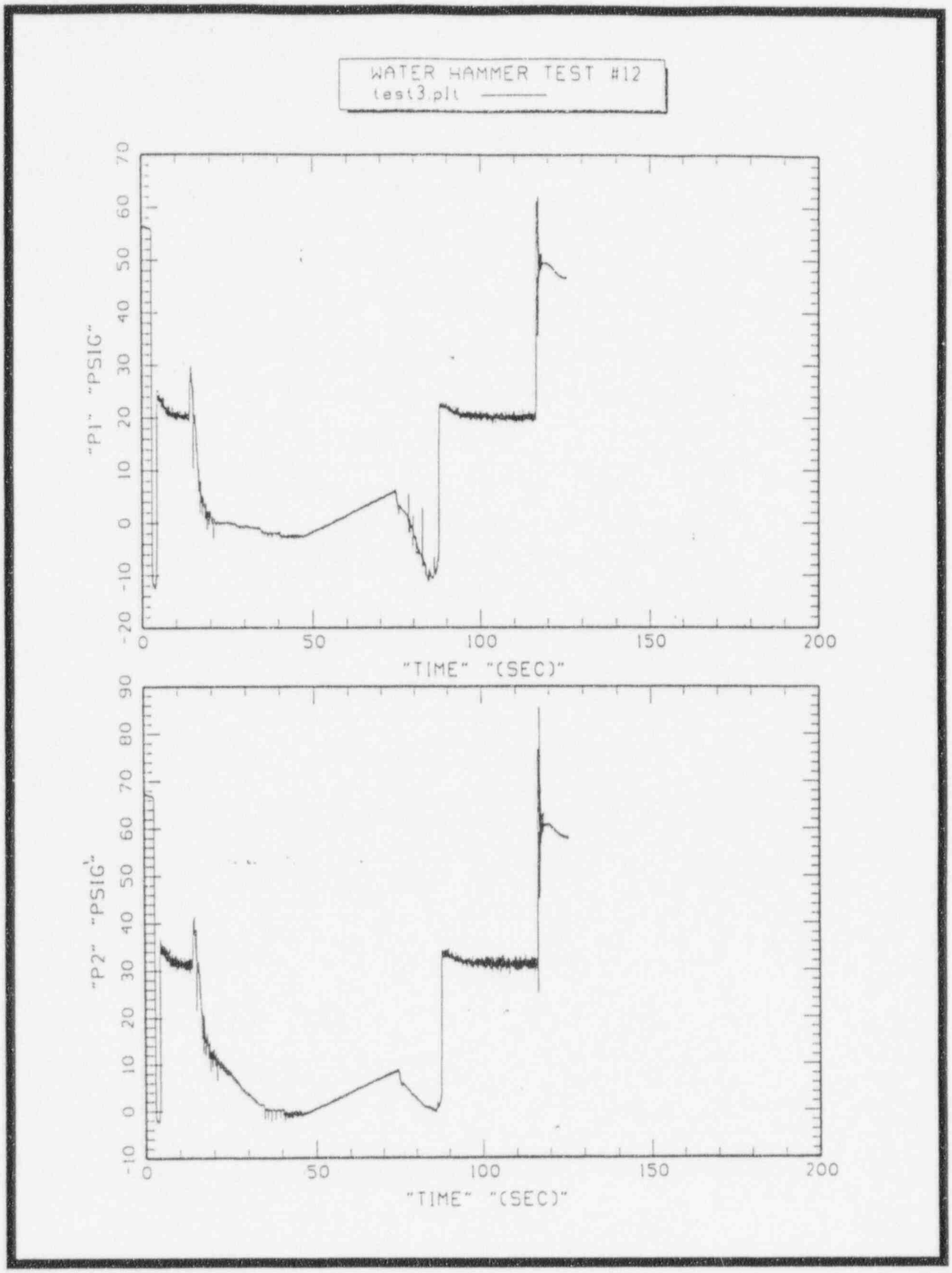

Figure 3-1 (Cont'd)

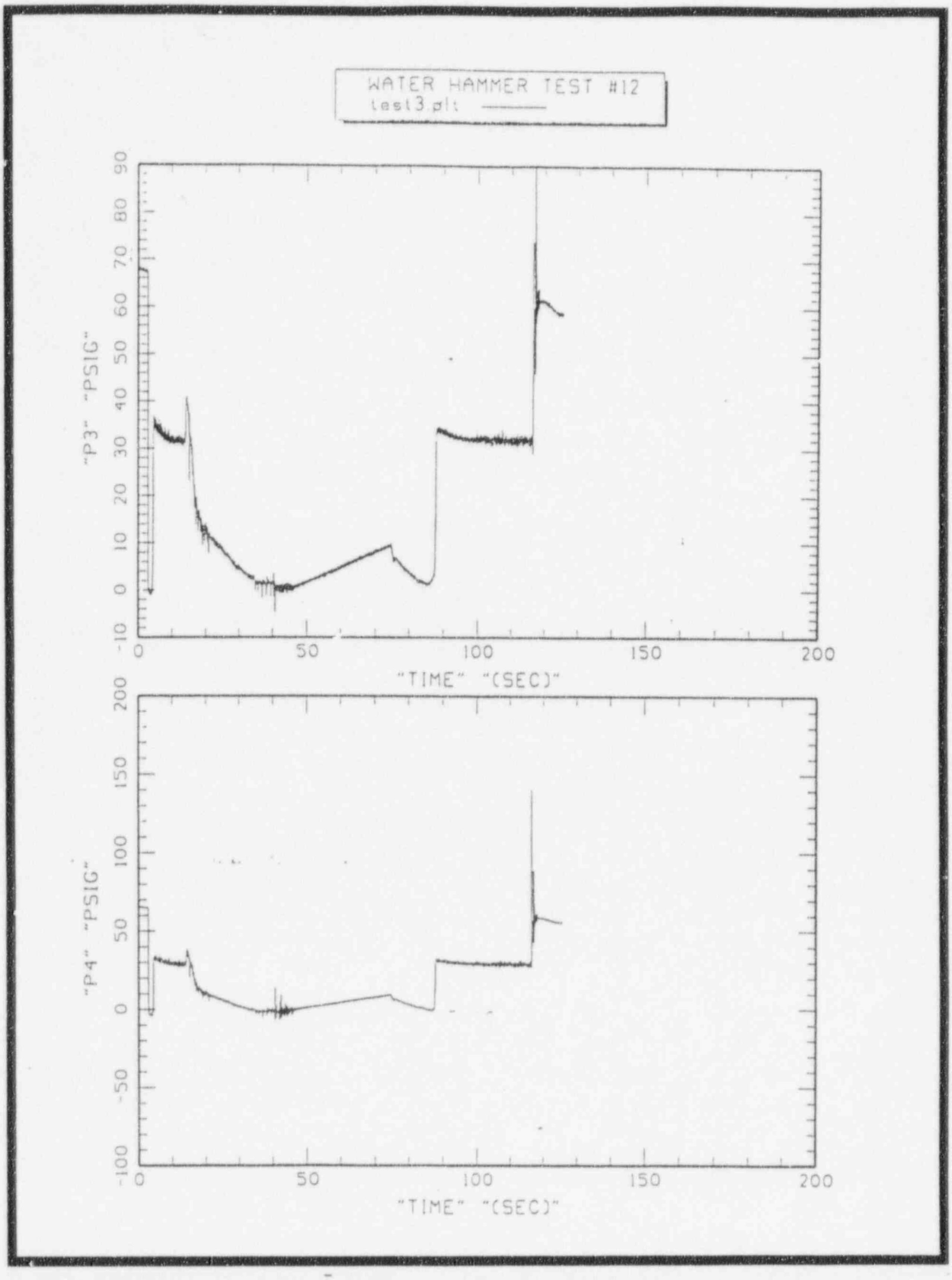

Figure 3-1 (Cont'd)

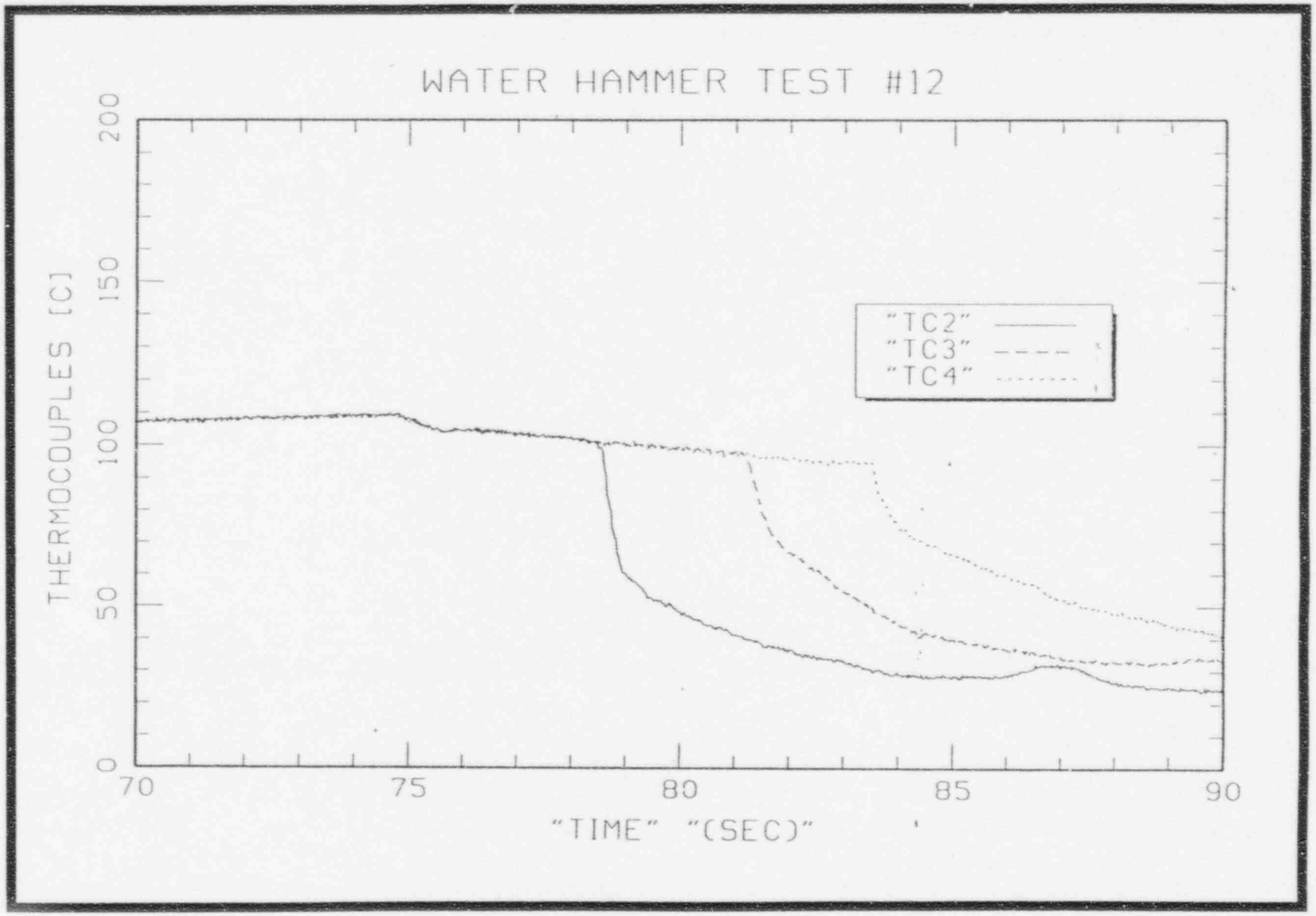
WATER HAMMER TEST #12
THERMOCOUPLES [C]
200
150
100
50
0
"TC2"
"TC3"
"TC4"
70
75
80
85
90
"TIME" "(SEC)"

Figure 3-2

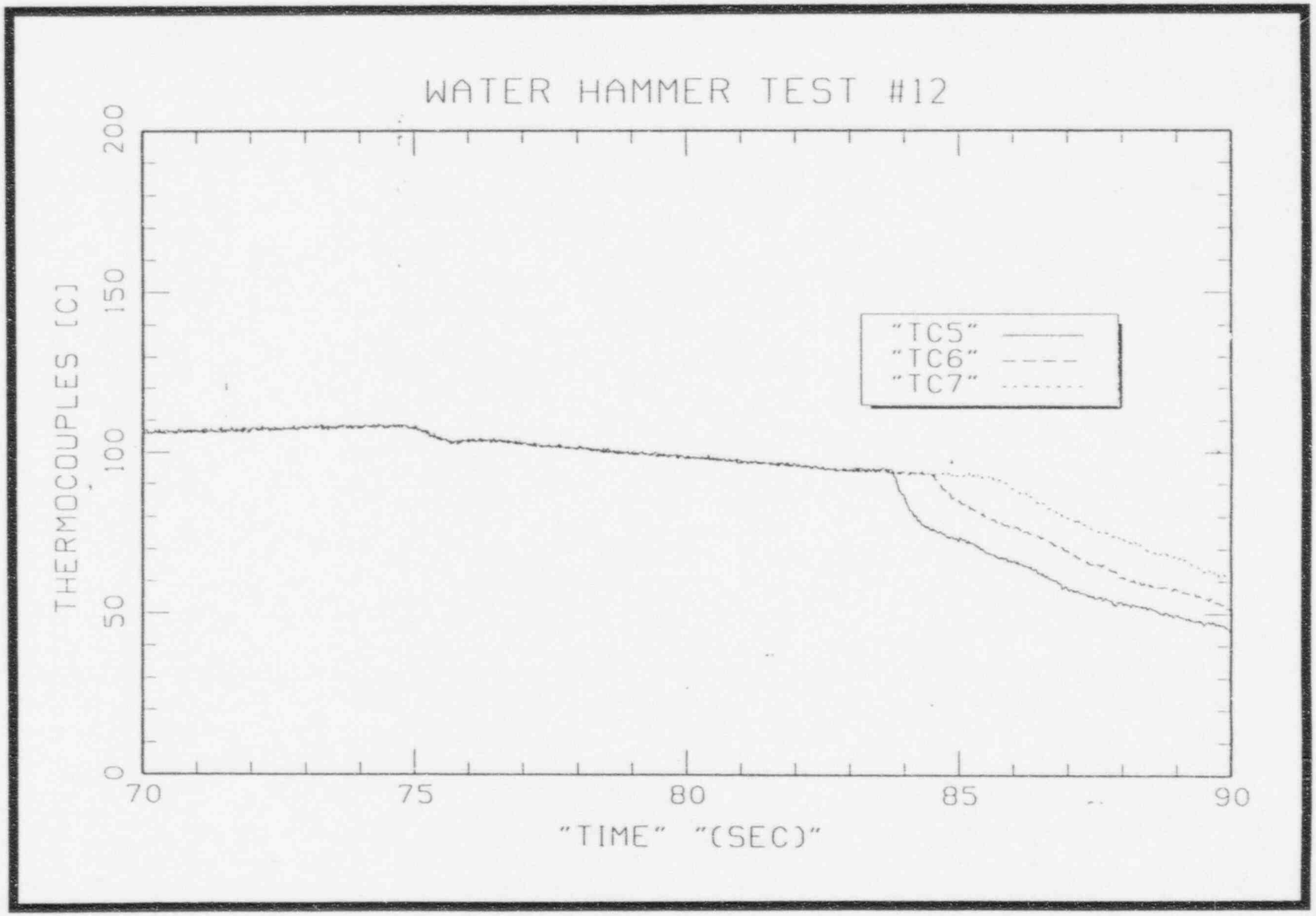
WATER HAMMER TEST #12
THERMOCOUPLES [C]
0
50
100
150
200
70
75
80
85
90
"TIME" "(SEC)"
"TC5"
"TC6"
"TC7"

Figure 3-3

This is particularly important for the service water system since these scaled experiments demonstrate no indications of significant waterhammer during the voiding and refill condition. In fact, the maximum pressure measured upon refilling of the test apparatus was the pressure necessary for steady flow through the system.

As discussed previously, the first test configuration was operated in a substantially different manner. In particular, there was no control valve upstream of the test section to control the water flow into the test apparatus. Thus, when cold water was initiated into the steam void, the pressure difference accelerating the water was approximately 30 psi and this was only opposed by the pipe friction. Consequently, the refill velocity could be substantially greater and as illustrated by the information given in Table 2-4, the refill rate corresponded to velocities of 10 to 20 ft/sec (3 to 6 m/sec). Correspondingly, the measured pressures associated with refilling of the test apparatus were substantially higher although considerably less than those that would be calculated from the waterhammer equation of a water column being stagnated on a solid boundary. Thus, the first nine experiments, while exhibiting substantial pressure increases, are a highly conservative representation of the behavior in the Point Beach service water system. Test results from configuration #2 are considered to be typical of the service water system response in the CFCS given the DBA conditions.

To assure that the experimental configuration would detect waterhammer, tests 15 and 16 were performed at very low Froude numbers, i.e. approximately 0.1. Under these conditions, the experiment observed substantial waterhammer activity in the upper horizontal portion during the voiding period. Figure 3-4 illustrates that activity in the interval between 10 and 35 seconds which is during the interval of steam addition. Thus, the experimental apparatus will indeed observe slugging phenomena when the Froude number is well below unity. This adds credibility to the Froude number scaling that is a fundamental basis for relating the experiment to the service water system.

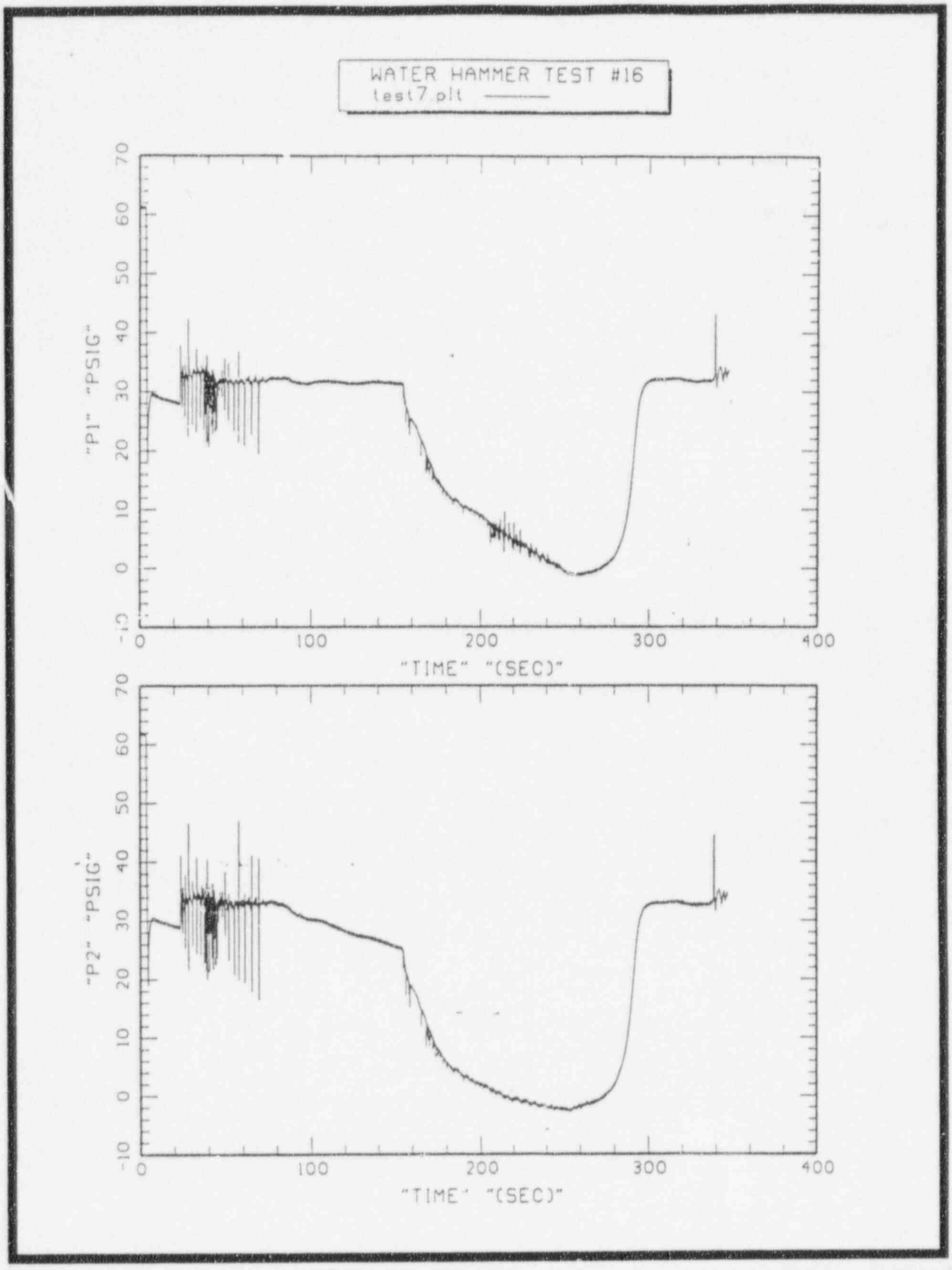
WATER HAMMER TEST #16
test7.plt
"P1" "PSIG"
"TIME" "(SEC)"
"P2" "PSIG"
"TIME" "(SEC)"

Figure 3-4

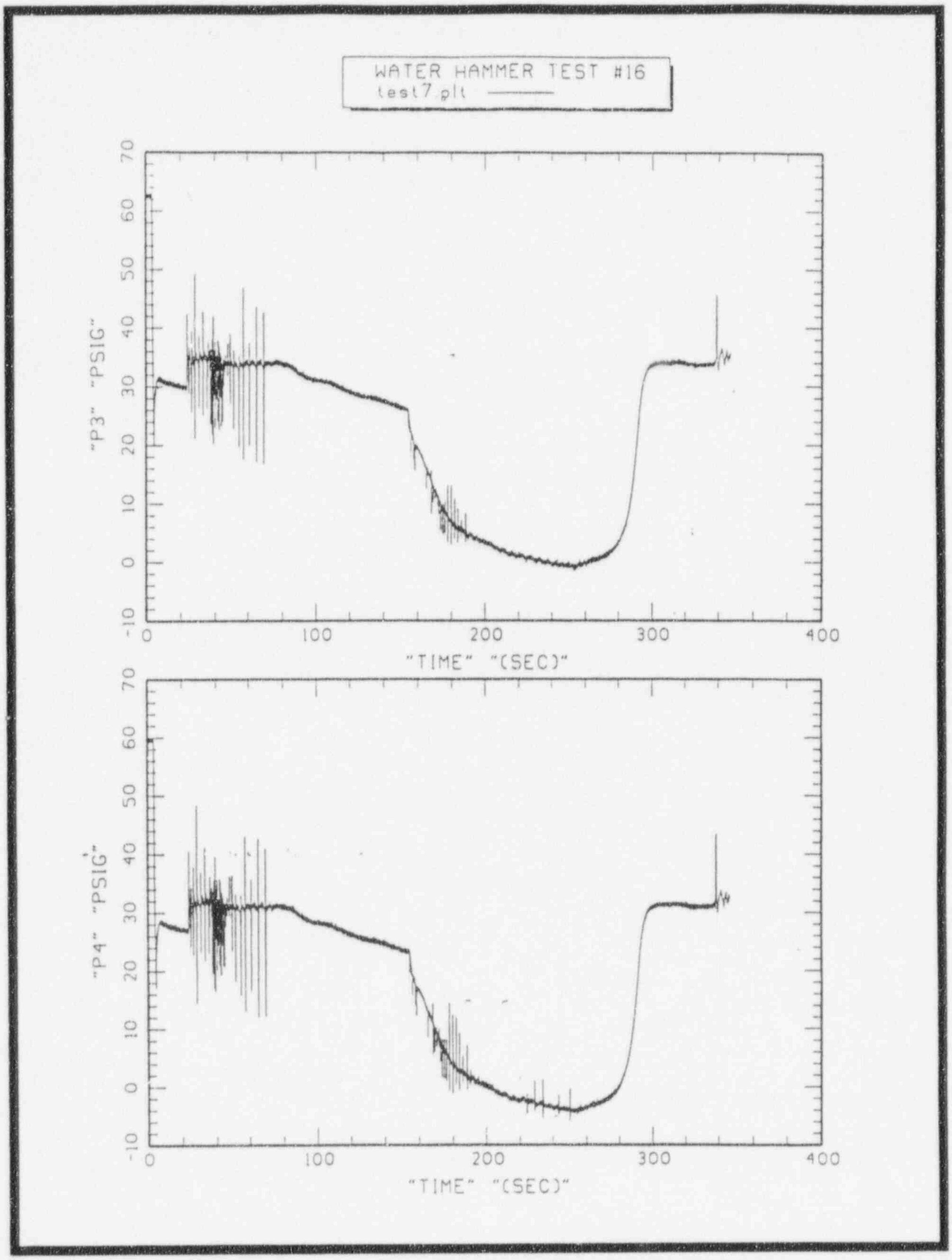

Figure 3-4 (Cont'd)

4.0 CONCLUSIONS

To determine the influence of substantial void formation in the Point Beach service water fan cooler discharge piping for DBA conditions, waterhammer experiments were performed to investigate the influence of substantial void formation and steam condensation as the cold water flow is re-established. These experiments, which were scaled using the Froude number, demonstrated that there were no significant waterhammer transients even when the void was measured to propagate all the way through the loop seal. Furthermore, the peak pressures were associated with refilling of the piping system and that the pressures observed were substantially less than those that would be calculated from the standard waterhammer expression. Thus, the approach taken by WEPCO to assess the piping loads based upon the refill velocity is a conservative representation of the loads that would be anticipated under the design basis conditions of interest. Specifically, these scaled experiments indicate that an impact pressure of 500 psi is a very conservative representation of the loads that would be imposed on the piping supports.

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ATTACHMENT D

PSA Evaluation of Water Hammer in SW Supply to Containment Accident Fan Coolers

A recently identified scenario brings into question the ability of the fan coolers to respond to a design-basis Large Break Loss of Coolant Accident, (LOCA) with a Loss of Offsite Power (LOOP). It is postulated that once the service water (SW) pumps stop due to the LOOP and the subsequent diesel generator start and SI sequencing, that the water in the fan coolers will boil. When the service water pumps restart, and cold water is introduced into the fan cooler SW lines, the rapid cooling will cause a water hammer condition that could jeopardize the integrity of the service water system in containment. This condition is only postulated to occur for LOCAs, ATWS, and Steam/Feedline breaks inside containment, because the containment temperature must be high at the time of the SI sequencing to cause boiling in the fan cooler heat exchangers. For simplicity in documentation, LOCAs will be the assumed initiator, but the actual initiating event frequencies used in the calculation included all the initiators listed in Table 1.

Further evaluation of the maximum possible severity of the water hammer event has shown that the service water piping would not be jeopardized, and the system would continue to function. This PSA evaluation is intended to be a bounding analysis, that calculates what the risk impact would be if it is assumed that the water hammer event would damage the service water piping, and render the fan coolers inoperable.

The PSA analysis will quantify the impact of the scenario on all PSA initiators that include elevated containment temperatures and pressures. The probability of a coincident Loss of Offsite Power, and the probability that the operator will successfully isolate the service water system break, are included. It is assumed that the water hammer event will fail the service water piping inside containment. If the operator successfully isolates the break, all the containment fan coolers are modeled to be failed, but the rest of the SW system will remain functioning. For this scenario, all the systems required to mitigate core damage are still available. If the break is not isolated, it is assumed that the entire SW system would be failed, and a release path from containment exists. For all of the initiators in this analysis, it is assumed that service water is required to prevent core damage.

Containment fan cooler system dependency on service water

Service water is a support system that impacts many PBNP PSA fault trees. This section will describe how this system affects the containment fan cooler operability in the PSA model. The PBNP containment accident fan coolers are dependent on service water flow to allow them to remove heat from containment. Since the PBNP PSA did not take credit for the containment spray system operating once containment sump recirculation is established, the fan coolers are the only credited containment heat removal means. Any core damage sequence that also results in a failure of containment accident fan coolers will increase the PBNP Fission Product Release Frequency (FPRF) by an amount equal to the Core Damage Frequency (CDF) for that sequence. The containment spray system is not dependent on service water during the injection phase of an accident. A failure of the containment due to a failure of containment accident fan coolers would occur very late, approximately 48 hours or greater following the accident initiator. Since this does not qualify as an "early" release, this would not result in an increase in the PBNP Large Early Release Frequency (LERF). While LERF is not currently a standard PBNP PSA measured criteria, it is the criteria of interest to NEI and the NRC. The only time a SW failure would be expected to lead to an early containment failure would be if the operator was unable to isolate a service water system break, which could result in a containment bypass.

Scenario probability

It is postulated that a water hammer event could happen anytime that a LOCA occurs coincident with a Loss of Offsite Power. From the PBNP PSA-93 model, the most recent available, the initiating event frequency for all initiators that could result in elevated containment pressures and temperatures early in the accident is summarized in Table 1. The total initiating event probability is 5.23E-3/yr. To determine the probability that a Loss of Offsite power will occur at the same time as these initiators, it is first necessary to describe how two events can happen simultaneously. The LOOP and LOCA could occur at roughly the same time due to dual random failures. Also, the LOOP and LOCA could occur as dependent failures, such that the occurrence of one somehow led to the occurrence of the other. Since PSA initiators result in a reactor trip and turbine trip, electric generation stops for the affected unit and the grid will be impacted. This will cause a transient which could lead to a LOOP. It is not considered feasible that an initial LOOP could result in an accident that includes elevated containment temperatures and pressures.

The PBNP PSA estimates that the conditional probability that a LOOP will occur following a reactor trip is 1.42E-3. Thus the total probability of a LOCA and LOOP is 5.23E-3 x 1.42E-3 or 7.43E-6/yr.

The postulated water hammer scenario could occur anytime a LOOP happens following a PSA initiator as long as containment temperatures are elevated. The probability that an independent initiator and LOOP will occur is dependent on the time period under evaluation. For purposes of this calculation, we will evaluate a 1 hr time frame following LOCA initiation. The probability of a random LOOP is 6E-2/yr. Thus the random probability of a PSA initiator, which would cause elevated containment temperatures, with a LOOP occurring within the next 1 hour is (5.23E-3/yr x 6E-2/yr x 1 hour/7315 hours per reactor-year) = 4.3E-8/yr. Therefore the frequency of a random LOCA and a random LOOP occurring simultaneously is not significant compared to 7.43E-6/yr, (i.e. less than 1%), and will not be considered further.

Total initiators frequency, and core damage frequency for all initiators from PSA in which containment temperatures and pressures are elevated		
	Initiator Frequency	CDF Frequency
S2	3E-3/yr	2.19E-6/yr
S1	1E-3/yr	1.42E-5/yr
A	5E-4/yr	6.48E-6/yr
X	7E-7/yr	7E-7/yr
ATWS	2.9E-5/yr	3.53E-7/yr
Tfb	7E-4/yr	3.33E-7/yr
Sum	5.23E-3/yr	2.43E-5/yr

Table 1. Initiator and CD Frequencies

Assumptions

A Loss Of Offsite Power occurring at the same time as the other PSA initiators evaluated will not significantly change the resulting CDF from that calculated in the PSA-93 results for those initiators. The PBNP PSA model is not up to date regarding the present emergency power supplies. The present PSA model takes credit for only two diesel generators, and an air-cooled gas turbine. The two new diesel generators, which are fully installed and available for use in the plant, are of a different design than the original diesels in that they are air-cooled. The two new diesels are therefore independent of Service Water. Due to the presence of four diesel generators (with different cooling means) and the gas turbine, even following a LOOP event it is predicted that there will be a high availability of emergency power. Therefore, the assumption that a coincident LOOP will not significantly change the calculated CDF for an initiator is considered justified.

Scenario	1.) LOCA and LOOP occur, operator fails to isolate SW, failing SW system.	2.) LOCA and LOOP occur, operator isolates SW which leaves SW system operating.
Initiators	All PSA scenarios with elevated containment conditions	All PSA scenarios with elevated containment conditions
A. Frequency	5.23E-3/yr (initiator frequency)	2.43E-5/yr (CDF)
B. LOOP	1.42E-3	1.42E-3
C. Operator action to isolate SW to containment fan coolers **(HEP value is 8.75E-3/yr)**	8.75E-3 (HEP value, fail to isolate)	1 ([1-HEP], successful isolation)
Total = A. x B. x C.	6.5E-8/yr	3.45E-8/yr
Result	Increase in CDF and LERF due to SW water hammer in fan cooler piping which fails SW system	Increase in FPRF due to assumption that an accident initiator coincident with a LOOP will cause failure of fan coolers

Scenario 1.) Total frequency = 6.5E-8/yr

Consequences: The Service Water system is assumed failed since the operator was not able to isolate the service water system break inside containment. This leads to a core damage event and a containment bypass. Thus this frequency represents an increase in both the PBNP CDF and the PBNP LERF

Scenario 2.) Total frequency = 3.45E-8/yr

Consequences: The Service Water system is assumed intact, since the operator was able to isolate the SW lines to the containment fan coolers. All systems that are required to mitigate core damage are unaffected by these scenarios, so the overall CDF from these initiators is unchanged from the PSA-93 model results. The fan coolers are assumed failed, which results in no credited means of containment heat removal. This results in an increase in the PBNP calculated FPRF, however it would not result in an increase in LERF, since the containment failure would occur late, nearly 48 hours after accident initiation.

Table 2. Quantification of PSA Risk Impact

Evaluating the impact of quantified PSA risk increases

The Nuclear Energy Institute (NEI) has established a generic method for using PSA evaluations to determine the severity of operability issues. This is documented in EPRI TR-105396, "PSA Applications Guide." This guide describes a change in core damage probability (CDP) as a result of a plant change. The CDP is simply the change in core damage frequency times the length of time that change is in effect. The application guide includes a figure (Figure 4-3, Quantitative Screening Criteria for Temporary Changes) to determine whether the temporary change is risk significant or not. A similar criteria is used to evaluate changes to Large Early Release Frequency, called LERP.

Table 3. below summarizes the criteria from Figure 4-3 of the PSA Applications Guide showing the three regions of increasing severity. For evaluating the CDP, anything less than 1E-6 is considered non-risk significant. This means

the change does not significantly increase the overall plant risk, and the change can be justified without the need for additional mitigating actions or analysis.

NEI PSA Applications Guide Summary		
	CDP	LERP
Risk Significant	>1E-5	>1E-6
Assess Nonquantifiable Factors	<1E-5 but >1E-6	<1E-6 but >1E-7
Non-Risk Significant	< 1E-6	<1E-7

Table 3. Summary of PSA Applications Guide Figure 4-3.

The modifications necessary to correct this potential design deficiency are planned to be completed during the 1997 outages for units 1 and 2. The longest time period this deficiency will exist would be 14 months for Unit 2. Using the increased CDF and LERF figures calculated above for Scenario 1., i.e. 6.5E-8/yr for each, the resulting CDP and LERP values would be 6.5E-8/yr x 14months/12months = 7.6E-8 for both CDP and LERP. This value is in the Non-Risk Significant category per the NEI guidance, and indicates that the existence of the deficiency would have almost no affect on the plant risk.

It is not necessary to calculate any CDPs and LERPs for Scenario 2. because the CDF and LERF were unchanged from the base case PSA-93 model, thus the CDP and LERP would be zero.

Conservatisms in the PSA analysis

This is a good time to restate that the PSA analysis that led to this conclusion contains many conservative assumptions. The PSA analysis assumed that with elevated containment conditions, anytime there were a LOOP condition there would be a water hammer in the service water piping to the fan coolers that would rupture the pipe. This assumption is conservative since all the calculations performed to estimate water hammer severity assumed worst case containment conditions, and determined the magnitude of any potential water hammer would be within the capabilities of the system.

The PSA analysis assumed that any elevated containment condition would cause the water hammer. This PSA analysis included initiators such as small-break LOCAs, and ATWS events, which would be expected to have very mild containment conditions during the first minute or so of the event.

The PSA analysis assumed that a loss of service water would lead directly to core damage for all the initiators evaluated. Some of the initiators, (Steamline/Feedline Break Inside Containment, and ATWS), can be recovered to prevent core damage even with service water unavailable.

HRA calculation for isolating service water to containment following a break in the fan cooler line

The operators would be responding to a Loss of Service Water condition.

This would be identified in the control room based on a low service water header pressure alarm which comes in at 50 psig. It will first be necessary to identify where the break is coming from. This would be done using AOP-9A, "Service Water System Malfunction."

It assumed that the operators would manually isolate the containment using local valves. These valves are SW-219 or SW-217 and SW-185 for 1W1A1; SW-219 or SW-209 and SW-182 for 1W1C1; SW-220 or SW-207 and SW-191 for 1W1D1, and SW-220 or SW-215 and SW-188 for 1W1B.

For success, the operator must shut both a suction valve and a discharge valve.

pe = error of commission (20-13, 2) = 3.75E-3 x 2 valves = 7.5E-3

Total = 7.5E-3

pc(e) = Placekeeping aids are not generally used in AOPs, not graphically distinct - .01

Total = pc + pe = .01 + 7.5E-3 = .0175

A factor of two recovery was applied for the opposite control operator since this is a shared system between the units. .0175/2 = 8.75E-3

The total HEP for this operator action is 8.75E-3