CONDENSATION-INDUCED WATZR HAMMER

EVALUATION FOR ABWR ECCS PIPING

MARCH 1988

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1.0 PURPOSE

Under certain conditions, a condensation-induced water hammer (CIWH) phenomenon can result in very large dynamic piping loads, and the intent of this memorandum is to assure that the ABWR ECCS piping does not experience this phenomenon.

This memorandum summarizes the work that has been done on this issue.

2.0 INTRODUCTION

The phenomena of Condensation-Induced Water Hammer takes place when a steam bubble is surrounded or exposed to cold water in the piping and condensation-induced steam void collapse occurs. This condition can potentially occur in BWR ECCS piping during transient and/or accident conditions involving reactor depressurization. Steam voids may occur in the piping if the reactor pressure falls below the saturation pressure of the water initially in the pipe. Subsequent startup of the system pump can introduce cold water into the pipe which may lead to condensation of the steam bubbles. If this event takes place rapidly, the sudden decompression following condensation can accelerate liquid slugs, and liquid-to-surface/liquid impact could lead to generation of pressure pulses which can propagate through the system and interact with the structural members.

The purpose of this study is to review ABWR Residual Heat Removal (RHR), High Pressure Core Flooder (HPCF), and Reactor Core Isolation Cooling (RCIC) system piping configuration from the point of view of CIWH. Since it is very difficult to define dynamic loads produced by CIWH, the objective of this study is to assure that the proposed ABWR piping configuration does not involve conditions which could lead to CIWH.

3.0 SUMMARY AND CONCLUSIONS

The following is a summary of the conclusions that have been drawn from CIWH analysis of ECCS piping. CIWH can only occur in piping used to inject cold water into the reactor. Consequently, the HPCF, RHR-LPFL, RCIC and FW injection piping was reviewed. It was concluded:

(a) The HPCF and RHR-LPFL (Low Pressure Flooder) mode in the LOCA event may have a potential for water hammer. This was concluded after analyzing the fluid conditions inside RPV at the corresponding nozzle height. However, detailed study of this piping demonstrated that CIWH would not occur (see Item (b).)

(b) The effect of depressurization transient during LOCA, i.e., flashing of saturated water in completely filled upstream LPFL pipe, was analyzed in order to calculate the quantity of water left in the pipe when the pressure drops to 250 psia. It was found that about 80% of water still remains in the pipe. Therefore, slow

injection of cold water by the LPFL injection valve into the horizontal LPFL pipe partially filled with saturated water will not cause CIWH. For discussion of the influence of saturated water, see Section 7.3.

(c) In HPCF system, the presence of two-phase mixture or saturated water at the nozzle height and in the piping inside RPV avoids occurrence of high water hammer loads. See Section 7.2 for a discussion of this effect. A pressure pulse of 10-20 psi is generated when a slug of saturated water which flashes into a highly compressible two-phase mixture accelerates and collides with a surface. This pressure is not considered significant to be added to piping loads.

(d) In RCIC/FW system, the water level in the reactor is above the nozzle level at the time of system initiation. Therefore there is no CIWH. See Section 7.5 for a discussion of this effect.

The overall conclusion is that the proposed ABWR injection piping configuration is not susceptible to CIWH.

4.0 RESIDUAL HEAT REMOVAL (RHR) SYSTEM

4.1 System Description

The RHR system consists of a group of related subsystems that share common components to perform separate functions at different times during normal plant operation, shutdown, and following postulated accidents. The primary system function is to remove heat from the reactor core during plant shutdown and refueling operations, and following a postulated design basis LOCA. The system consists of three independent pump loops which inject water into the vessel and/or remove heat from the reactor core or containment. Each loop contains the necessary piping, pumps, valves and heat exchangers. The RHR system for ABWR has four principal subsystems which are as follows:

(a) Low Pressure Flooder (LPFL) Subsystem
(b) Shutdown Cooling Subsystem
(c) Wetwell land Drywell Spray Subsystem
(d) Suppression Pool Cooling Subsystem

From the above four subsystems only, the first two, i.e., (a) LPFL Subsystem and (b) Shutdown Cooling Subsystem, inject cold water into the reactor and were thus reviewed from the point of view of CIWH. The latter two are not considered because in these modes of RHR the reactor vessel pressure boundary is isolated from the RHR system.

4.2 LPFL Subsystem

The LPFL subsystem provides reactor core cooling (i.e., removal of reactor core decay heat) following a postulated LOCA such that fuel cladding temperatures are maintained within limit specified in the related codes and standards. The LPFL is automatically initiated and provides flow into the reactor vessel within 36 seconds following receipt of a high drywell or low reactor water level initiation signal

and low reactor pressure permissive. In the core cooling mode, water is drawn by each loop from the suppression pool and injected into the vessel outside the core shroud via feedwater line in one loop and via RHR LPFL spargers in the other two loops.

4.3 Shutdown Cooling Subsystem

The shutdown cooling subsystem is activated when the reactor is in the normal shutdown mode. Water is taken from the vessel through RHR suction lines and pumped through the heat exchangers in each loop and is returned to the vessel through RHR LPFL nozzles in two loops and through the feedwater nozzle in the third loop.

5.0 HIGH PRESSURE CORE FLOODER (HPCF) SYSTEM

The HPCF system together with RHR (in LPFL mode) and RCIC provides coolant inventory makeup following a design basis LOCA event. The system is automatically initiated at a low water level (level 1.5) signal.

The HPCF system consists of two independent loops. Each loop consists of a pump, piping and valves that convey water from the suppression pool to the core spray sparger.

Figure 1 shows the ABWR piping configuration for the HPCF system piping inside the vessel. It may be noted that the U-loop of piping inside RPV leads to a high point in the piping outside RPV.

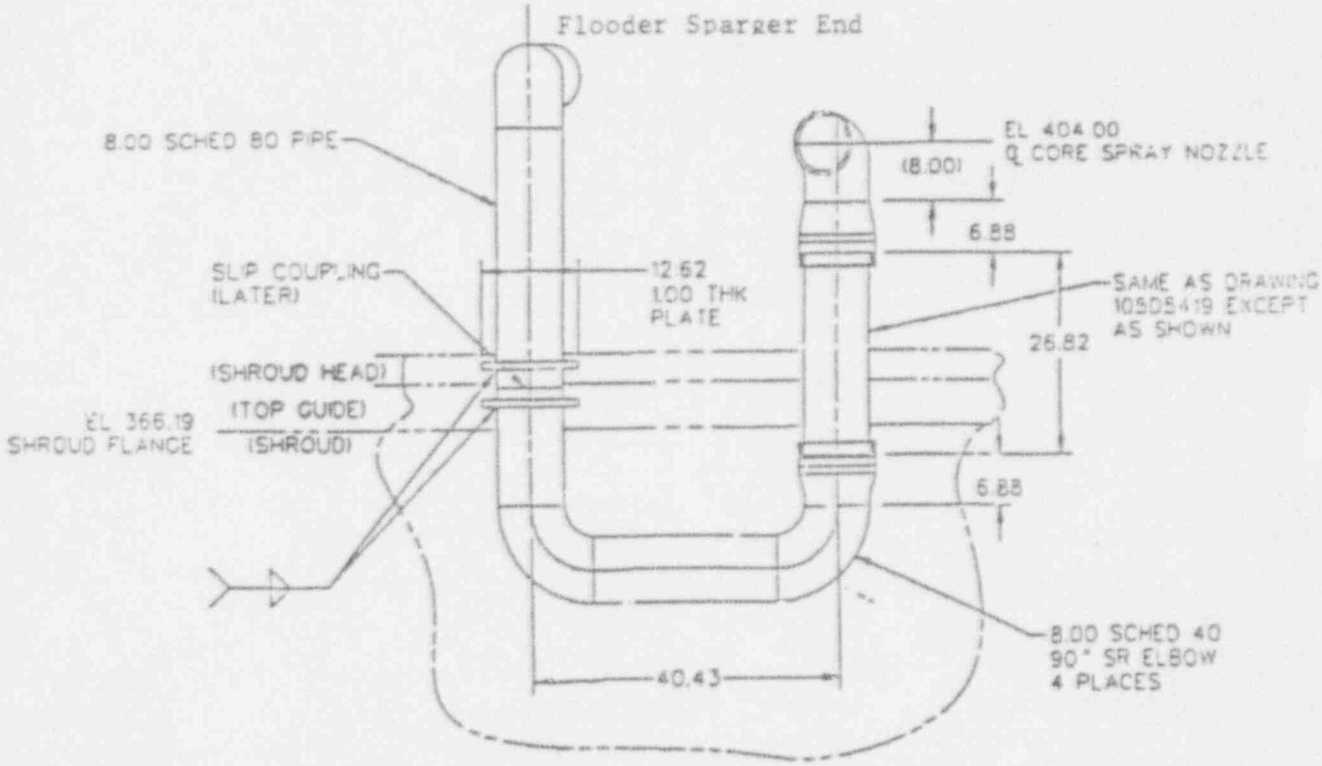


Figure 1. HPCF Piping Inside RPV (Reference 7).

6.0 REACTOR CORE ISOLATION COOLING (RCIC) SYSTEM

The RCIC system supplies makeup water to the reactor vessel to assure that sufficient reactor water inventory is maintained to permit adequate core cooling to take place. The RCIC system operates during the following conditions:

(a) In a LOCA event due to a break in a small process line or instrument line, the RCIC system in conjunction with the two HPCF system loops is designed to pump water into the vessel while it is fully pressurized, and will provide adequate core cooling until vessel pressure drops to a point at which the LPFL mode of RHR can be placed in operation.

(b) In the event when the reactor vessel is isolated and the feedwater is unavailable, the water level in vessel will drop due to continued steam generation by decay heat. The RCIC system is automatically initiated when the water level in the vessel reaches level 2.0 (see Table 1).

The RCIC pump draws water from the Condensate Storage Pool or the Suppression Pool, and the pump discharge water is injected into the vessel through feedwater lines.

7.0 CIWH ANALYSIS

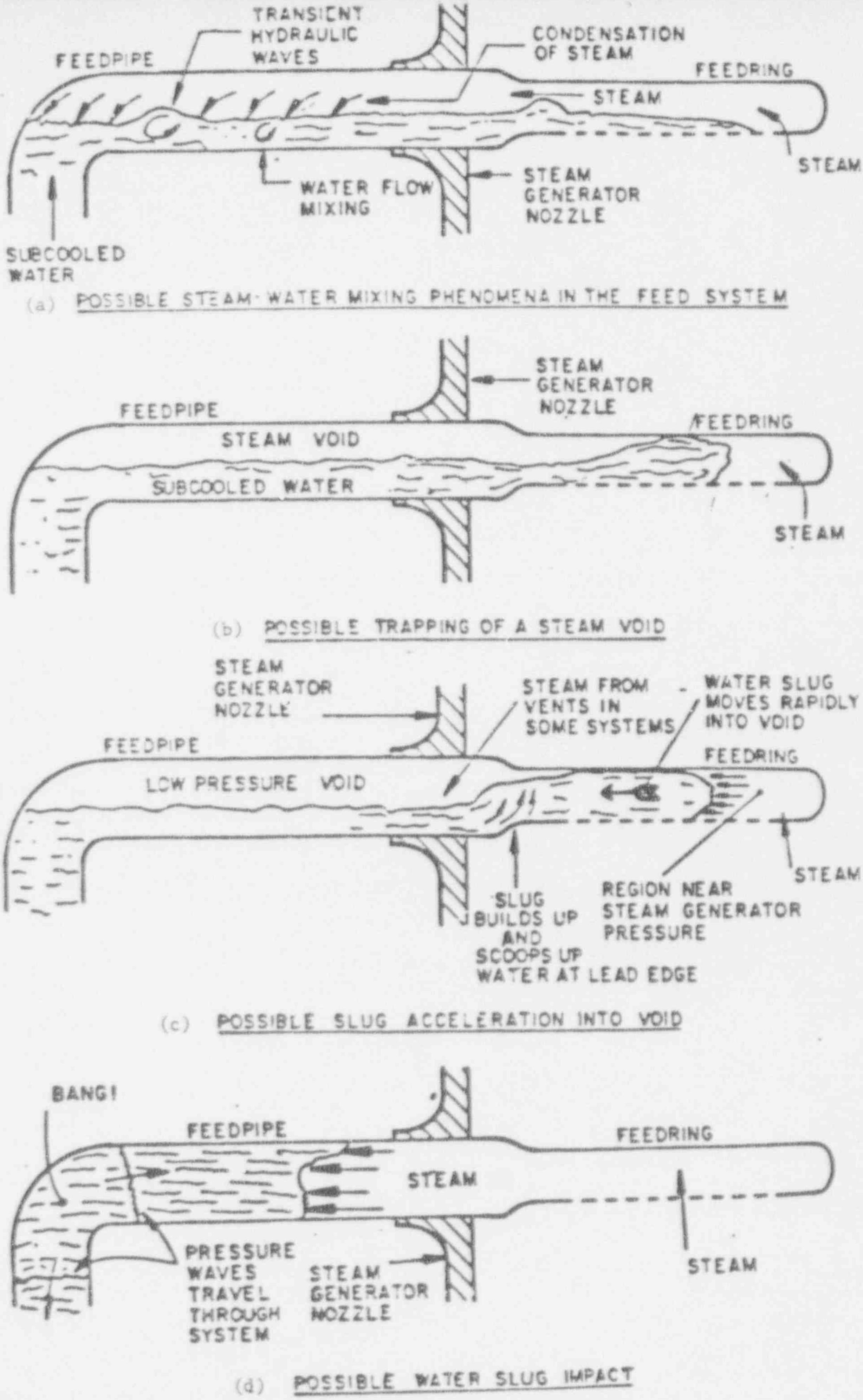
Based on operating experience, the potential for CIWH exists under the following conditions:

(a) Cold water is injected into steam-filled lines that have a continuously available steam supply. The cold water injection rate is sufficiently low so that the steam filled pipe runs partially full and it is high enough to result in ripple/wave formation that can trap a steam bubble. This type of phenomena is illustrated in Figures 2(a) through (d) (taken from Reference 9) as it occurs in steam generator feedring sparger of pressurized water reactors. This type of phenomena would occur in a BWR for comparable geometric conditions.

(b) Cold water is injected into steam filled lines and the steam supply path is subsequently blocked by water, thereby trapping a steam bubble. This type of phenomena is illustrated in Figure 3 (a) and (b) which may occur in BWR plants.

(c) Piping containing water that is heated to relatively high temperatures during normal plant operation and is arranged such that it is subject to trapping a steam bubble in a portion of the pipe when the water in the pipe flashes during reactor depressurization. The steam bubble may be exposed to subcooled water during system operation that causes condensation of steam and water slug is forced by pressure into the low pressure region caused by condensation of steam bubble (see Figure 4 (a) and (b)).

ABWR ECCS injection piping will be analyzed for conditions (a)and (b) above. Condition (c) type situation occurred at RHR and recirculation system piping junctions in earlier plants which is not present in ABWR.



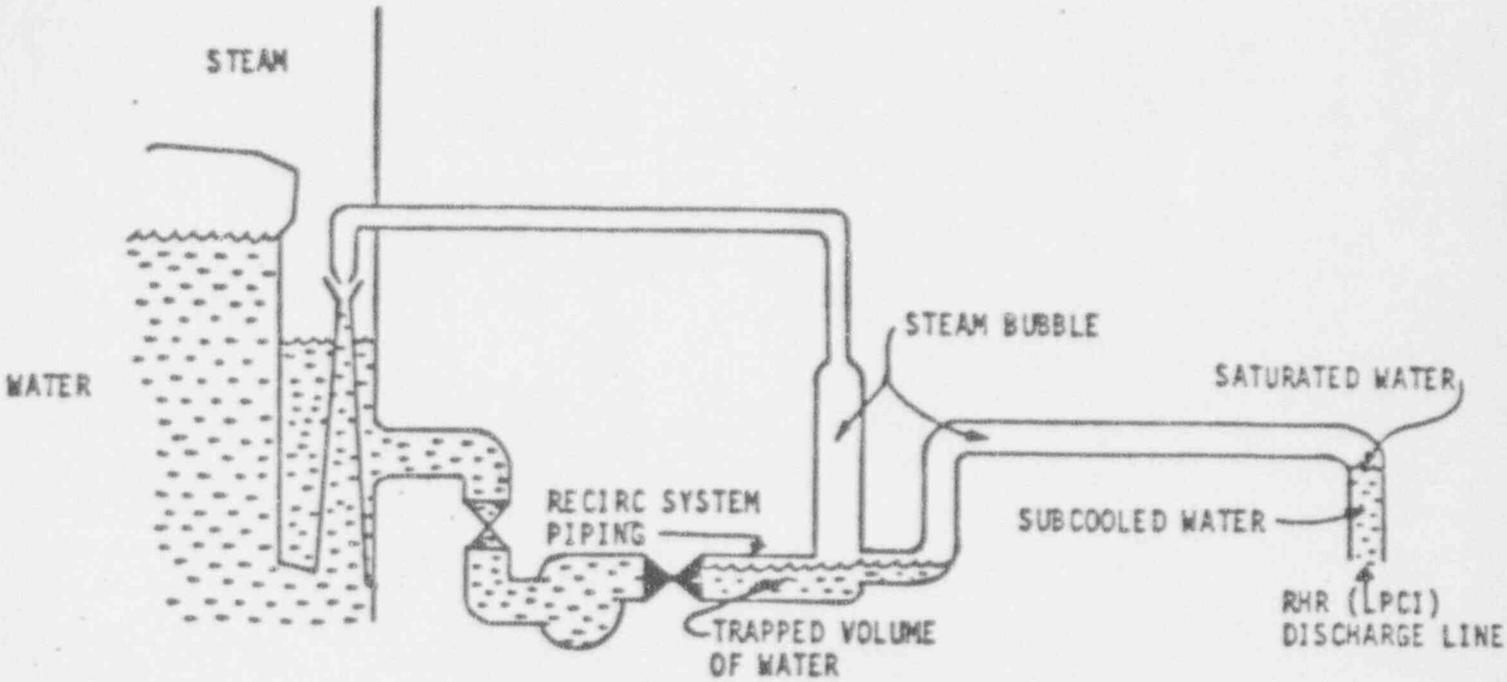
(a) POSSIBLE STEAM-WATER MIXING PHENOMENA IN THE FEED SYSTEM

(b) POSSIBLE TRAPPING OF A STEAM VOID

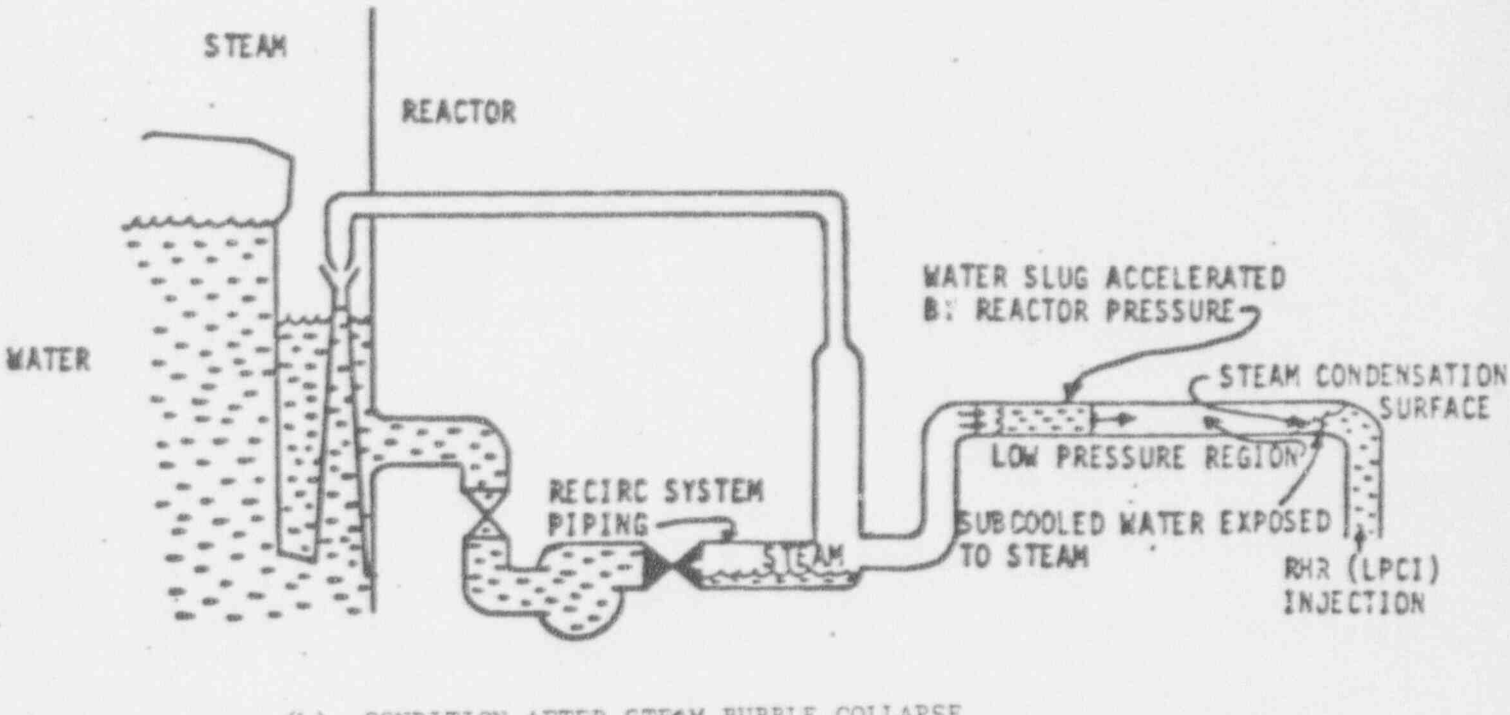
(c) POSSIBLE SLUG ACCELERATION INTO VOID

(d) POSSIBLE WATER SLUG IMPACT

FIGURE 2. POSSIBLE SEQUENTIAL EVENTS LEADING TO CIWH.

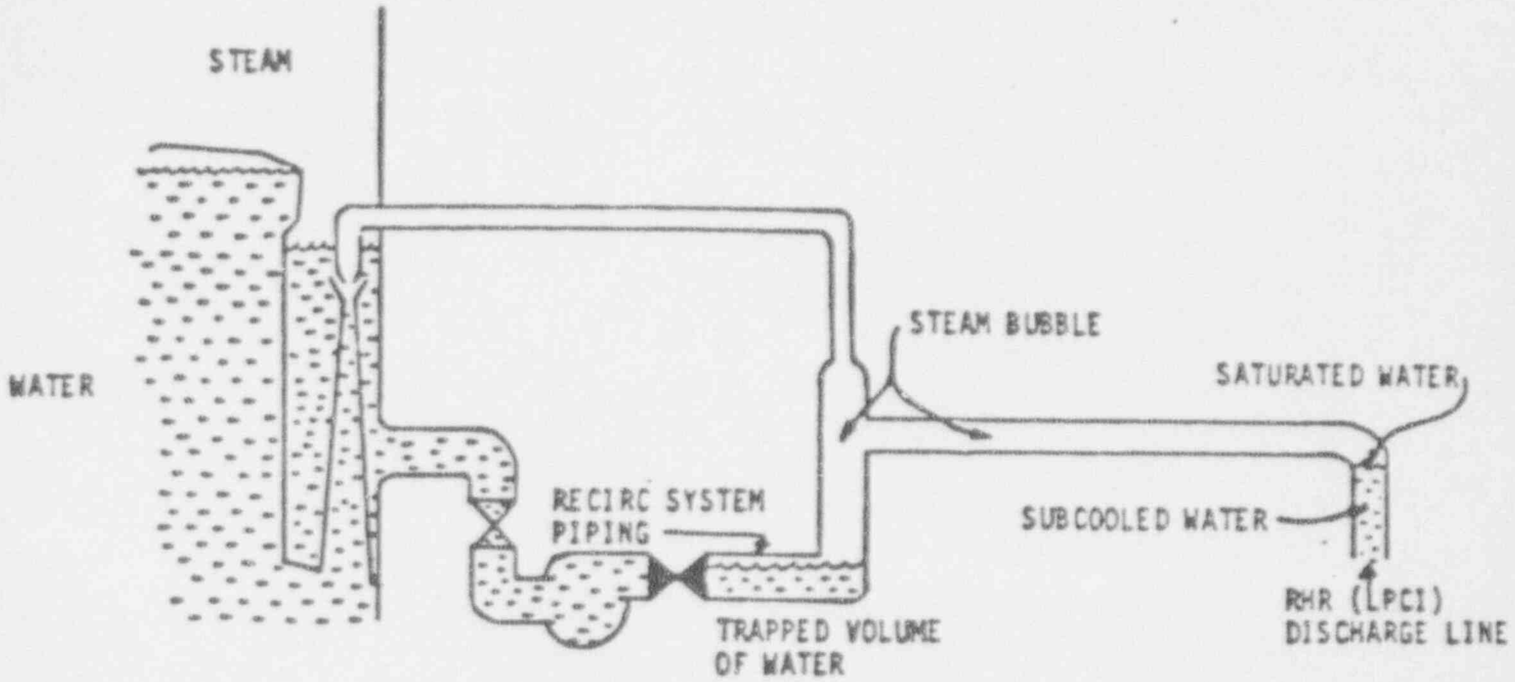


(a) CONDITION AFTER STEAM BUBBLE FORMATION AND PRIOR TO STEAM BUBBLE COLLAPSE

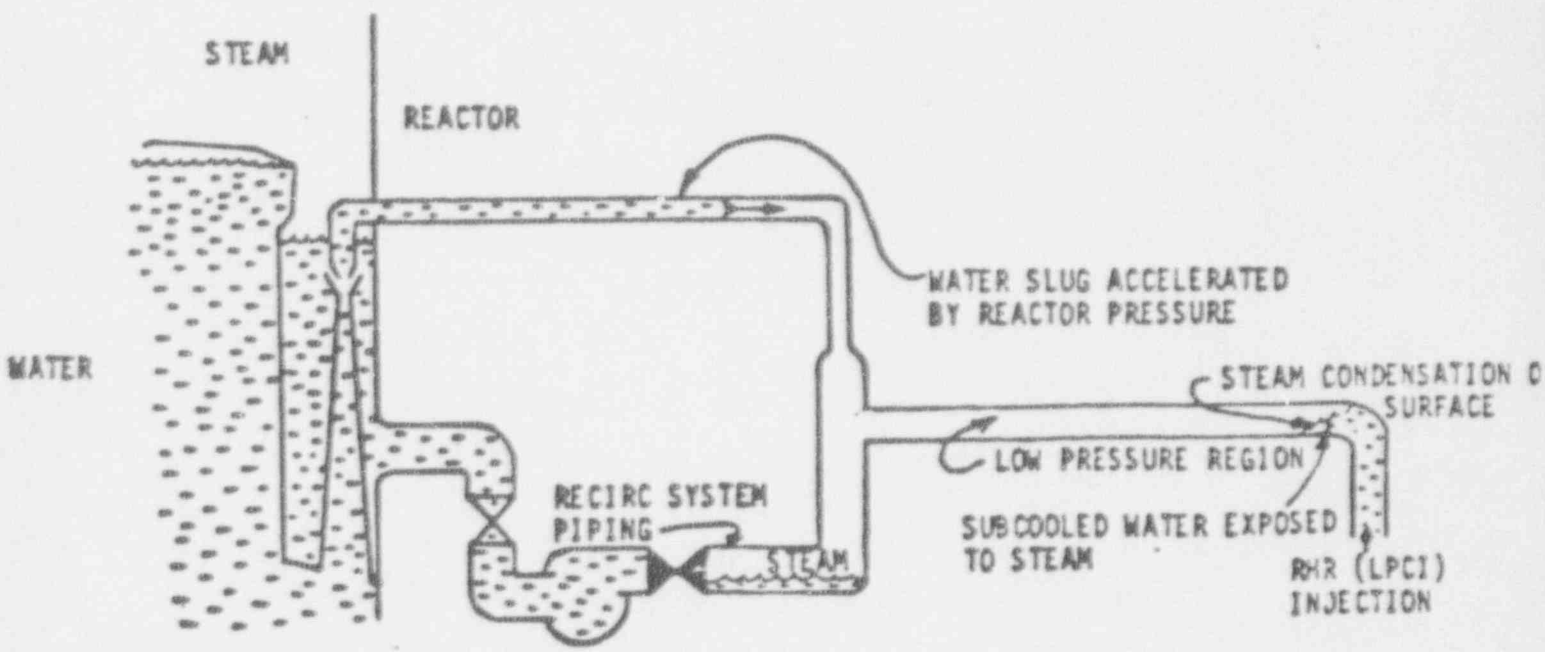


(b) CONDITION AFTER STEAM BUBBLE COLLAPSE

FIGURE 3. CIWH IN RECIRCULATION AND RHR SYSTEM INTERFACE OF BWR (LOCA CONDITION)



(a) CONDITION AFTER STEAM BUBBLE FORMATION AND BEFORE BUBBLE COLLAPSE.



(b) CONDITION AFTER STEAM BUBBLE COLLAPSE

FIGURE 4. CIWH IN RECIRCULATION AND RHR PIPING INTERFACE IN BWR.

7.1 Fluid Conditions Inside RPV at the Time of Initial ECCS Flow Initiation

Fluid conditions at the different spargers under LOCA condition were analyzed. This is an important consideration because the fluid conditions at the point where an injection line enters the reactor vessel can have a large influence on the CIWH phenomenon. For example, if the injection location is covered by liquid or two-phase mixture, the injection line will not be filled with steam and so there is no CIWH when the ECCS subcooled water is injected. However, when the fluid condition at the nozzle is steam, the injection line may also be voided with steam and a slow injection of ECCS subcooled water may lead to CIWH. The LOCA considered was due to RHR Shutdown Cooling Suction line break and Main Steam Line break inside the containment. The summary of conclusions is given in Appendix A. Table 1 summarizes RPV nozzle heights for different spargers, water level in RPV at the time of initiation and the fluid condition at the sparger at the time of flow injection as obtained from the conclusions in Appendix A. It appears that the only areas of concern are the HPCF and RHR-LPFL piping system. This is because the HPCF is exposed to a two-phase mixture and has a high point loop and RHR-LPFL is in steam environment in the reactor vessel under LOCA conditions and at system initiation. As discussed above, both of these conditions have the potential for causing CIWH effects at the time the system is initiated.

TABLE 1

Vessel Nozzle	Height from Vessel Zero (mm) (Ref. 4)	Initiation Level	Initiation Water Ht. (mm) (Ref. 5)	Fluid Condition at Injection Sparger
HPFL Sparger	10312	1.5 (Ref. 2)	10263	Water/2-Phase Mixture
RHF-LPFL Sparger	10921	1.0 (Ref. 3)	9425	Steam
FW Sparger (RCIC)	11613	2.0 (Ref. 6)	11710	Water

7.2 CIWH Analysis in HPCF Piping

In the event of LOCA, the high pressure flooder spargers located inside the shroud are immersed in a two-phase mixture at the time of flow initiation (injection valve signalled to open). However, during the flashing transient (transient in the period prior to HPCF initiation when the RPV is depressurizing and water in the piping can flash), some of the water in the piping may flash and form a steam bubble at the high point loop of the piping, and therefore there is concern about CIWH. The sequence of event postulated to occur is as follows:

(a) Water in the HPCF piping inside containment is in saturated state when the reactor is depressurized. The high pressure flooder sparger is in a two-phase mixture inside the shroud.
(b) Any flashing taking place inside the piping high point will form saturated steam or two-phase mixture in equilibrium with the saturated water. A steam bubble may get trapped at the high point loop in the piping.
(c) At the time of opening of HPCF injection valve, condensation of steam due to coming in contact with subcooled water at the high point in the piping will cause decompression inside the pipe. Any water slug accelerated from the reactor side towards the upstream piping will flash into a two-phase mixture because the water is in a saturated condition. A slug of two-phase mixture which is highly compressible colliding with another surface has been analyzed and found to produce a pressure pulse of the order of 10-20 psi. This analysis was done earlier for typical BWR/5 and BWR/6 piping using TRACB01 computer code. The model used was the same as described above; i.e., exposure of cold water to a steam bubble trapped in a high point loop and the injection point immersed in a two-phase mixture.
(d) CIWH loads due to 10-20 psi pressure pulse are not considered significant to be added to other piping loads. It is concluded CIWH is not a problem for the HPCF injection piping.

7.3 CIWH in RHR-LPFL Subsystem

In the LOCA event, the RHR low pressure flooders are in saturated steam environment inside the RPV (see Table 1) at the time of flow initiation (injection valve signaled to open). However, the upstream piping (see Figure 5) at the beginning of the flashing transient is filled with saturated water at reactor operating pressure. During the flashing transient (depressurization of reactor), water in the LPFL pipes will start flashing into steam. This steam will leave the pipe and enter the reactor pressure vessel. This steam flow may possibly entrain some of the liquid in the pipe and carry it into the vessel. In order to determine the steam-water entrainment characteristic during depressurization, a thermodynamic analysis was done to find out the extent of water entrainment and the point at which a separated water surface is formed inside the pipe. The following conditions were assumed for the analysis:

a) Initial pressure at time zero (t = 0) = 1000 psia.
b) Saturated water at 1000 psia in the upstream horizontal portion of LPFL pipe.
c) Depressurization transient given in Appendix A, Figure 3, assuming t = 0 secs, at initial pressure 1000 psia.
d) There is no heat transfer to the surroundings from the LPFL pipe fluid.

Appendix B gives the details of the analysis performed. Following items are covered in different sections of Appendix B.

(a) In Section B-1, a void fraction distribution function was determined using a series of steady-state analyses (quasi-steady state). The void fraction distribution is a function of time and space in the pipe.

(b) In Section B-2, the assumption of quasi-steady state was proved to be valid.

(c) In Section B-3, the"vapor mass flow rate" versus "time" and "mass of water left in the pipe" versus time were calculated and are shown tabulated in Table B-3.

(d) In Section B-4, free separation of water and vapor was analyzed and concluded that the water surface is freely separated from the vapor at the beginning of the transient.

(e) In Section B-5, the effect of flashed vapor velocity along the pipe length (towards reactor nozzle) was analyzed and concluded that it is insignificant to produce any rapid blowout of the remaining water in the pipe.

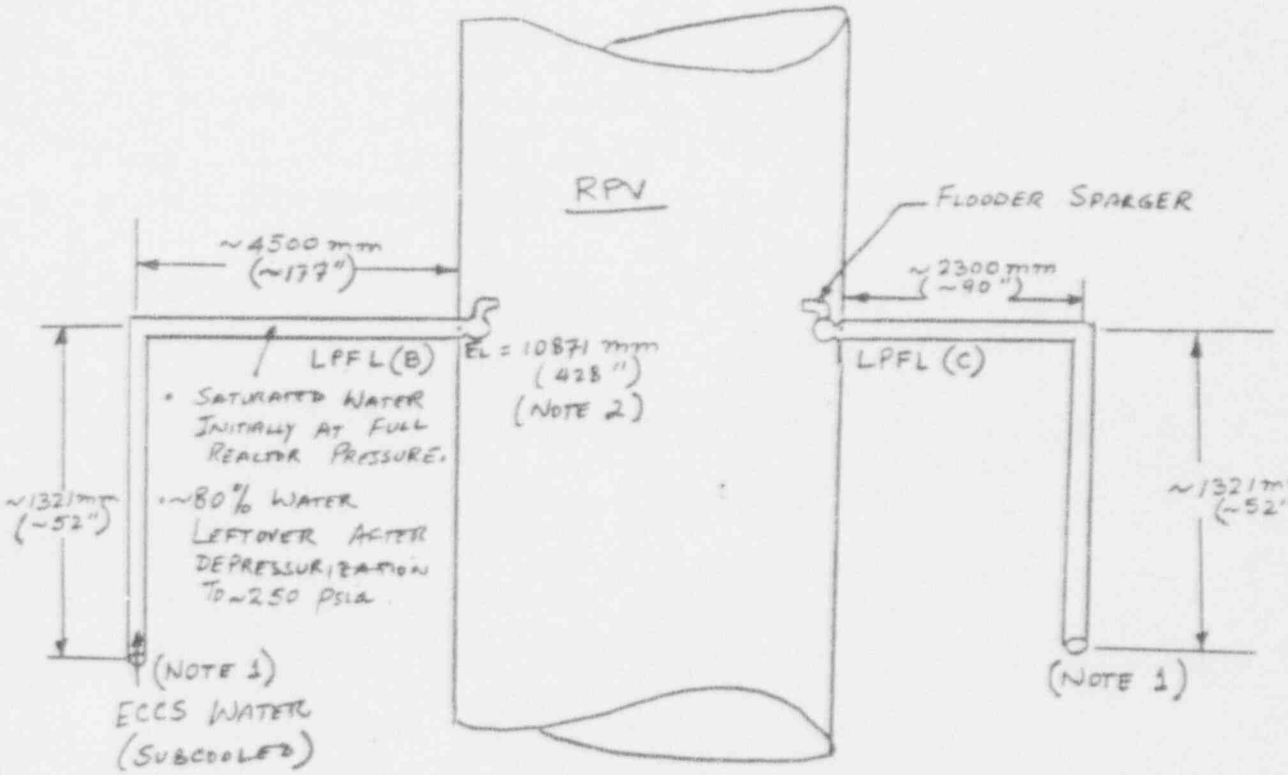
The above analysis performed shows that after depressurization, the pipe is about 80% full of saturated water. Therefore injection of subcooled water will not lead to ripple/wave formation phenomena causing CIWH. The ripple/wave formation that leads to CIWH takes place when the pipe is completely filled with steam. A pipe partially filled with saturated water and partially with steam will not lead to CIWH when subcooled is injected, because condensation of steam will cause rapid flashing of saturated water into a highly compressible two-phase mixture cushion in front of the oncoming water column thus avoiding CIWH. In summary, it is concluded CIWH is not a concern for the RHR-LPFL injection piping.

7.4 CIWH in RHR - Shutdown Cooling Subsystem

In the RHR Shutdown Cooling mode of operation, the water level in the reactor is above level 3 (505.5 inches) so that the RHR suction and injection nozzles are below the water level at all times. In ABWR there is no connection of the RHR to the reactor recirculation system (as there was in BWR-6 and earlier designs) where the CIWH occurred due to formation and subsequent collapsing of steam bubbles formed at the junction (see Section 7.0 c). Therefore, CIWH in the Shutdown Cooling mode is not a problem in RHR of ABWR.

7.5 CIWH in RCIC/Feedwater Lines

During RCIC system initiation, the water level in the reactor is at level 2 which is higher than the feedwater nozzle height (see Table 1). Therefore, the fluid condition at the feedwater sparger is water when RCIC water is pumped into the vessel. Therefore, CIWH will not occur at the time of RCIC makeup water injection into the reactor vessel.



Note 1: The remaining portion of the line within drywell is in a horizontal plane.

Note 2: Elevation of flooder nozzle from vessel zero.

FIGURE 5. RHR LPFL LPIPING CONFIGURATION
(REFERENCE 5, 8)

8.0 REFERENCES

1) Reynolds, W.C., Thermodynamics, Second Edition.

2) 22A6278, Rev. 1.
Title: "High Pressure Core Spray System," Design Specification for ABWR.

3) 22A6275, Rev. 1
Title: "Residual Heat Removal System," Design Specification for ABWR.

4) 795E997, Rev. 1.
Title: "Reactor Vessel," for ABWR.

5) 795E877, Rev. 1
Title: "Nuclear Boiler System P&ID" for ABWR.

6) 22A6290, Rev. 1.
Title: "Reactor Core Isolation Cooling," Design Specification for ABWR.

7) 796E400, Rev. D
Title: "Core Spray Sparger" for ABWR.

8) Hitachi Dwg. # 10Q250-953, PAE 1.d.18a
Title: "Upper Drywell Arrangement Drawing, T.M.S.L. 12300," for ABWR.

9) NUREG-0927, Rev. 1
Evaluation of Water Hammer Occurrence in Nuclear Power Plants.

Appendix A.

CC: C.D. SAWYER
A. SALLMAN

To: A.J.JAMES

From: F.M.PARADISO F.M. Paradiso 2/2/88

Subject: Will the ECCS Injection Spargers Be Uncovered at the Time of Initial ECCS Flow Injection?

To answer the subject question the FSAR LOCA analyses performed with the SAFER model were reviewed. The following is a summary of our conclusions from that review:

1) HPFL sparger (inside shroud)

The HPFL will realistically initiate on a high drywell pressure signal and inject in less than 40 seconds for any LOCA inside the containment. For this short space of time the water level inside the shroud will remain high (i.e. up in the separators) following any LOCA.

Therefore, it is concluded that the HPFL sparger will never be uncovered at the time of HPFL injection for any LOCA.

2) RCIC injection into the FW sparger

The attached Figures 1 to 3 show the system response to a shutdown suction line break. These results show that the FW sparger is uncovered at the time of RCIC initial injection. Even with a more realistic break flow and RCIC startup time, it still would be close. However, since the RCIC will realistically inject in less than 30 seconds , the system pressure would not be low enough at the time of injection to have caused flashing in the FW line. To confirm this for all LOCAs, the steamline break inside the containment (see attached Figures 4 to 6) which has the most rapid system depressurization of any LOCA, was checked. The pressure transient for this case (Figure 6) shows that the system pressure at 30 seconds is about 750 psia. This is well above the saturation pressure of the 420 F FW flow (about 320 psia).

Therefore, it is concluded that for any LOCA the RCIC will inject well before the water in the FW lines begins flashing.

3) LPFL spargers and LPFL injection into the FW sparger

The level response in Figure 1 shows that both spargers will be uncovered at the time of initial LPFL injection. Calculations based on a more realistic break flow would probably still show uncovery of these spargers since the elevation of the shutdown suction line nozzle is the same as the LPFL injection spargers and below the FW spargers.

Therefore, it is concluded that for some LOCAs both spargers will be uncovered at the time of initial LPFL injection and the system pressure will be the realistic shutoff head of the LPFL system.

FIG 1

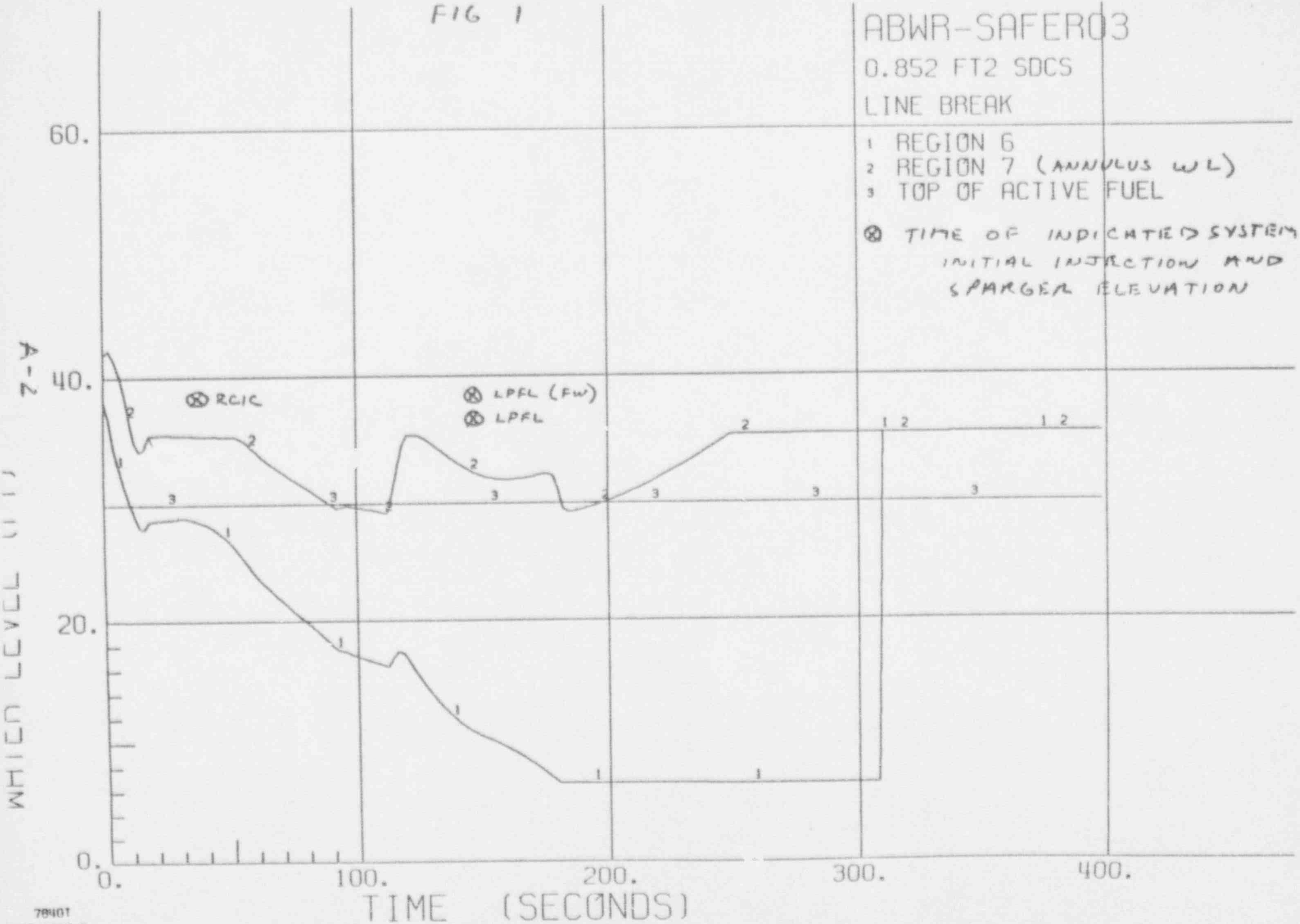


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FIG 2

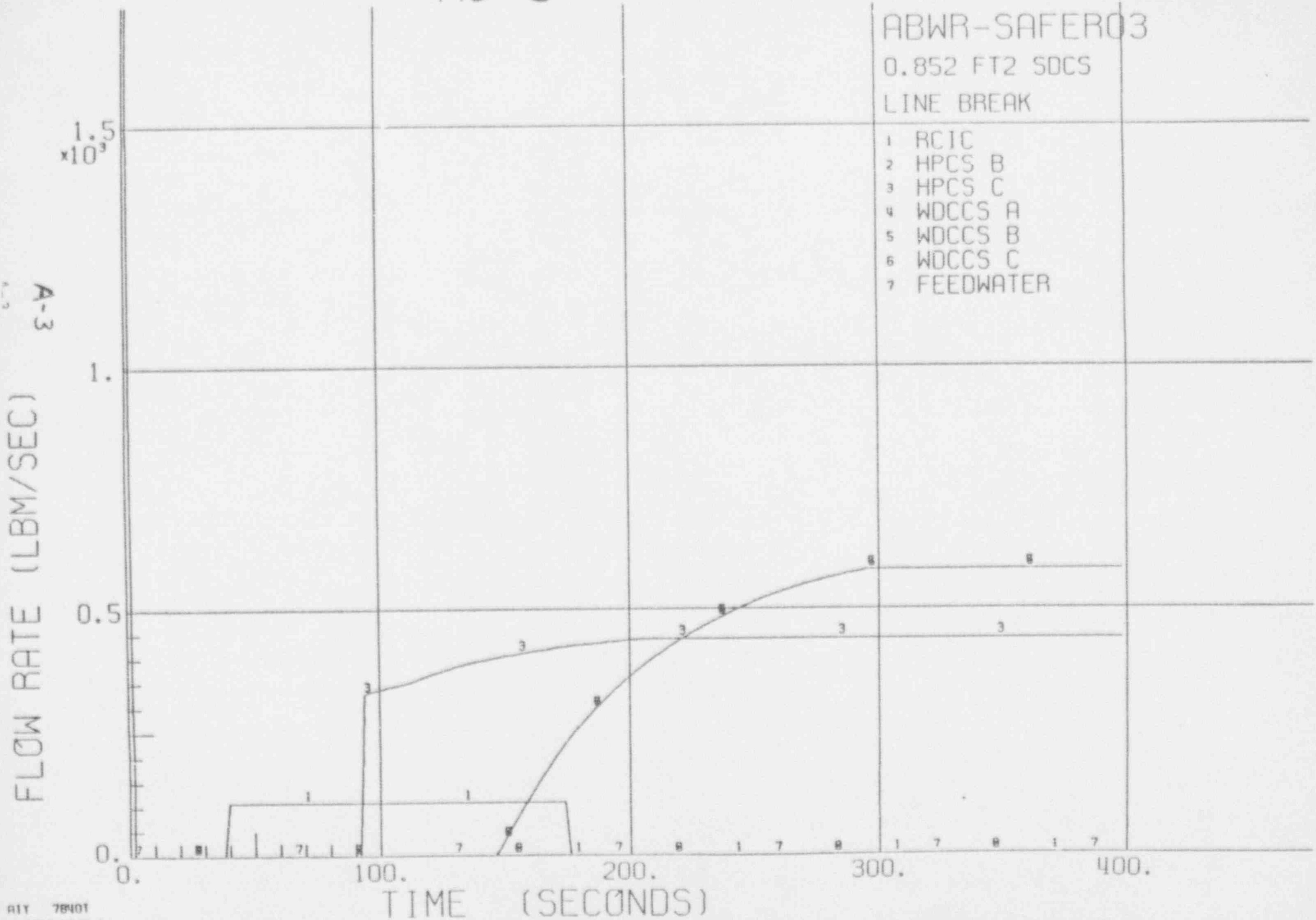

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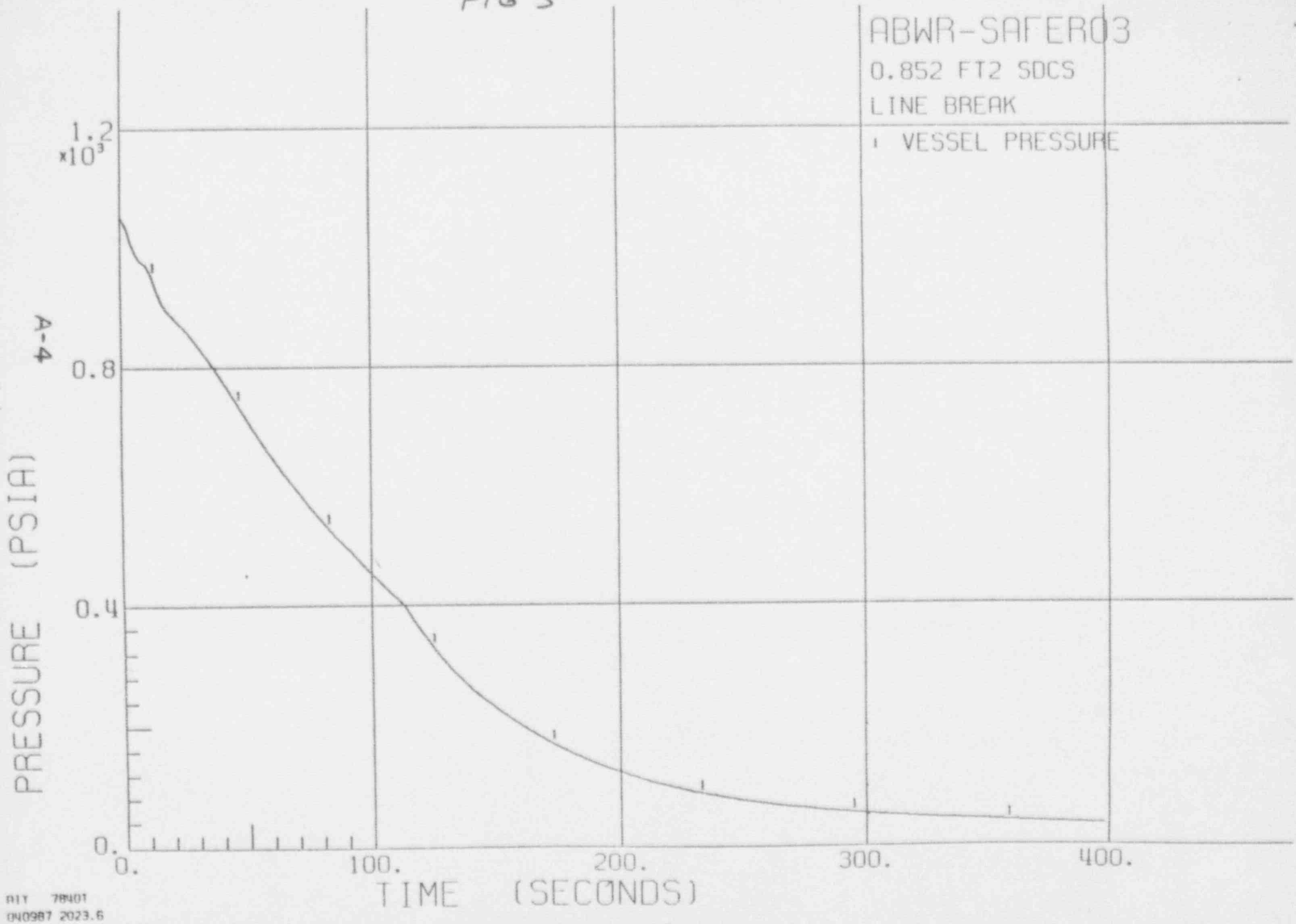
FIG 3



ABWR-SAFER03
0.852 FT2 SDCS
LINE BREAK
VESSEL PRESSURE
1.2
x10^3
0.8
0.4
0.
PRESSURE (PSIA)
0.
100.
200.
300.
400.
TIME (SECONDS)
RIY 78401
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FIG 4

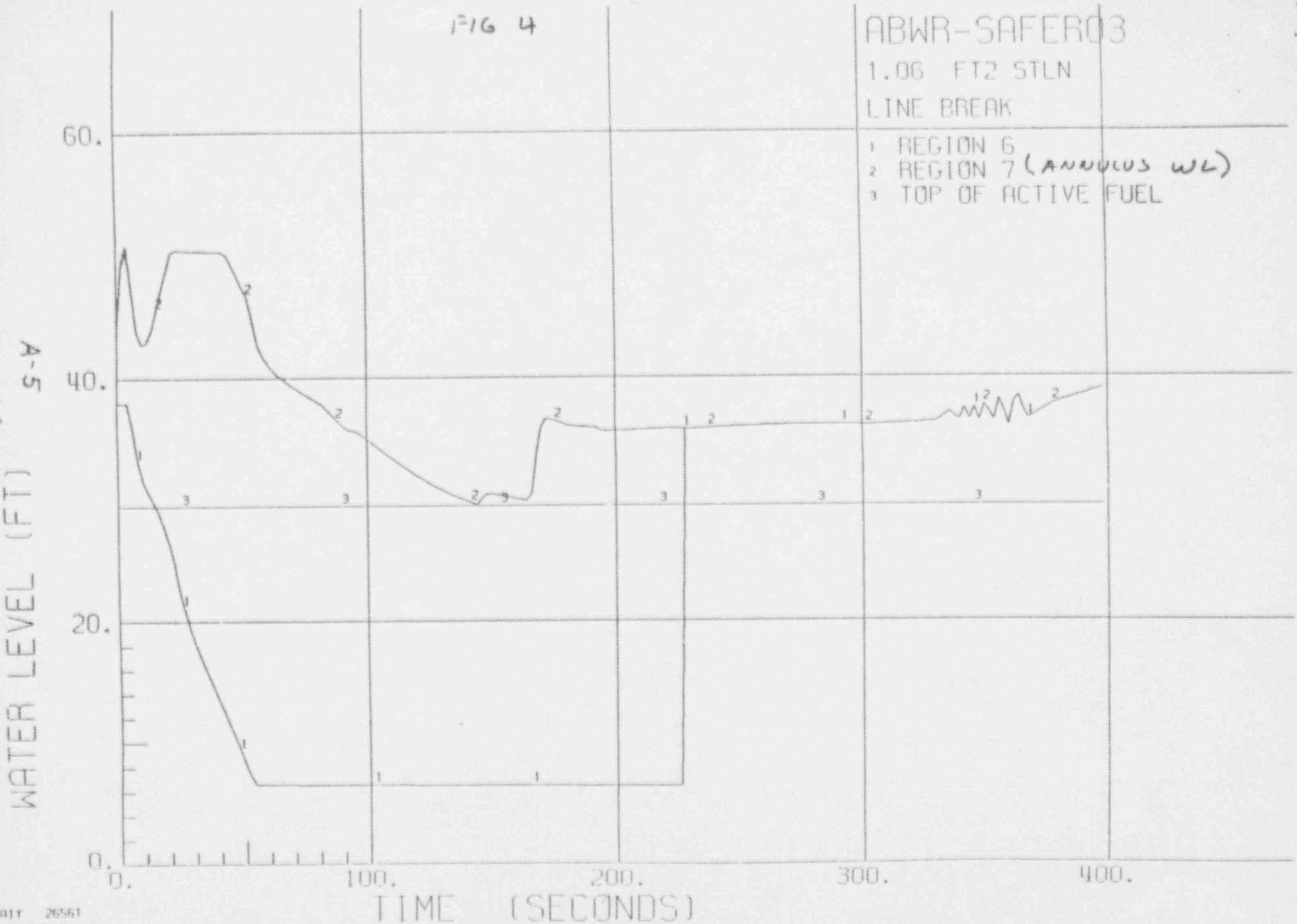

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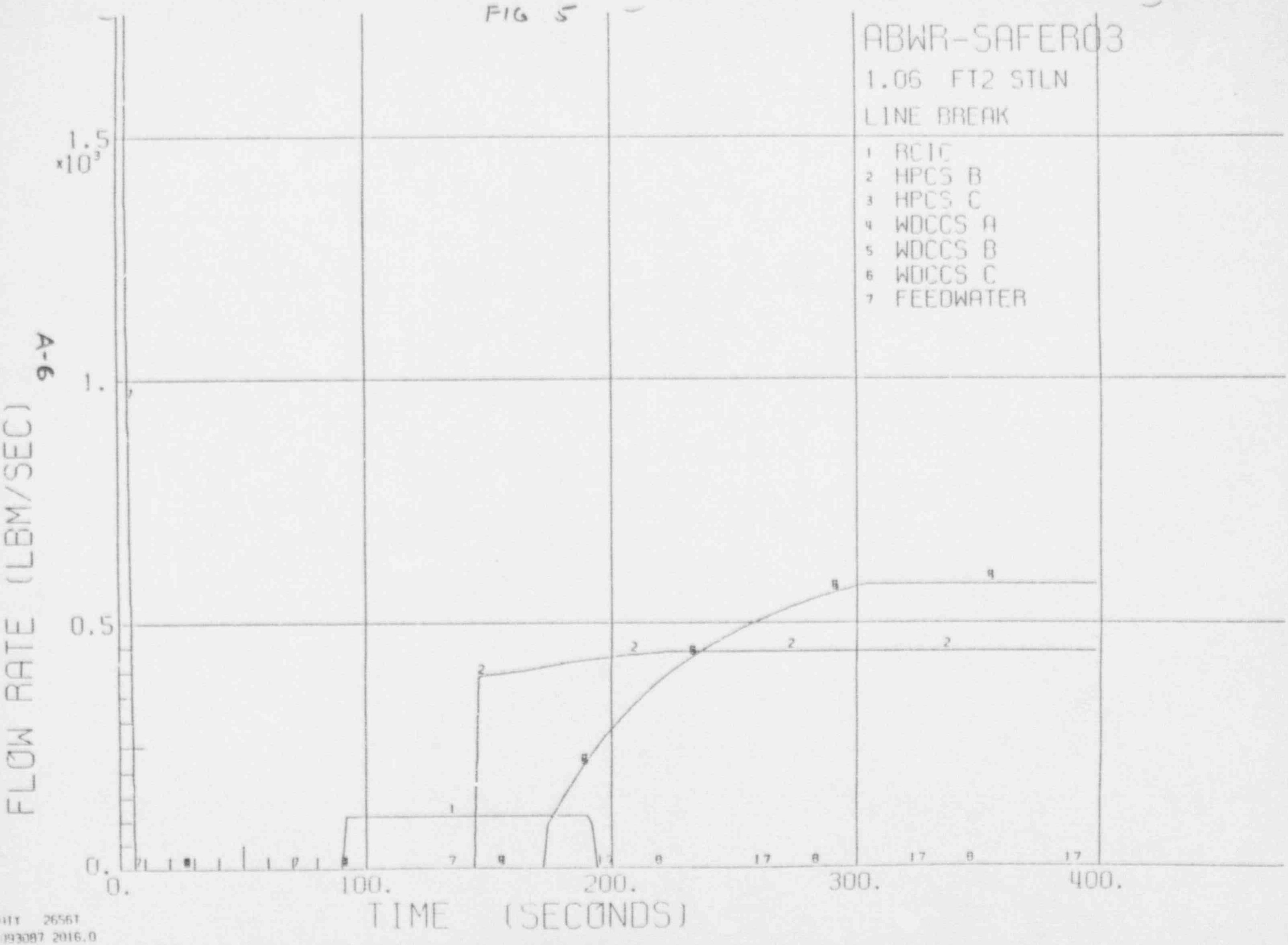
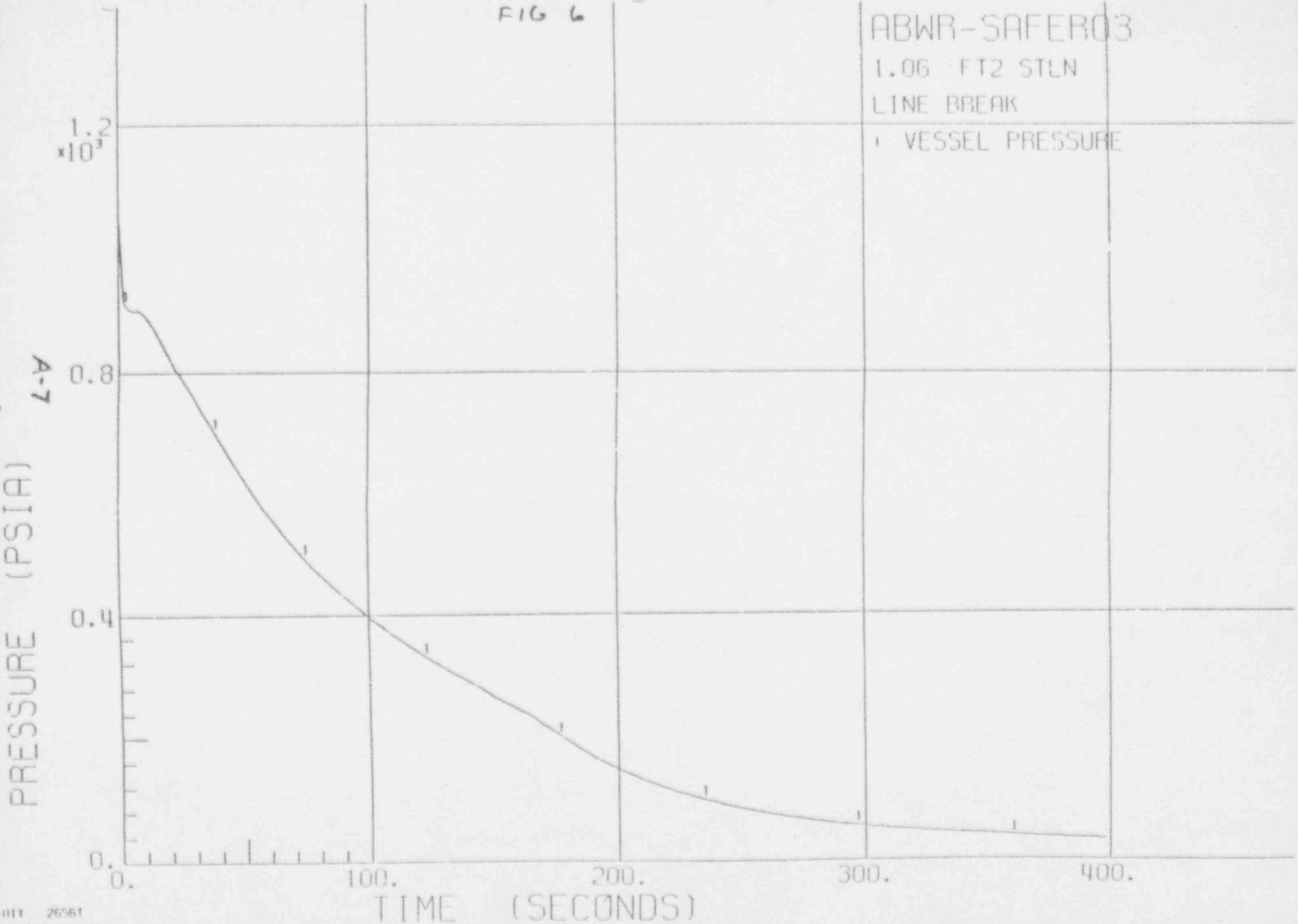
FIG 5


ABWR-SAFER03
1.06 FT2 STLN
LINE BREAK
1 RCIC
2 HPCS B
3 HPCS C
4 WDCCS A
5 WDCCS B
6 WDCCS C
7 FEEDWATER
FLOW RATE (LBM/SEC)
1.5
x10³
1.
0.5
0.
0.
100.
200.
300.
400.
TIME (SECONDS)

A-6

FIG 6



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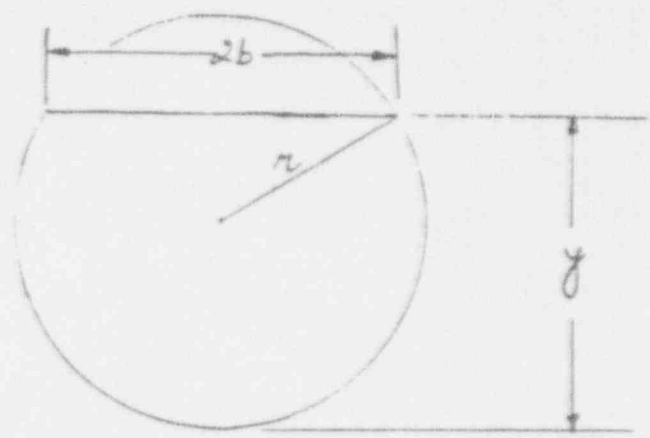
APPENDIX B

B-1 VOID FRACTION DISTRIBUTION ANALYSIS



Consider cross section of a pipe having radius r and unit axial dimension. The pipe is filled with water at 1000 psia saturated condition, and is subjected to depressurization following the pressure - time curve shown in Figure 3 Appendix A.

It is required to determine void fraction distribution in the cross section of the pipe.

The void fraction is a function of time t and the coordinate y taken zero at the bottom of pipe. Assuming a Quasi-Steady State, continuity of flow of vapor at longitudinal section at height y can be written as follows:

Mass of vapor crossing the section per unit time
= Mass of vapor formed in the water below this section per unit time.

The lefthand side of the continuity equation

$$= \frac{\alpha \times (2b) \times u_b \times 1}{v_g} \qquad \text{—— (1)}$$

where u_b = bubble velocity.

The righthand side of the mass conservation equation can be derived as follows:

Consider an adiabatic process of pressure change from P to P+dP for saturated water of mass M. The rate of vapor formed $\dot{m}_v$ is given by the mass conservation

$$m_v^{\cdot} + \frac{dM}{dt} = 0$$

$$\text{or, } m_v^{\cdot} = -\frac{dM}{dt} \qquad \text{——— ②}$$

Energy Conservation –

Enthalpy of vapor flow + change in enthalpy of water = 0.

$$\text{or, } m_v^{\cdot} h_g + \frac{d}{dt}(U_f + PV) = 0$$

$$\text{or } m_v^{\cdot} h_g + \frac{dU_f}{dt} + \frac{PdV}{dt} + \frac{VdP}{dt} = 0$$

$$U_f = Mu_f \quad , \quad V = Mv_f .$$

$$\therefore \quad \frac{dU_f}{dt} = \frac{Mdu_f}{dt} + u_f \frac{dM}{dt}$$

$$= \frac{Mdu_f}{dt} - u_f m_v^{\cdot}$$

$$\& \quad \frac{dV}{dt} = \frac{Mdv_f}{dt} + v_f \frac{dM}{dt}$$

$$= -v_f \frac{dM}{dt} \quad , \text{ assuming incompressible liquid } \frac{dv_f}{dt} = 0.$$

$$\therefore \quad m_v^{\cdot} h_g + \frac{Mdu_f}{dt} - u_f m_v^{\cdot} - Pv_f m_v^{\cdot} + Mv_f \frac{dP}{dt} = 0.$$

$$\text{or, } m_v^{\cdot} h_g - m_v^{\cdot} h_f + \frac{Mdu_f}{dt} + Mv_f \frac{dP}{dt} = 0.$$

$$\text{or } m_v^{\cdot}(h_{fg}) + M\frac{d}{dt}(u_f + Pv_f) = 0.$$

$$\text{or } m_v^{\cdot} = -\frac{M}{h_{fg}} \frac{dh_f}{dt} = \text{Right hand side of continuity eqn.} \qquad \text{——— ③}$$

Continuity equation of vapor flow can be written as (② & ③)

$$\frac{2b u_b \alpha}{v_g} = -\frac{M}{h_{fg}}\frac{dh_f}{dt}$$

$$= -\frac{V}{v_f h_{fg}}\frac{dh_f}{dt} \qquad \left(\because M = \frac{V}{v_f} \text{ where } V = \text{vol. of water below line at } y\right).$$

$$\therefore \alpha = -\left(\frac{1}{h_{fg}}\frac{dh_f}{dt}\frac{v_g}{v_f}\right)\left(\frac{V}{2b}\right)\times\left(\frac{1}{u_b}\right)$$

$V = A \times 1$ where A = area below level at y (x-sectional area).

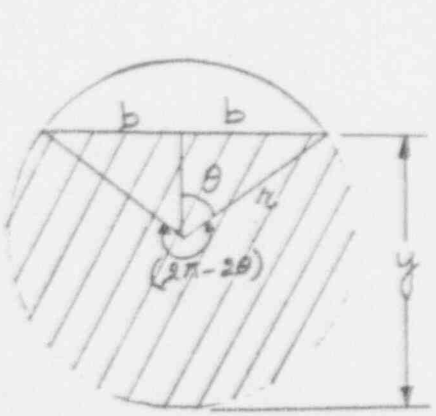
$$\text{or, } \alpha = -\frac{1}{h_{fg}}\frac{dh_f}{dt}\frac{v_g}{v_f}\cdot\frac{A}{u_b \cdot 2b} \quad \text{------ ④}$$

Equation ④ consists of two functions

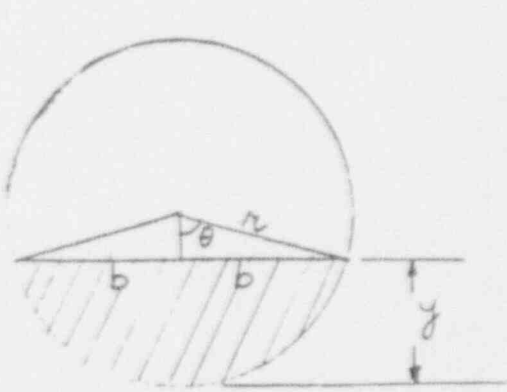
1) $\rightarrow -\frac{1}{h_{fg}}\left(\frac{dh_f}{dt}\cdot\frac{v_g}{v_f}\right) = f(t)$ - function of time only

2) $\rightarrow \frac{1}{u_b}\cdot\frac{A}{2b} = f_1(y)$ - function of y only.

$A/2b$ as a function of y can be evaluated as follows:



CASE 1 $Y \geq r$



CASE 2 $Y \leq r$.

Case 1 -

For $y \geq r$.

Shaded area $A = \frac{1}{2} r^2 (2\pi - 2\theta) + \frac{2b}{2} (r^2 - b^2)^{1/2}$

$\sin\theta = b/r$

$A = \frac{1}{2} r^2 \left(2\pi - 2\sin^{-1}\frac{b}{r}\right) + b(r^2 - b^2)^{1/2}$

or $\frac{A}{2b} = \frac{r^2}{2b} \cdot \frac{1}{2}\left(2\pi - 2\sin^{-1}\frac{b}{r}\right) + \frac{1}{2}(r^2 - b^2)^{1/2}$

$= \frac{r^2}{2b}\left(\pi - \sin^{-1}\frac{b}{r}\right) + \frac{1}{2}(r^2 - b^2)^{1/2}$

expressing b in terms of r & y.

$r^2 = b^2 + (y - r)^2$

or $b^2 = 2ry - y^2$

$\therefore \frac{A}{2b} = \frac{r^2}{2\sqrt{2ry - y^2}}\left(\pi - \sin^{-1}\frac{\sqrt{2ry - y^2}}{r}\right) + \frac{1}{2}(y - r)$

or, $\frac{A}{br} = \frac{\pi - \sin^{-1}\sqrt{2\frac{y}{r} - \left(\frac{y}{r}\right)^2}}{\sqrt{2\frac{y}{r} - \left(\frac{y}{r}\right)^2}} + \left(\frac{y}{r} - 1\right).$

Case 2 -

For $y \leq r$.

Shaded Area

$A = \frac{1}{2} r^2 . 2\theta - 2 \cdot \frac{1}{2} b (r - y)$

$= \frac{1}{2} r^2 . 2\sin^{-1}\frac{b}{r} + br(y/r - 1)$

or $A/br = \frac{\sin^{-1}\sqrt{2\frac{y}{r} - \left(\frac{y}{r}\right)^2}}{\sqrt{2y/r - \left(\frac{y}{r}\right)^2}} + \left(\frac{y}{r} - 1\right)$

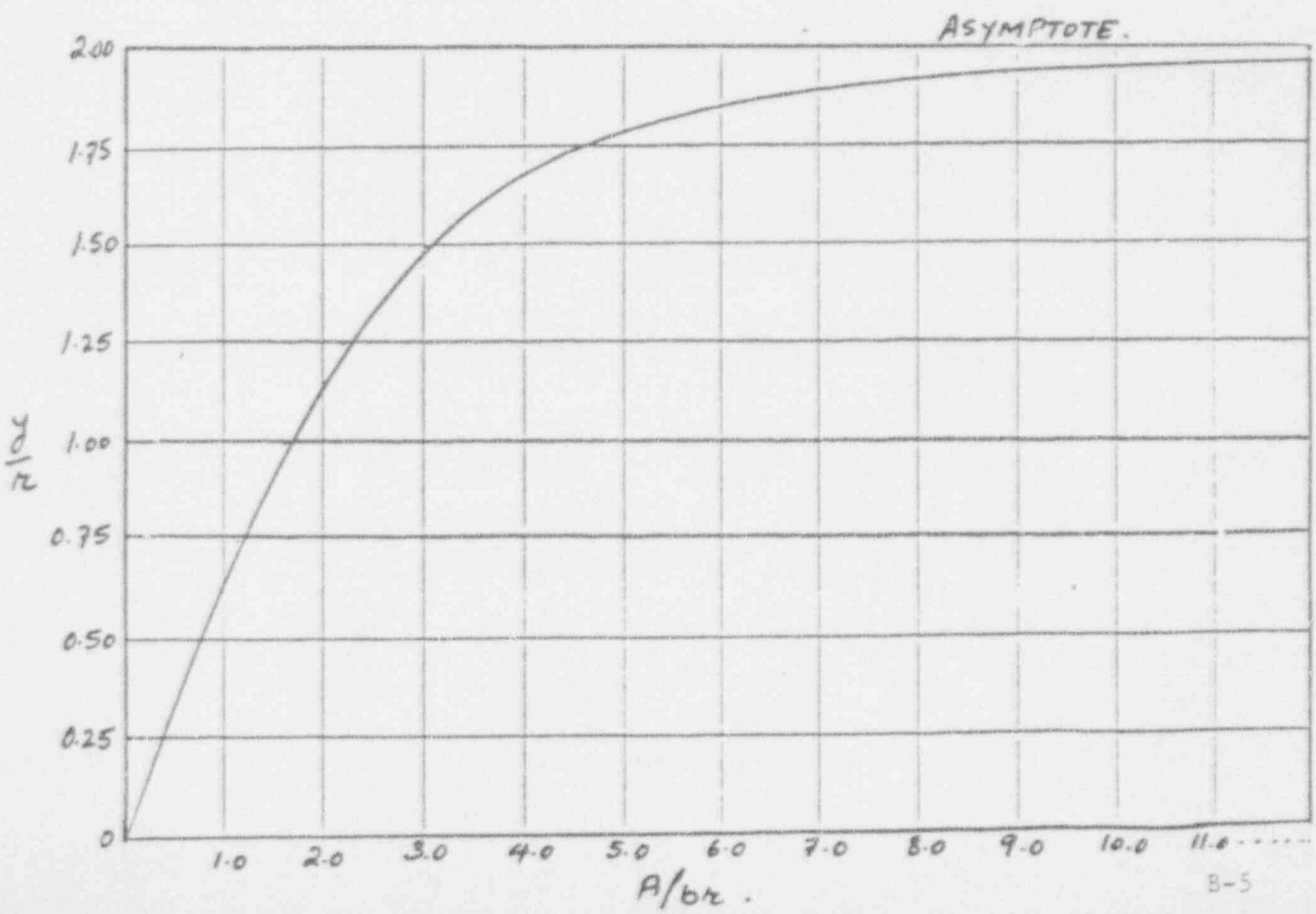
Summary — Case 1 → $\dfrac{A}{br} = \dfrac{\pi - \sin^{-1}\frac{b}{r}}{\frac{b}{r}} + \left(\frac{y}{r} - 1\right)$

Case 2 → $\dfrac{A}{br} = \dfrac{\sin^{-1}\frac{b}{r}}{\frac{b}{r}} + \left(\frac{y}{r} - 1\right)$

Plot A/br ~ y/r.

TABLE B-1.1

y/r	b/r	A/br
0	0	0
0.25	0.66	0.34
0.50	0.866	0.71
0.75	0.97	1.11
1.00	1.00	1.57
1.25	0.97	2.13
1.50	0.866	2.91
1.75	0.66	4.40
2.00	0	∞



Refer to equation (4), it reduces to

$$\alpha = \frac{r}{2u_b} f(t) \cdot \frac{A}{br} \quad \text{——} \quad (5).$$

where $f(t) = -\frac{1}{h_{fg}} \cdot \frac{v_g}{v_f} \cdot \frac{dh_f}{dt}$

Assume $u_b = 1 ft/sec$ (average bubble velocity)

$r = 9.56/2 = 4.78'' = 0.4 ft$, $\frac{r}{2} = 0.2 ft$.

TABLE B-1.2

P	t	h_{fg}	h_f	V_g	V_f	$f(t) \cdot \frac{r}{2u_b}$
1000	0	649.4	542.4	0.445	0.021	0.0071
950	10	659.1	534.6	0.471	0.021	0.007[illegible]
900	15	668.8	526.6	0.500	0.021	0.0077
850	23	678.8	518.3	0.532	0.021	0.0081
800	31	688.9	509.7	0.568	0.021	0.0086
750	41	699.2	500.8	0.609	0.0207	0.0092
700	45	709.7	491.5	0.655	0.0205	0.0098
650	54	720.5	481.8	0.708	0.0203	0.0106
600	64	731.6	471.6	0.769	0.0201	0.0114
550	74	743.1	460.8	0.842	0.02	0.0125
500	85	755.0	449.4	0.927	0.0197	0.0136
450	95	767.4	437.2	1.03	0.0195	0.0151
400	105	780.5	424.0	1.16	0.019	0.0169
350	114	794.2	409.7	1.32	0.019	0.0191
300	125	809.0	393.8	1.54	0.019	0.022
250	136	825.1	376.0	1.84	0.0186	0.026

$\frac{dh_f}{dt} \approx -1.1$ Btu/lbm sec.

$\frac{r}{2} = 0.2 ft$

$u_b = 1 ft/sec$

Note: Ref. 1 used to obtain steam and water properties.

Units –

- P — Psia
- t — secs.
- h_{fg} — Btu/lbm.
- h_f — Btu/lbm.
- v_g — ft^3/lbm.
- v_f — ft^3/lbm.
- $f(t) \cdot \frac{r}{2u_b}$ — non-dimensional time function.

B-2 JUSTIFICATION OF QUASI-STEADY STATE ASSUMPTION USED IN VOID FRACTION DISTRIBUTION ANALYSIS

Consider vapor formation in a volume V of saturated water due to depressurization. Let there be no outflow of vapor out of the volume

Rate of increase of void fraction

$$\dot{\alpha} = \frac{d\alpha}{dt} = \dot{\alpha}_{Stored} = \frac{d\alpha}{dP} \cdot \frac{dP}{dt}$$

Now assume vapor flow out of the pipe - so that outflow volume flow rate $\dot{V_g} = \dot{m_g} v_g$

$$\dot{\alpha}_{out} = \frac{\dot{V_g}}{V} = \frac{\dot{m_v} v_g}{V}$$

If $\dot{\alpha}_{out} >> \dot{\alpha}_{stored}$, Quasi-Steady State Assumption is valid.

Check: (1) Depressurization from 1000 psia to 950 psia.

$$\frac{d\alpha}{dt} = \frac{0.19}{10} = 0.019 = \dot{\alpha}_{stored}.$$

$$\dot{\alpha}_{out} = \frac{\dot{m_v} v_g}{V} = \frac{0.04 \times 0.445}{0.5} = 0.0356.$$

$$\therefore \dot{\alpha}_{out} >> \dot{\alpha}_{stored}$$

Quasi-Steady State Assumption is valid.

Check: (2) Depressurization from 300 psia to 250 psia.

$$\dot{\alpha}_{stored} = \frac{d\alpha}{dt} = \frac{0.014}{11} = 0.0013$$

$$\dot{\alpha}_{out} = \frac{\dot{m_v} v_g}{V} = \frac{0.025 \times 1.84}{0.5} = 0.092$$

$$\therefore \dot{\alpha}_{out} >> \dot{\alpha}_{stored}.$$

Quasi-Steady State assumption is valid.

The above calculations indicate that the Quasi-Steady State assumption is valid at the extreme end of the transient; therefore, it is also valid at every point of the transient.

B-3 CALCULATION OF MASS FLOW OF SATURATED VAPOR OUT OF THE PIPE

Equation 3 -

$$\dot{m}_v = - \frac{M}{h_{fg}} \cdot \frac{dh_f}{dt}$$

Where M - Mass of water at time t
h_{fg} - Enthalpy of vaporization at time t
h_f - Enthalpy of water per unit mass at time t
$\dot{m}_v$ - mass flow of vapor

TABLE B-3

t	h_{fg}	$-\frac{dh_f}{dt} \simeq$	M	$\dot{m}_v$
0	649.4	1.1	23.15(1)	0.04
10	659.1	1.1	22.75	0.038
15	668.8	1.1	22.56	0.037
23	678.8	1.1	22.26	0.036
31	688.9	1.1	21.97	0.035
41	699.2	1.1	21.62	0.034
45	709.7	1.1	21.48	0.033
54	720.5	1.1	21.11	0.032
64	731.6	1.1	20.78	0.031
74	743.1	1.1	20.46	0.030
85	755.0	1.1	20.10	0.029
95	767.4	1.1	19.80	0.028
105	780.5	1.1	19.51	0.027
114	794.2	1.1	19.26	0.026
125	809.0	1.1	18.97	0.025
136	825.1	1.1	18.69	0.025

<u>Units</u>

t - secs.
h_{fg} - Btu/lb_m
$\frac{dh_f}{dt}$ - Btu/lb_m sec.
M - lb_m
$\dot{m}_v$ - lb_m/sec

Note: M & $\dot{m}_v$ are based on 1 ft length of pipe.

(1) @ t=o $M = \frac{V_{t=0}}{v_f} = \frac{0.5x1}{0.0216} = 23.15\ lb_m$

B-4 FREE SEPARATION OF LIQUID AND VAPOR

Void fraction variation is given by

$$\alpha = \frac{r}{2u_b} f(t) \cdot \frac{A}{br}.$$

where $r/2u_b \cdot f(t)$ function of time is given by Table B-1.2 last column and spatial function A/br is given by Table B-1.1.

$@\ t=0\ ,\quad \alpha = 0.0071\ A/br$

$\text{for } \alpha=1\ ,\quad A/br = 140.8$

This value of A/br occurs at a point very close to $y/r=2$; i.e., $y/r \simeq 1.9999$. This indicates that at the beginning of the transient the void fraction at the top of the pipe cross section is 1. For the remaining portion of the transient, the level of water in the pipe will drop according to mass flow rate $\dot{m}_v$ of vapor and the remaining mass of liquid M in the pipe given by Table B-3. The void fraction at the freely separated surface is always 1 above the mass M. The validity of results of Table B-1.2 and Table B-3 can be proved as follows:

Assume mass M left in the pipe at time t,

Continuity Equation -

Vapor outflow rate = Vapor leaving the surface of the liquid per unit time.

The left side as given by Equation 4.

$$= -\frac{M}{h_{fg}} \cdot \frac{dh_f}{dt}$$

The right side is given as

$$= \frac{\alpha (2b) \times 1 \times u_b}{v_g}$$

$$\therefore -\frac{M}{h_{fg}} \cdot \frac{dh_f}{dt} = \frac{\alpha \cdot 2b \times u_b}{v_g}$$

$$\text{or, } \alpha = -\frac{1}{2bu_b} \times v_g \cdot \frac{M}{h_{fg}} \cdot \frac{dh_f}{dt}.$$

$$= -\frac{1}{2bu_b} \cdot \frac{v_g}{v_f} \times \frac{A \times 1}{h_{fg}} \times \frac{dh_f}{dt}$$

$$= -\frac{r}{2u_b} \cdot \frac{v_g}{v_f} \cdot \frac{1}{h_{fg}} \cdot \frac{dh_f}{dt} \cdot \frac{A}{br}.$$

$$\text{or, } \alpha = -\frac{r}{2u_b} f(t) \cdot \frac{A}{br}.$$

This equation is same as Equation 5.

Example:

At $t = 10$ secs.

From Table B-3, $M = 22.75\ lb_m$, $\dot{m_v} = 0.038\ lb_m/Sec.$

Calculate b/r for $M = 22.75\ lb_m$

$$v_f = 0.021\ ft^3/lb_m$$
$$v_g = 0.471\ ft^3/lb_m$$
$$r = 0.4 ft$$
$$L = 1 ft.$$

$$M = \frac{V}{v_f} = 22.75. = \frac{A \times 1}{v_f}$$

$$A = 0.477\ ft^2.$$

$$\frac{A}{2b} = \frac{r^2}{2b} \sin^{-1}\frac{b}{r} + \frac{1}{2}\left(r^2 - b^2\right)^{1/2}$$

$$\text{or } A = r^2 \left\{ \sin^{-1}\frac{b}{r} + \frac{b}{r}\left(1 - \frac{b^2}{r^2}\right)^{1/2} \right\}$$

Plot A~b/r. r = 4.78" = 0.4 ft.

b/r	A(ft^2)
0	0, 0.5
0.2	0.06, 0.44
0.4	0.12, 0.38
0.6	0.18, 0.32
0.8	0.22, 0.28
1.0	0.35, 0.25

For A = 0.477, b/r ≃ 0.076 . b = 0.03 ft.

$$\therefore \frac{A}{br} = \frac{0.477}{0.3 \times 0.4} = 39.75.$$

$$\text{flow rate} = \frac{2b \cdot \alpha \cdot u_b}{v_g}$$

$$= \frac{2 \times 0.03 \times 1 \times 1}{0.471} = 0.127\ lb_m/Sec.$$

Actual flow rate from sparger to vessel = 0.038 lb_m/Sec. ($\dot{m_o}$).

The flow rate m_v' = 0.038 lb_m/Sec.) emerging into the vessel is much less than the vapor flow across section of the pipe where b = 0.03 ft. Therefore, freely separated surface of water also exists after 10 seconds. Similarly, it is evident that freely-separated liquid surface exist in the pipe during the entire transient. The remaining mass of water left in the pipe (per ft. length) is 18.69 lb_m (from Table B-3) at t = 136 secs and vessel pressure = 250 psia. This represents 80% of the initial mass which indicates that the pipe cross-sectional area will be approximately 80% full when the LPFL injection valve is signalled to open.

B-5 EFFECT OF VAPOR FLOW VELOCITY ON THE FREELY SEPARATED SURFACE IN LPFL-PIPE

Table B-3 gives the values of M and $\dot{m}_v$ - the total mass and vapor mass flow per unit length of the LPFL pipe. Assuming a 10 ft. length of pipe, the total vapor flow in the last 1 ft. close to the LPFL nozzle is given by

$$\dot{m}_{vt} = \dot{m}_v \times 10 \text{ lb}_m/\text{sec.}$$

@ t = 10 sec. $\dot{m}_{vt} = 0.038 \times 10$
$= 0.38 \text{ lb}_m/\text{sec.}$

$$\text{Flow area} \simeq \frac{23.15 - 22.75}{23.15} \times 0.5 \text{ ft}^2$$
$$\simeq 0.0086 \text{ ft}^2$$

$$\text{Vapor sp. volume } v_g = 0.471 \text{ ft}^3/\text{lb}_m$$

$$\text{Flow velocity} = \frac{0.38 \times 0.471}{0.0086}$$
$$V_{t=10} = 20 \text{ ft/sec}$$

Assuming there is no entrainment of water along with vapor, the velocity of vapor @ t = 15 secs, 23 sec -- can be similarly calculated and is given by

t = 15 sec	$V_{t = 15 \text{ secs}}$	= 14.5 ft/sec.
t = 23 sec	$V_{t = 23 \text{ secs}}$	= 10 ft/sec.
t = 31 secs	$V_{t = 31 \text{ secs}}$	= 4 ft/sec.

The above results show that the vapor flow velocity over the water surface in the pipe is continuously decreasing. The maximum velocity occurs at the very beginning of the transient in the portion just upstream of the nozzle. Considering velocity of vapor at 10 secs V = 20 ft/sec. which could be visualized to be the same as a 13.5 mph breeze which would produce a quite insignificant effect on the surface of water over which it blows. Initial vapor flow may entrain a negligible quantity of water from the pipe, however, as the transient progresses, greater area becomes available for the flow of vapor and therefore the vapor velocity decreases very rapidly. It is thus concluded that the vapor velocity is very small to blow-out any mass of water from the pipe.