Westinghouse Non-Proprietary Class 3

WCAP-14749
Revision 0

Justification for Increasing Postulated Break Opening Times in Westinghouse Pressurized Water Reactors

Westinghouse Energy Systems

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Justification for Increasing Postulated Break Opening Times in Westinghouse Pressurized Water Reactors

R. E. Schwirian
Reactor and Auxiliary Equipment Analysis

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Approved: R. E. Schwirian
R. E. Schwirian, Technical Lead
Reactor and Auxiliary Equipment Analysis

Approved: Charles H Boyd
C. H. Boyd
Reactor and Auxiliary Equipment Analysis

Westinghouse Electric Corporation
Energy Systems Business Unit
P.O. Box 355
Pittsburgh, PA 15230-0355

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1 EXECUTIVE SUMMARY

This report provides justification for increasing the break opening time (BOT) which is assumed in the analysis of breaks in the piping of Westinghouse pressurized water reactor (PWR) systems as a means of more realistically determining calculated loads on system components during a Loss-of-Coolant Accident (LOCA) event. In Section 2.0, Introduction, the "waterhammer" nature of these loads and the parameters which affect them, such as BOT, are discussed.

In Section 3.0, Break-Opening Time Selection Criteria, Background, the historical Westinghouse BOT design basis of 1.0 msec is reviewed in the context of U.S.N.R.C. requirements (References 13 and 16) on the subject. It is concluded that these requirements permit BOT-values larger than 1.0 msec through the use of analytical or experiment demonstrations. Such demonstrations are provided in Sections 4.0 to 6.0.

Section 4.0 describes experiments performed on stainless steel and carbon steel piping by Battelle Memorial Institute to determine crack propagation speed and BOT for longitudinal and circumferential breaks. In all these experiments, artificially created flaws were used to initiate break-opening. The results of these experiments indicate that a value of [ ][a,c,e] is a conservatively low estimate of a double-ended guillotine BOT for piping diameters typical of PWR primary coolant piping. A correlation model for break-opening area vs. time was developed from these data by Battelle for longitudinal breaks.

In Section 5.0, analyses of break-opening by Westinghouse, Combustion Engineering, Babcock & Wilcox, and Kraftwerk Union AG are discussed. These analyses confirm that [ ][a,c,e] is a conservatively low estimate of BOT for piping diameters typical of reactor primary coolant piping. This section also discusses BOT design practice by FRAMATOME and Kraftwerk Union AG. In the latter case, BOT for circumferential breaks is an increasing function of piping diameter, i.e., is tailored to the piping diameter.

Section 6.0 presents comparisons of LOCA loads calculated by Westinghouse with the MULTIFLEX program, and by the NRC using the WHAM/MOD-007 program. The MULTIFLEX loads are generally larger than the WHAM/MOD-007 loads, and demonstrate the conservatism inherent in MULTIFLEX. This section also illustrates the vessel thrust load reduction benefits to be (potentially) derived by using larger, more realistic break opening times in such calculations.

Using information from previous sections, Section 7.0 proposes a break-opening time design basis for PWR piping. The area versus time correlation developed by Battelle is proposed for longitudinal breaks (Section 4.0). An area vs. time correlation based on the work done by Kraftwerk Union AG (Section 5.0) is proposed for circumferential breaks. Should larger BOT-values than are provided by these correlations become desirable, options based on the U.S.N.R.C. requirements of Reference 13 and 16 are proposed.

2 INTRODUCTION

For a postulated Loss-Of-Coolant Accident (LOCA) in a Pressurized Water Reactor (PWR), the first 10-100 milliseconds of the fluid transient is dominated by subcooled acoustical or "water hammer" wave transmission. During this portion of the LOCA transient, the pressure loads acting on the affected system components can be large, even though their duration is brief. Calculation of these loads is typically done by computer models which subdivide the fluid system into a number of smaller elements, and then solve discretized equations of mass, momentum, and energy transfer between the elements to determine pressure as a function of time and position. For LOCA events, the calculated loads using such techniques can be quite large.

As a result of these high calculated loads, efforts have been made to reduce the conservatisms inherent in their calculation. Broadly speaking, load-reduction calculation techniques have incorporated the following effects: 1) constraints which limit break size, 2) increasing break-opening time, 3) Accounting for fluid-structure interaction effects, and 4) Leak-Before-Break (LBB) arguments. The last, or LBB approach, has received a great deal of attention in recent years and is basically a technology to demonstrate that through-wall cracks will be detected by leakage monitors before reaching "large" break size. While LBB can be a powerful tool for reducing LOCA loads, its application for this purpose is the subject of other, independent programs and activities, and will not be considered here.

In the Reactor Coolant System (RCS), accounting for constraints which limit piping displacement - and thus break size - to less than full, double-ended guillotine values is an approach which has been used by all three U.S. domestic NSSS vendors - Westinghouse, Combustion Engineering, and Babcock & Wilcox - to reduce LOCA loads. Combustion Engineering (Reference 1) and Babcock & Wilcox (Reference 2) have also incorporated calculations of piping and break dynamics into their LOCA design bases. This allows the calculated break area - time relationship to be used as the basis for LOCA load calculations. Westinghouse has historically used a lower bound break-opening time of 1.0 millisecond and, where possible, has developed fluid-structure interaction calculational models (e.g., - References 3, 4, and 5) to reduce LOCA loads. While this approach has been successful in reducing LOCA loads in many cases, there remain some applications in which calculated loads have been excessive. An example of this is the high calculated LOCA loads on control rod guide tubes, which have led to the practice of assuming that no control rods can be inserted during a large break LOCA. Another example in which load reduction may be desirable is in the analyses of the piping loads associated with steam line breaks.

One area in which the no-rod-inserted assumption has raised an issue is in the potential for recriticality after a LBLOCA event. In June, 1992, the NRC issued SECY-92-208, "Possible Recriticality Following Large Break LOCA" (Reference 6), which concluded that, although control rods and the borated safety injection systems in PWRs have abundant neutron absorption capability, the rate of negative reactivity addition from these sources is uncertain, particularly during the early reflood stages of a large break LOCA. This uncertainty stems from uncertainties in the amount of primary system water that remains in the reactor vessel after blowdown, and in the number of control rods which can be inserted during the blowdown.

The NRC contacted the PWR Owner's Groups (Westinghouse, Combustion Engineering, and Babcock & Wilcox) to identify this concern and to determine the Owner's Groups' plans to address it.

In response to the NRC concern, the Westinghouse Owner's Group (WOG) initiated efforts to determine if the current practice of not taking credit for control rod insertion during a large break LOCA could be adjusted to allow some credit to be taken for control rod insertion. The Brookhaven study on which the NRC concerns were based concluded that "if only a small portion of the control rods did insert into the core, the excess reactivity would be eliminated and a return to criticality precluded." The WOG and Westinghouse subsequently initiated a program to evaluate the feasibility of taking credit for control rod insertion by developing methods to reduce LOCA loads on guide tubes to a point where sufficient insertability would be assured. Two approaches were considered: a) application of LBB to RCS piping, and b) increasing the break-opening-time from the current lower bound value of 1 msec to a more realistic value of [ ]^{a,c,e}. Reference 7 summarizes the results of the break-opening-time approach and concludes that for a subset of Westinghouse plants designed for 17x17 fuel assemblies, increasing the BOT to 20 msecs should permit approximately 95% of the control rods to be inserted during a large break LOCA.

The purpose of this document, therefore, is to present information to justify the use of larger break-opening times in Westinghouse calculations of LOCA-induced component loads, and to request NRC concurrence in this change. The result will be a break-opening time design basis which includes a break-size dependent methodology for calculating BOT. The supporting information, which justifies this design basis, consists of 1) experimental data on pipe break-opening-times (References 9 and 10); 2) Westinghouse calculations of break-opening-times; 3) established practice by Combustion Engineering, Babcock & Wilcox and foreign nuclear suppliers; and 4) comparisons of Westinghouse and NRC LBLOCA load calculations. Finally, estimates of realistic break-opening times for primary and secondary system piping will be made to demonstrate that a BOT of [ ]^{a,c,e} provides a conservative representation of break-opening times.

3 BREAK-OPENING TIME SELECTION CRITERIA - BACKGROUND

Historically, Westinghouse has conservatively assumed a 1.0 msec BOT for design basis LOCA load calculations since the publication of Reference 3. Fabic, in Reference 11, concluded that "it is obvious that it would be quite unreasonable to postulate break-opening times shorter than one millisecond". In Reference 12 the following statements are made: "For the purpose of LOCA analysis of Westinghouse plants, postulated guillotine failure will be assumed to take place instantaneously (i.e., in one millisecond)", and "Postulated longitudinal rupture is assumed to take place instantaneously - - - - ". Presumably, "instantaneously" implies a 1.0 msec BOT for the longitudinal rupture. Also, taken in the context in which they appear, these statements treat 1.0 msec as a conservative, lower bound for break-opening time.

In the NRC review and approval (Reference 13) of the LOCA analysis methodology (MULTIFLEX) described in Reference 3, the use of a BOT greater than 1.0 msec is not proscribed, but is, for practical purposes, limited by the following statement: "The Westinghouse proposal to use a one millisecond break-opening time, coupled with the developed equivalent pipe network representation for a PWR system, for MULTIFLEX licensing calculations is acceptable. Longer break-opening times will not be considered unless Westinghouse demonstrates that the proposed break-opening time with the current equivalent pipe network adequately predicts the results of applicable experimental data".

This statement effectively assumes that there exists a single "equivalent pipe network representation for a (Westinghouse) PWR", and that applicable experimental data are available against which to compare calculations. There are experimental data, to be sure: References 14 and 15 describe experiments which have been conducted for the purpose of qualifying computer analysis codes for LOCA load calculations. The difficulty is that the published data are presented over time periods of hundreds of milliseconds rather than milliseconds. To evaluate the effect of BOT, detailed test data in the millisecond range are needed, data which are not presently and are not likely to become available. Such data would also have to include information on break-opening time, or whatever is the equivalent of BOT in a specific test. It is not clear that such data were even recorded in the original tests (e.g. - References 14 and 15).

A more flexible requirement for justifying BOTs greater than 1.0 msec is provided by NUREG-0800, Reference 16: "A rise time not exceeding one millisecond should be used for the initial pulse, unless a combined crack propagation time and break-opening time greater than one millisecond can be substantiated by experimental data or analytical theory based on dynamic structural response". This requirement recognizes that the break opening time is a physical parameter which can be measured and calculated, and has a proper value independent of the analysis approach used. NUREG-0800 is a more general requirement than that of Reference 13, and permits either an analytical or experimental determination of break-opening time itself. It is also a more recent document. For these reasons, it is considered that Reference 16 takes precedence over Reference 13, which does not apply to a broad range of applications. Since Reference 13 applies specifically to MULTIFLEX calculations, it is sufficient to demonstrate that, if it can be shown that MULTIFLEX yields conservative results relative to other acceptable methods of calculation, then MULTIFLEX calculations are also acceptable,

provided that the assumed break-opening time is a realistic or conservative value. This is the approach that will be set forth here. To establish conservative break-opening times for LBLOCA calculations, relevant BOT test data, analytical calculations of BOT, and industry practice will be discussed. The conservatism of MULTIFLEX will be demonstrated by comparison to load calculations performed by the NRC with an independent analysis code. Finally, an approach for defining BOT for general break sizes, will be outlined.

4 EXPERIMENTAL DATA ON BREAK-OPENING TIMES

Experimental data on pipe break-opening times come primarily from two series of experiments, both conducted by Battelle Memorial Institute. These tests include both stainless steel and carbon steel piping, which are used in the primary and secondary system piping of pressurized water reactors. The first series of tests (Reference 9) were conducted on pressurized pipes in which artificial, longitudinal flaws had been created. These tests measured crack propagation speed along and perpendicular to the crack, and permitted the development of a correlation for break-opening area as a function of time. In the second test series (Reference 10), artificial circumferential flaws were created on the inner diameters of pressurized piping which was also subjected to four-point loading. In one of the tests, circumferential crack propagation speed was measured, but data sufficient to determine break-opening area-time behavior were not taken, probably because the applicability of such data would be limited to the piping and support configuration tested. Both of these test series are discussed below.

4.1 TESTS WITH LONGITUDINAL FLAWS (REFERENCE 9)

In the classic Battelle Memorial Institute Tests of the 1960s (Reference 9), experiments on A106B carbon steel and 316 stainless steel pipes were conducted to explore the dynamics of pipe breaks. The breaks were induced by creating artificial, longitudinal flaws in the pipes and then increasing their internal pressures until a rupture occurred. Pressurization was effected by heating the water contained in the pipe specimens and test facility (Figures 4-1 and 4-2). The A106B pipe sizes tested were 24-inch Schedule 40 and Schedule 100; and 12.75-inch Schedule 80. The 316 stainless steel pipe tested was 24-inch Schedule 100.

4.1.1 Artificially-Induced Defects

Two types of artificial defect were created: a surface flaw (SF), shown in Figure 4-3a; and a through-wall flaw (TW), shown in Figure 4-3b, which was sealed with 3/8-inch carbon steel and 1/16-inch 304 stainless steel patches whose strengths were too small to affect crack propagation in the piping. Fracture "speed" and "growth" wires (Figure 4-1) were used to measure the fracture development. Prior to fracture initiation, crack-opening-displacement gages, basically spring clips with strain gages, were used to measure the lateral growth of the artificial flows during pressurization.

4.1.2 Fracture Speed

A total of 30 tests were conducted, 6 of these with 316 stainless steel piping, 24 with carbon steel piping. Table 4-1 summarizes the relevant data from the Battelle Test series. Of the six tests with 316 stainless steel piping, only for test 26, one with a surface flaw, could measurements of fracture speed be made, yielding a value of 370 ft./second.

In the A106B tests, fracture speeds were measured in four tests, one with a surface flaw, and three with through-flaws. All these cases involved 24-inch A106B piping. In the surface flaw case, the piping was Schedule 100, and a fracture speed of 530 ft./sec. was determined. Two of the through-wall flaw cases involved Schedule 100 piping also, yielding fracture speeds of

365 ft./sec. and 366 ft./sec. The third through-wall flaw case involved Schedule 40 piping, and yielded a fracture speed of 458 ft./sec.

From the data, it appears that crack propagation speed for carbon steel may be slightly higher than for stainless steel. The A106B data indicate that the fracture speed with an initial surface flaw will be somewhat higher (530 ft./sec.) than it will be for a through-flaw (365-366 ft./sec.). Fracture speed for a thin-walled pipe (Schedule 40 - 458 ft./sec.) is apparently higher than that of a thick-walled pipe (Schedule 100 - 365 ft./sec.). It may be inferred, therefore, that the single fracture speed data point of 370 ft./sec. point for 316 stainless steel (an initial surface flaw) represents an appropriate fracture speed estimate for the conditions typical of a pressurized water reactor.

4.1.3 Break-Opening Area Versus Time

Figure 4-4 illustrates the measured longitudinal and transverse fracture data for experiment 26, 316 stainless steel Schedule 100 piping with a surface flaw. This is the only experiment for which crack propagation data in both directions were provided. The asymptotic behavior for both directions is a constant speed: 4430 ips (370 ft./sec.) in the longitudinal or crack propagation direction, and 452 ips (38 ft./sec) in the transverse direction. In Reference 9, a break-area vs. time relationship was derived by fitting a straight-line time-X curve to the longitudinal data, a hyperbolic time-Y curve to the transverse data, and assuming a cosine Y-X shape for the break area. This relationship is given and plotted on Figure 4-5.

In the Reference 9 tests in which rupture occurred, ten cases, all ruptures were arrested before the break flow area reached the cross-sectional flow area of the pipe ID. The maximum break flow area obtained was 28.5% of the pipe ID cross-sectional area.

4.2 TESTS WITH CIRCUMFERENTIAL FLAWS (REFERENCE 10)

The test series of Reference 10 were conducted on 304 SS piping with artificial, circumferential flaws. Unlike the Reference 9 tests; however, the pressure and temperature (55° F) inside the pipe were kept constant while failure was induced by four point bending. Both through wall (TW) and surface flaw (SF) tests were conducted; only the SF tests were pressurized. For present purposes, the relevant test is experiment number 4141-4, the only one in which fracture propagation speed was measured. The piping for this test was 304 SS with an O.D. of 16.28 inches and a wall thickness of 1.031 inch.

4.2.1 Artificially-Induced Defects

The surface flaw for experiment 4141-4 was produced in the I.D. of a submerged arc weld (SAW) by an EDM process, as illustrated in Figure 4-6. The surface crack length was 50% of the pipe circumference, and was 0.689 inches deep; the geometrical particulars are summarized in Figure 4-6. Timing wires along the direction of crack propagation were used to measure crack propagation speed.

4.2.2 Fracture Speed

Figure 4-7 illustrates both the crack growth and crack propagation speed measured by the timing wires during experiment 4141-4. The peak crack propagation speed observed was on the order of 300 feet/sec.; the average crack propagation speed is estimated in Reference 10 to be 150 feet/sec. As Figure 4-7 shows, crack propagation speed continually decayed during the experiment as it propagated around the pipe circumference.

4.3 CRACK PROPAGATION TIME FOR LBLOCA BREAK

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]^{a,c,e}

Table 4-1 Test Data Summary from Battelle Tests (Reference 9)

		Pipe			Notch			Patch				Fracture Extension[a]	
Test No.	Specimen Length(')	Diam. (")	Wall Thickness(")	Material	Type	Length(")	Depth(")	Length(")	Width(")	Shell(")	Fracture Speed (ps)	N end	S end
1	8	24	1.674	A106B	TW	18.5	1.674	30	18	0.188	-	3.25	3.9
2	10	24	1.593	A106B	TW	18.5	1.593	29	16	0.062	-	10.00	8.4
3	9	24	1.735	A016B	TW	24.5	1.735	35	15	0.062	-	5.3	5.8
4	22	24	1.703	A106B	SF	28.4	1.30	-	-	-	-	4.5	4.3
5	11.25	24	1.640	A106B	TW	18.5	1.640	38.5	18	0.062	-	rupture	
6	7.2	24	1.715	A106B	TW	11.6	1.715	31.6	18	0.062	-	8.5	8.6
7	8.25	24	1.535	A106B	TW	18.5	1.635	38	18	0.062	365	rupture	
8	11.5	24	1.720	A106B	SF	24.5	1.27	-	-	-	530	rupture	
9	11.5	24	1.650	A106B	SF	24.5	1.45	-	-	-	-	leak	
10	10.7	24	1.640	A106B	TW	18.5	1.640	3.85	18	0.062	366	rupture	
11	9	24	0.705	A106B	TW	10.25	0.705	30.25	18	0.062	-	rupture	
12	9	24	0.710	A106B	TW	5.25	0.710	25.25	18	0.062	-	rupture	
13	8	24	0.700	A106B	TW	14.5	0.700	34.5	18	0.062	-	rupture	
14a	8.3	24	1.533	A106B	TW	24.5	1.533	44	18	0.062	-	rupture	
14b	8.3	24	1.533	Type 316	TW	24.5	1.533	44	18	0.062	-	0.5	0.5
14c	8.3	24	1.533	Type 316	TW	24.5	1.533	44	18	0.062	-	patch leaked	
15a	12	24	1.640	A106B	TW	18.5	1.640	38.5	18	0.062	-	patch leaked	
15b	12	24	1.640	A106B	TW	18.5	1.640	38.5	18	0.062	-	rupture	
16a	10	24	0.700	A106B	TW	2.5	0.700	22	18	0.062	-	patch leaked	
16b	10	24	0.700	A106B	TW	2.5	0.700	22	18	0.062	458	rupture	
17	10	24	1.650	A106B	TW	6.0	1.650	26	18	0.062	-	rupture	
18	8	24	0.700	A106B	SF	10.75	0.355	-	-	-	-	3.25	3.0
19	10.5	24	1.619	A106B	SF	11.6	1.05	-	-	-	-	rupture	
20	8	24	0.682	A106B	SF	5.25	0.35	-	-	-	-	8	8
21	7	12.75	0.710	A106B	TW	2.50	0.710	14.5	10	0.062	-	rupture	
22	7	12.75	0.707	A106B	TW	5.25	0.707	17.25	10	0.062	-	7	8
23	7	12.75	0.700	A106B	TW	10.25	0.700	22.25	10	0.062	-	6	6
24	10	24	1.500	Type 316	SF	11.6	0.900	-	-	-	-	0	0
25	9	24	1.500	Type 316	SF	6.0	0.900	-	-	-	-	leak	
26	9	24	1.500	Type 316	SF	11.6	0.700	-	-	-	370	rupture	

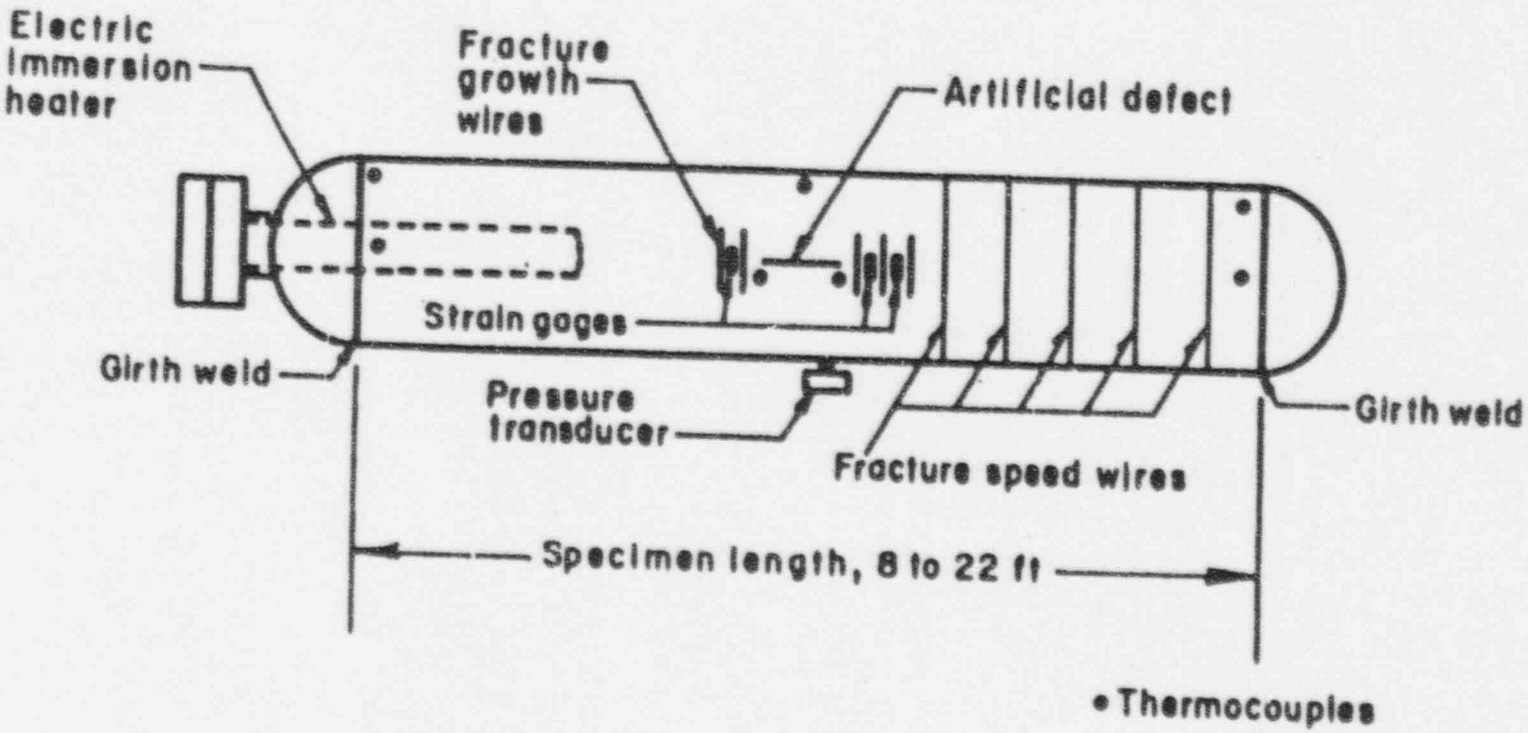


Figure 4-1 Specimen Configuration (Reference 9)

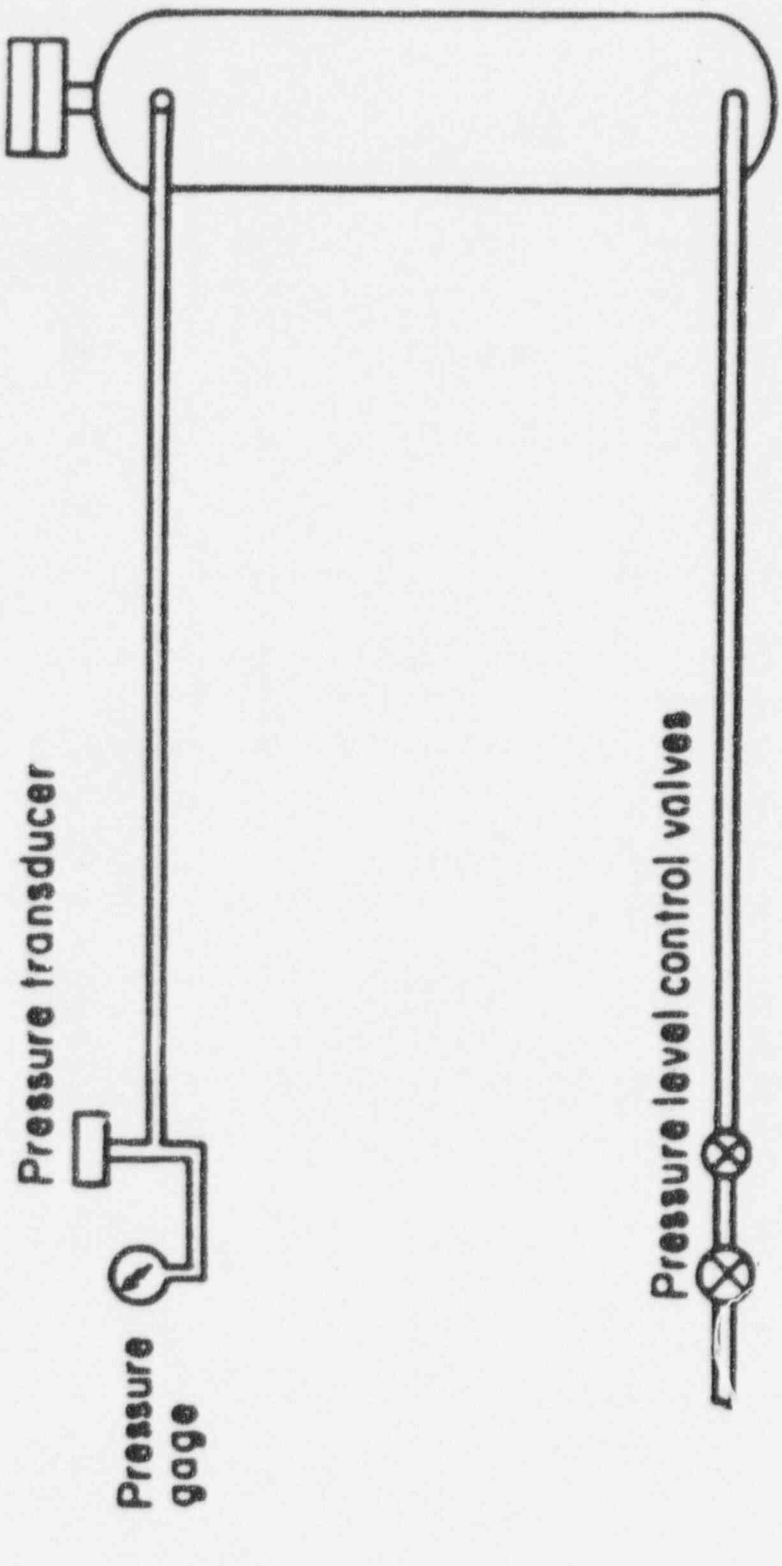
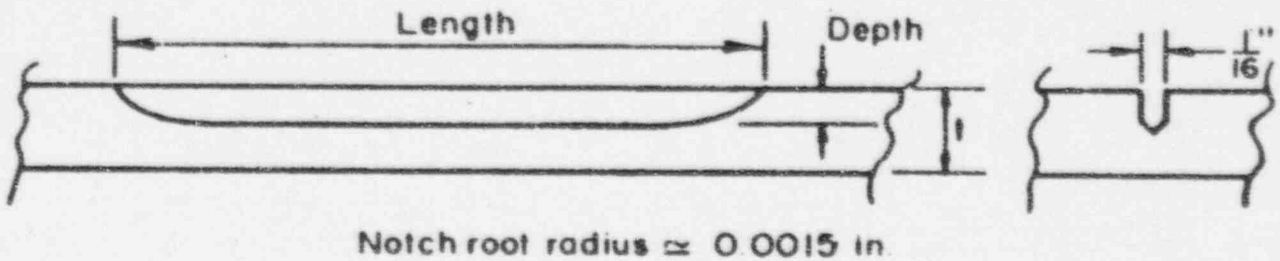
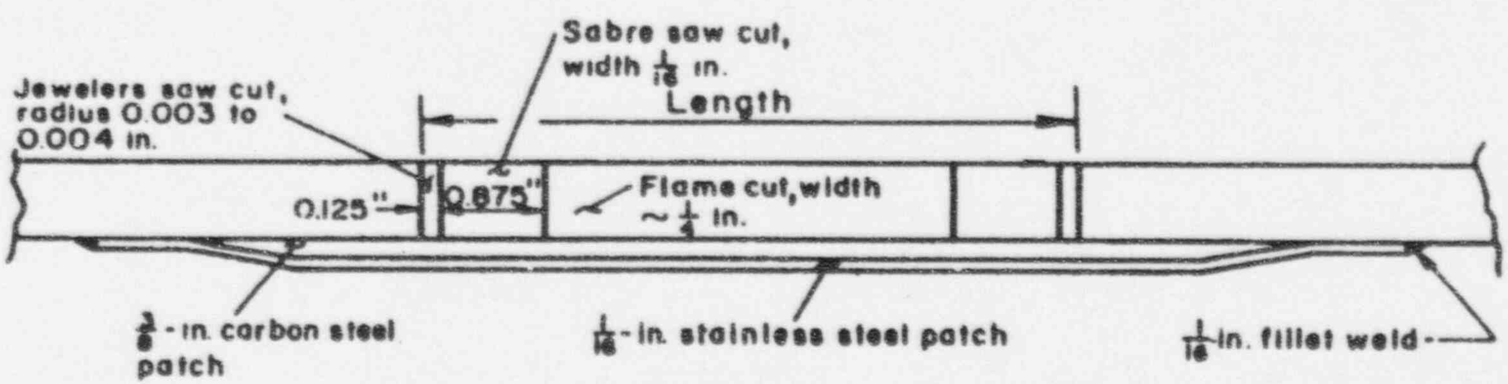


Figure 4-2 Specimen Control Piping (Reference 9)



(a) Surface Flaw Configuration

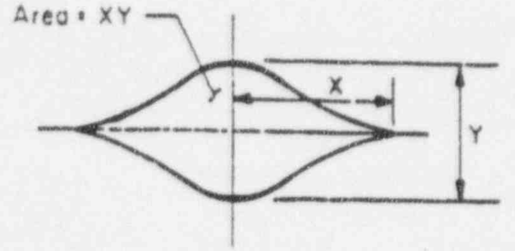


Carbon steel patch is not held in place and is 6 in. wide by the notch length plus 10 in.

Stainless steel patch is fillet welded in place and is approximately 18 in. wide by the notch length plus 20 in.

(b) Through-Wall Flaw Configuration

Figure 4-3 Artificial Flaw Configurations (Reference 9)



Assumed Rupture Shape

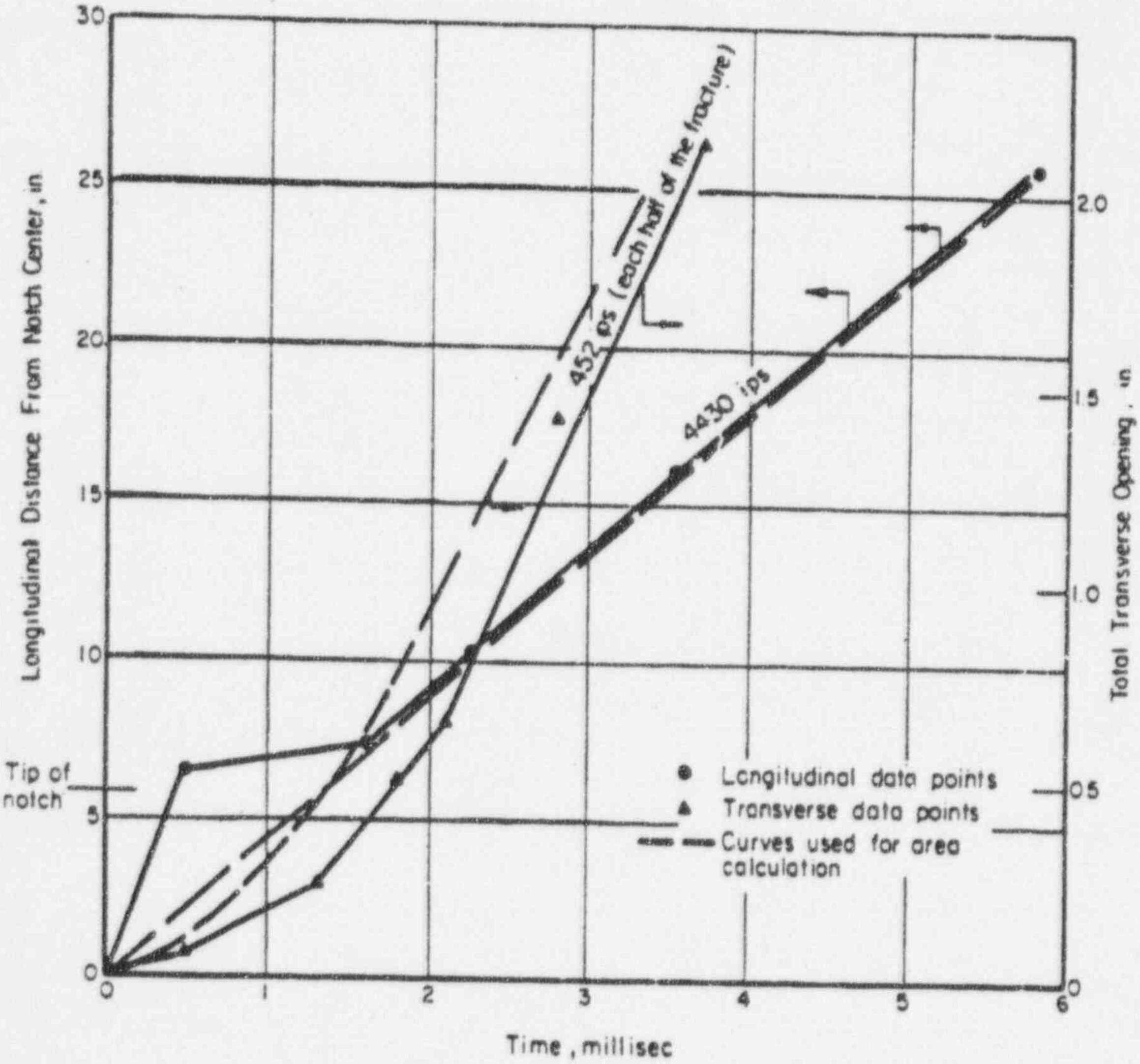


Figure 4-4 Longitudinal (x) and Lateral (y) Fracture Movement as a Function of Time for 24-Inch Schedule 100, 316 SS Piping (Experiment 26, Reference 9)

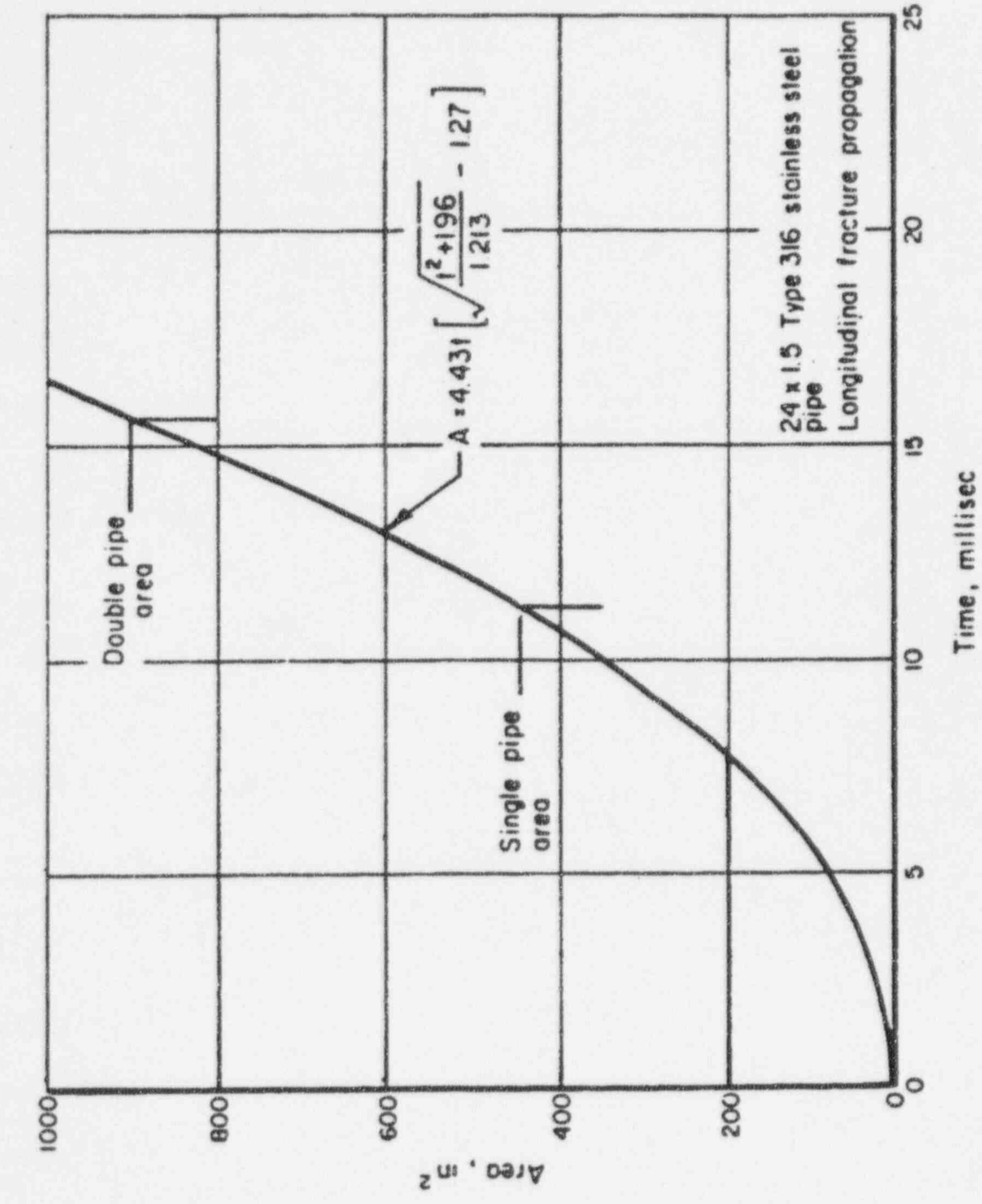
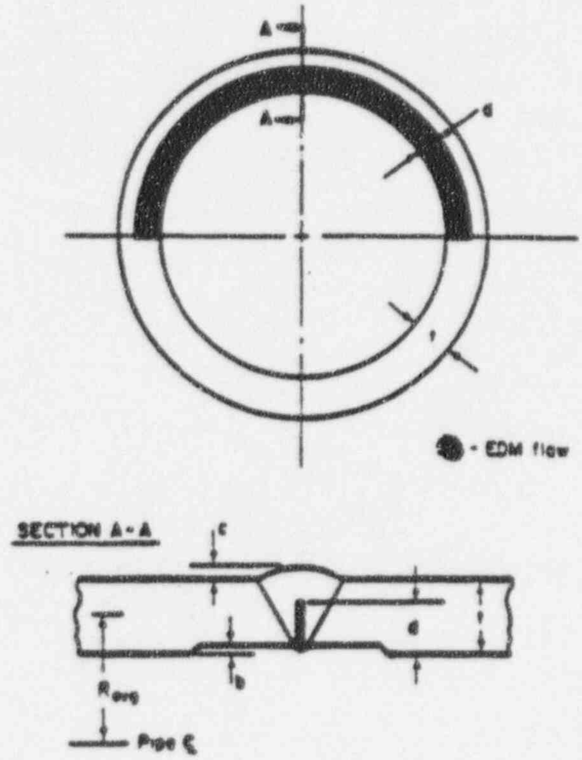


Figure 4-5 Approximate Opening Areas as a Function of Time (Experiment 26, Reference 9)



Experiment Number	Pipe Radius (R_m), inch (mm)	Wall Thickness (t), inch (mm)	Crown Height (C), inch (mm)	Counter-Bore (b), inch (mm)	Flaw Depth (d), inch (mm)	Yield Stress, ksi (MPa) Base Metal	Yield Stress, ksi (MPa) Weld Metal	Ultimate Stress, ksi (MPa) Base Metal	Ultimate Stress, ksi (MPa) Weld Metal
4141-2	3.02 (76.7)	0.584 (14.8)	0.02 (0.5)	~0.1 (2.5)	0.378 (9.6)	20.52 (142)	47.1 (327)	65.2 (450)	67.6 (466)
✓ 4141-4	7.17 (182)	1.031 (26.2)	0.093 (2.4)	~0.1 (2.5)	0.689 (17.5)	26.1 (180)	47.1 (327)	68.0 (469)	67.6 (466)
4141-6	7.675 (195)	1.040 (26.4)	~0.090 (2.3)	~0.1 (2.5)	0.697 (17.7)	26.1 (180)	28.3(a) (195)	68.0 (469)	67.5(a) (465)

(a) Values for solution-annealed weld metal.

Figure 4-6 Internal Surface Crack Geometry (Reference 10)

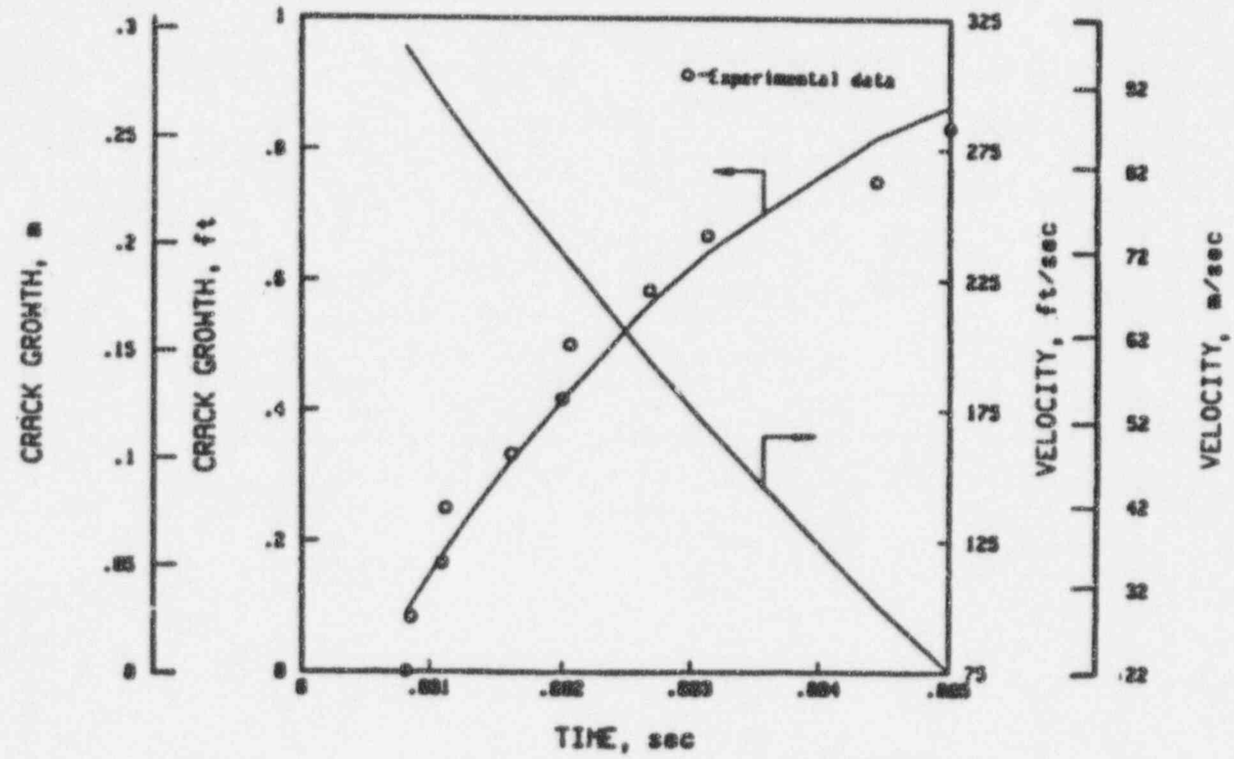


Figure 4-7 Crack Length and Instantaneous Crack Velocity as a Function of Time for Experiment 4141-4, a 16-Inch (406-mm) Diameter Schedule 100 SA-358 TP304 Stainless Steel Pipe with an Internal Surface Crack In a Circumferential As Welded (SAW) (Reference 10)

5 PIPING DYNAMICS OF BREAK-OPENING

It was noted earlier that there are two components of break-opening time: a) the time for a crack to propagate to completion, and b) the time required to open the crack to the break flow area. The NRC, in NUREG-0800, Section 3.6.2 (Reference 16) allows, for analysis purposes, the use of a "rise time" which is a combination of crack propagation and break-separation times, if it can be justified by experiment or analysis (see Section 2.0).

For longitudinal breaks, as has been discussed in Section 3.0, Battelle (Reference 9) has developed a correlation for break-opening area vs. time, which was shown to yield BOTs of approximately [ ]^{a,c,e} for typical Westinghouse cold leg and hot leg piping. For circumferential breaks, however, the break-opening, and therefore the BOT, will depend on the system piping dynamical characteristics as well, and cannot therefore be evaluated by a single correlation. The purpose of this section will be to show that, even though piping system dynamics can affect the overall BOT, a BOT of [ ]^{a,c,e} is still conservative for LBLOCA applications. To provide this demonstration, the results of Westinghouse, Combustion Engineering, and Babcock & Wilcox calculations of break-opening will be used.

5.1 WESTINGHOUSE (W) CALCULATIONS OF BREAK-OPENING TIME

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]^{a,c,e}

5.2 COMBUSTION ENGINEERING (CE) CALCULATIONS OF BREAK OPENING TIME

Reference 1 describes the criteria and analytical methods used to establish the design basis for the mechanical effects of postulated pipe breaks in Combustion Engineering two loop (two hot legs, four cold legs) reactor coolant system piping. Included in the report are the methods and criteria for determining pipe break locations, types, sizes, and opening times in RCS main loop piping. Figure 5-4 illustrates the locations of the postulated breaks for Combustion Engineering plants.

As Figure 5-4 illustrates, circumferential breaks are postulated only at the terminal ends of the reactor coolant system piping with the reactor pressure vessel, steam generators and reactor coolant pumps. Longitudinal breaks are postulated at only two locations in each pump suction leg at the elbows.

Calculation of circumferential break-opening area vs. time were performed in a manner similar to those performed (Section 4.1) for Westinghouse plants: by creating and running a finite element model of the RCS piping systems, and assuming instantaneous crack propagation to severance at the break location. To obviate the need for iteration, the blowdown pressure transients for each break were calculated assuming break-opening times between 7 and 20 milliseconds, these being selected on the basis of prior calculational experience. This is in contrast to the current Westinghouse practice of assuming a 1.0 msec BOT for such calculations. Figure 5-5 illustrates the calculated break-area vs. time relationship for a circumferential break at the steam generator terminal end of the hot leg. The abrupt peak at about 14 msecs is due to the restraint provided by an elastic-plastic pipe stop at the pipe elbow. The break flow area development is similar to those calculated for Westinghouse plants, although somewhat larger. Figure 5-6 illustrates the break-opening behavior at the hot leg terminal end at the reactor. This behavior is quite similar to those shown in Figures 5-2 and 5-3 for Westinghouse plants. [

]^{a,c,e}

Break-opening calculations were also performed for the CE postulated longitudinal break. Calculations were performed for straight 30 inch and 42 inch sections of piping. The results are shown in Figure 5-7, with the 42 inch pipe break area reaching a maximum of 812 square inches in 7 msecs, and the 30 inch pipe break area reaching a maximum of 532 square inches in 5 msecs. Both of these maxima are smaller than the single-ended flow areas of their pipe IDs. A simple extrapolation of the curves in Figure 5-7 to the double-ended guillotine break areas of each pipe would more than double the BOT of each. Furthermore, the inherent conservatisms in the calculations are, in all likelihood, causing underprediction of the BOT. Some of these

conservatisms are: a) an initial through-wall longitudinal crack, two pipe diameters in length, is assumed to initiate the transient with no credit taken for crack propagation time, b) no credit is taken for the additional stiffness at the elbows, where longitudinal cracks are postulated, and c) there are no iterations performed in the calculation of BOT. Inclusion of these factors would likely result in calculated longitudinal break area vs. time relationships similar to the Battelle correlation (Reference 9) with test data shown in Figure 4-5.

5.3 BABCOCK & WILCOX (B&W) CALCULATIONS OF BREAK-OPENING TIME

Reference 2 describes the criteria which have been established by Babcock & Wilcox for postulated pipe breaks in the primary system. Only guillotine-type breaks are considered credible in B&W plants. This position is justified on the basis of detailed research and analysis of "split-type" failures, which show that "no conditions exist for which significant growth of internal axial surface flaws can be anticipated". Appendix C of Reference 2 provides the comprehensive justification of this position.

Circumferential breaks are assumed to occur at all the terminal ends of main piping runs and branch piping runs. Breaks are also postulated based on fatigue usage factor and stress intensity, as described in Reference 2. Break-opening area vs. time calculations, based on structural dynamic analysis of the primary piping, are performed for Babcock and Wilcox plants in a manner similar to those performed for Westinghouse (Section 4.1) and Combustion Engineering (Section 4.2) plants. Unlike the W and CE approach, however, iterations are performed between the blowdown loads which drive the piping system dynamics, and the break area-time relationship which drives the blowdown loads. That is, iterations are performed until neither the blowdown transient nor the break area-time relationship changes significantly. In this way, compatibility between the blowdown forces and the break area-time behavior from which they were calculated is assured.

Figure 5-8 shows the calculated break area (as a fraction of the single-ended pipe flow area) as a function of time for a reactor vessel outlet nozzle break. This particular calculation does not represent the final iteration. Nevertheless, it does demonstrate behavior similar to the Westinghouse and Combustion Engineering calculations of Sections 4.1 and 4.2, peaking at a value of 0.32 times the single-ended pipe flow area, at a time of 40 msecs after pipe rupture. As with the W and CE calculations, this transient time does not include the crack propagation time before severance.

5.4 BREAK-OPENING TIME EVALUATIONS BY KRAFTWERK UNION AG

The paper by Schramm (Reference 17) compares the German RSK guidelines to those in the NRC Standard Review Plan, Chapter 3.6.2 (Reference 16). The German RSK guidelines prescribe a BOT of 15 msecs for the primary loop - without requiring analytical or experimental proof - whereas the U.S.N.R.C. in Reference 16 (see Section 2.0 of the present document) prescribes 1.0 msec, without proof. Schramm expresses the opinion that the U.S.N.R.C. approach "is extremely conservative and appears to be extremely unrealistic".

Other than the discussion of German RSK vs. U.S.N.R.C. guidelines, Reference 17 is concerned primarily with LOCA-induced loads on piping. There is no specific discussion concerning, for instance, loads on the reactor internals. However, the remark is made that "the effect of break opening time on the pressure wave transient is a relatively sensitive parameter. . . . . . .". It is the LOCA blowdown pressure transient, primarily the rate of depressurization, which affects the magnitudes of reactor internals loads.

The paper describes calculations of break opening area vs. time for a number of piping systems. The analytical procedure neglects the crack propagation time contribution to the BOT and is iterative to assure compatibility of the blowdown transient and the break opening area predictions. The results of these studies indicate that a parabolic dependence of break-opening area with time, according to the following formula, is appropriate:

$$\frac{A(t)}{2Ap} = (\frac{t}{t_B})^2$$

where

A(t) = break opening area

t = time

Ap = single-ended pipe flow area

t_B = break opening time

Schramm also recommends selection of break opening time as follows:

Piping Diameter (mm)	t_B (msecs)
0 - 50	1.0
50 - 250	5.0
450 - 700	15.0

For reference purposes, 700 mm is approximately 27.5 inches, the cold leg ID in most Westinghouse plants. Figure 5-9 illustrates the break opening results presented by Schramm for several piping systems in a pressurized water reactor (PWR). Schramm refers to this figure as illustrating "the spectrum of shortest opening times for auxiliary piping systems". The systems analyzed are summarized below.

Main Steam System	DN 700
Feedwater System	DN 450
SG Blowdown System	DN 100
SG Blowdown System	DN 150

Volume Control System	DN 100 (injection line)
Volume Control System	DN 50 (injection line)
Volume Control System	DN 100 (discharge line)
Pressurizer Blowdown Line	DN 250

The numerical designations - DN50, DN100, etc. apparently refer to the piping diameter in millimeters.

5.5 FRAMATOME (FRA) PRACTICE RELATIVE TO BREAK-OPENING TIME

Westinghouse has a limited amount of information about FRAMATOME BOT assumptions and their justifications. It is known that FRAMATOME postulates the same breaks as Westinghouse (see Reference 12 and Figure 5-1), which is not surprising, given the fact that FRAMATOME plants are based on Westinghouse designs.

On BOT, FRAMATOME provided the following to Westinghouse in 1985:

- Rupture time: The time from the initial moment of pipe rupture to complete severance. This time is assumed to be equal to 5 milliseconds.
- Opening time: The time from the moment the two severed loop sections separate to the moment of impact on the restraint. Depending on the break type and the mass of the system in motion, realistic opening times of 5 to 30 milliseconds are obtained.
- Although the above realistic opening times are based on sound empirical principles, the following break opening times have been postulated:
  - — 1 millisecond in the calculation of loads imposed on vessel internals
  - — 10 milliseconds in the calculation of loads imposed on the reactor coolant loop
- For the purposes of analysis, the initial moment of both rupture time and break opening time are assumed to coincide at zero millisecond.

There are several items of interest here. The first is that FRA recognizes a time interval of 5 msecs before pipe rupture occurs; this can be compared to a crack propagation time. The last statement, however, essentially indicates that the "rupture time" is not included in the overall BOT, since both are initiated at time zero. This begs the question as to why "rupture time" is even identified as a parameter.

The second item of interest is that FRA uses different BOTs for reactor internals and reactor coolant loop loads. The reason for this may be that a 1.0 msec BOT may not necessarily be conservative for calculating piping loads and dynamics; a low value of BOT may lead to more rapid depressurization and hence to lower loads on piping elbows. Schramm (Section 4.4) seems to come to a similar conclusion as well when he refers to Figure 4-2 of Reference 17 and states: "The influence of break opening time on (pipe) reaction forces is shown in Figure 4-2.

Given that the integral of force over time is the important parameter for the design of pipe restraints, it can be readily concluded that longer opening time leads to higher loads." His subsequent arguments, however, are not in favor of a conservatively high BOTs for piping analysis, but for iteration to determine realistic values.

Finally, FRA recognizes that realistic break-opening times are higher than 1.0 msec; their estimates are 5-30 msecs. This is in agreement with the available experimental data and calculations by Westinghouse and other vendors discussed earlier in this section.

In response to a more recent request by Westinghouse for clarification of their LOCA load design bases, FRA provided the following in 1992:

- In France, a generic code agreement does not exist. Agreement is given only to specific safety analysis on a case-by-case basis.

  Most of LOCA force related analysis since 1986 has been made by FRAMATOME with the ATHIS code that integrates features of the SUPERFLEX approach. (Note: SUPERFLEX is an advanced version of the MULTIFLEX computer code developed by Westinghouse.)

- The minimum 1 millisecond break opening time is the bounding assumption for the RPV, internals and fuel LOCA force analysis.

- Besides the standard break opening times mentioned above, other more realistic break opening times, derived from the displacements given by the mechanical response analysis of the primary circuit, have been used according to particular needs and situations.

These responses clearly represent a relaxation of the 1985 FRA LOCA design bases. A BOT of 1.0 msec is now a "bounding" assumption, for calculating vessel internals and fuel loads. Furthermore, "more realistic break opening times .... have been used according to particular needs and situations." It would appear, from this statement, that FRAMATOME has been permitted by the French regulatory authority to adjust its BOT design basis to allow for the realities of break-opening dynamics. That is, FRA has been permitted to do what the WOG is currently requesting from the U.S.N.R.C.

That FRAMATOME has used this flexibility in BOT is a fact. In a recent program with a Belgian utility to evaluate LOCA loads on reactor internals, FRA presented results for two breaks in which a [ ]^{a,c,e} BOT was assumed: a) a one square foot break at the reactor vessel inlet, and b) a double-ended guillotine break in the crossover leg.

Of interest also in the 1992 FRA responses is the fact that generic code approval is not presently required in France. The ATHIS code - which is based on SUPERFLEX - is used to perform the same functions as MULTIFLEX, but requires only a case-by-case review and approval of analysis results. This allows FRA to employ whatever codes are appropriate for a given LOCA load evaluation, rather than attempt to evaluate all LOCA loads in the context of an approved code, which can sometimes lead to overly conservative results.

a,c,e

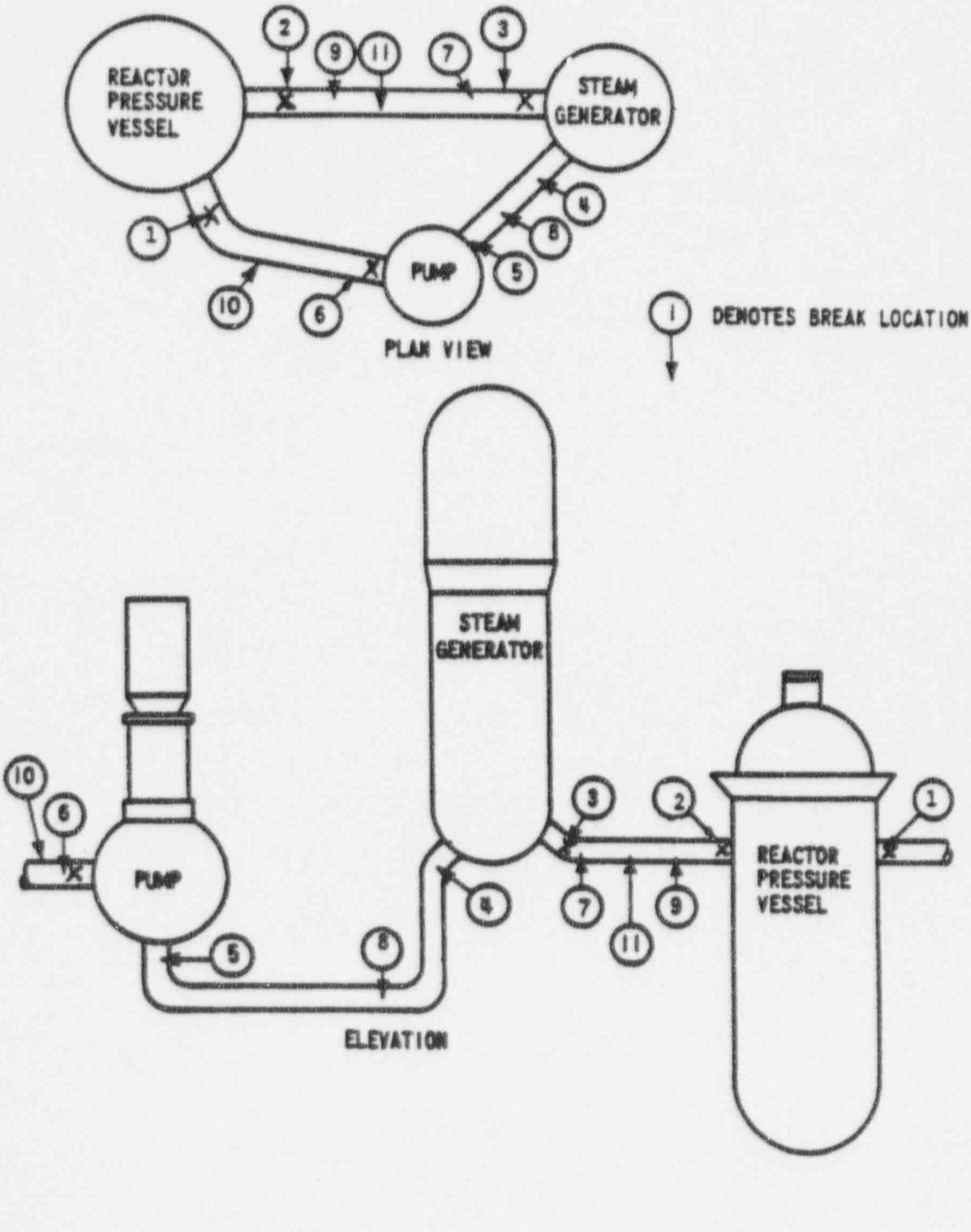

Figure 5-1 Locations of Postulated Breaks in Westinghouse Plants

a,c,e

Figure 5-2 RPV Inlet Nozzle Break - Time History Break Opening Area (Westinghouse 4-Loop Plant)

a,c,e

Figure 5-3 RPV Outlet Nozzle Break - Time History Break Opening Area (Westinghouse 4-Loop Plant)

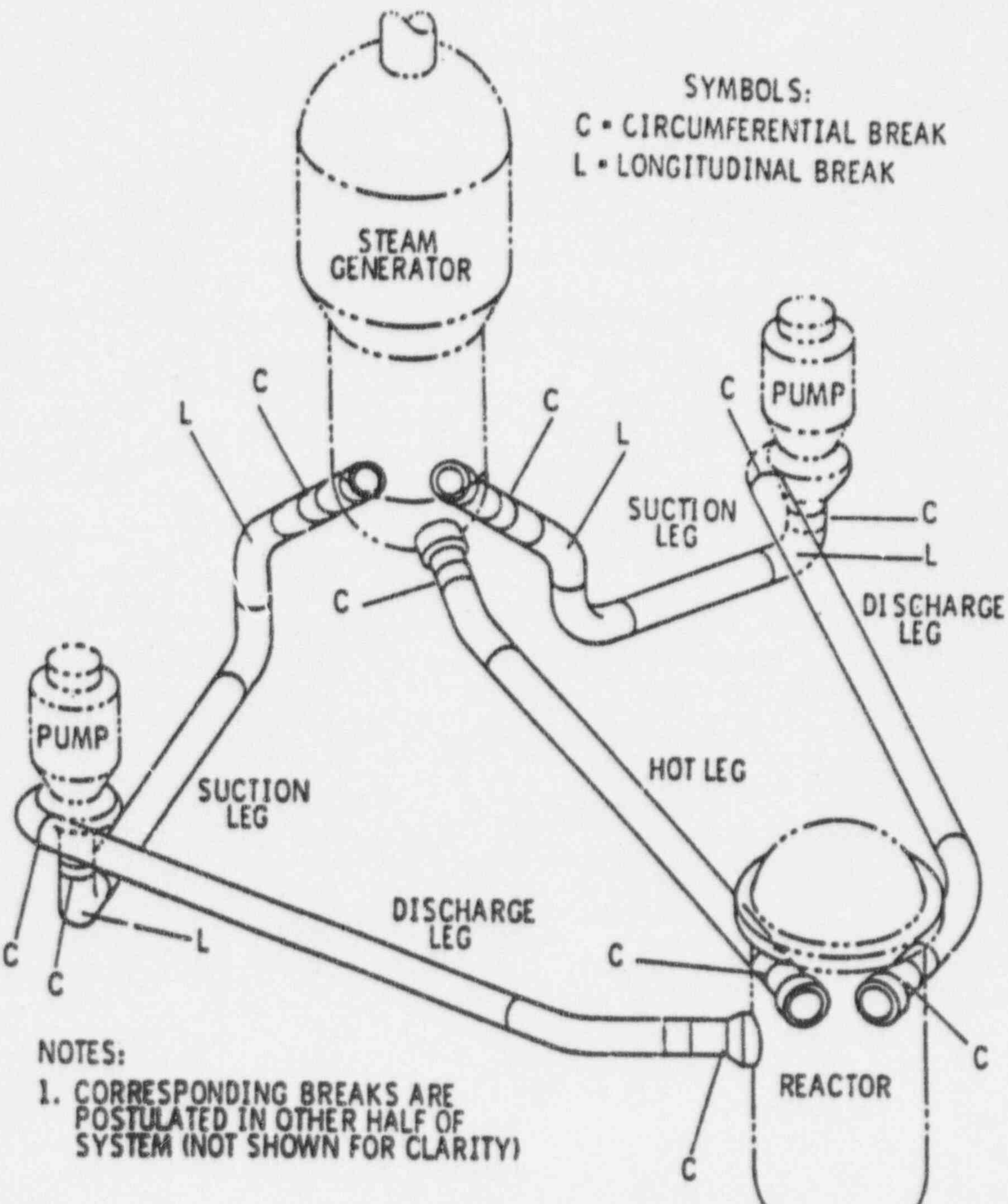

Figure 5-4 Locations of Postulated Breaks in Combustion Engineering Plants

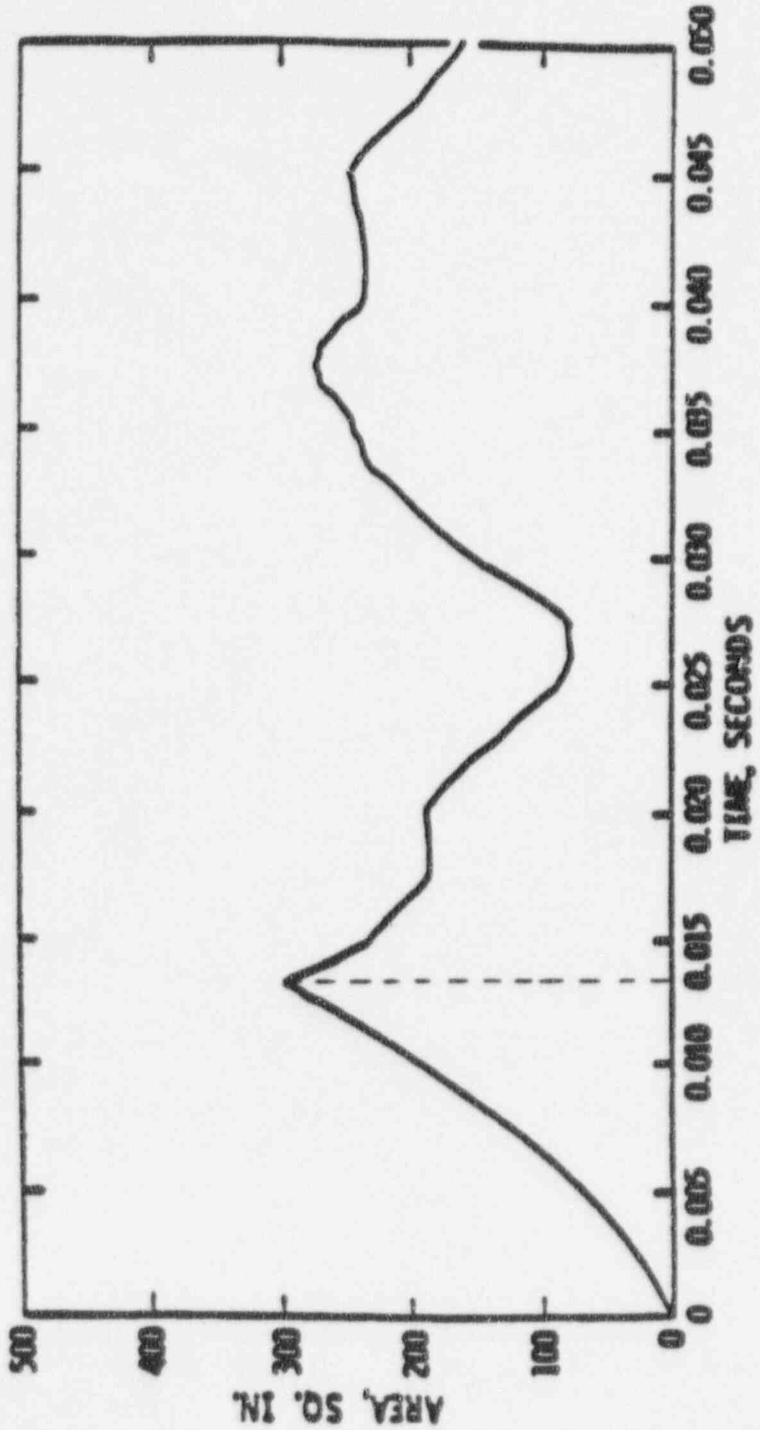

Figure 5-5 Combustion Engineering Calculations of a Circumferential Break Opening Area Versus Time at the Steam Generator Terminal End of the Hot Leg

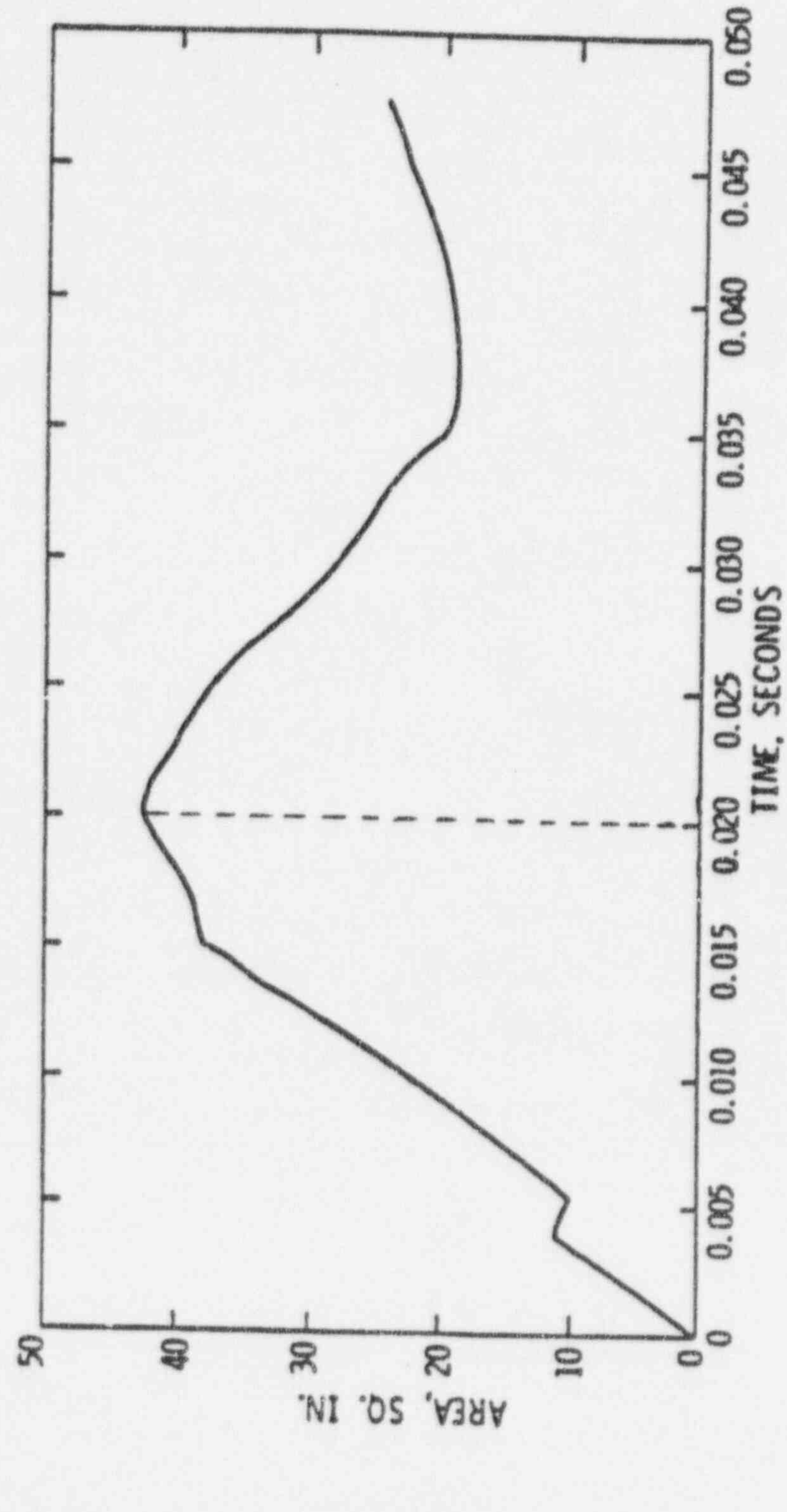

Figure 5-6 Combustion Engineering Calculations of Circumferential Break Opening Area Versus Time at the Hot Leg Terminal End at the Reactor

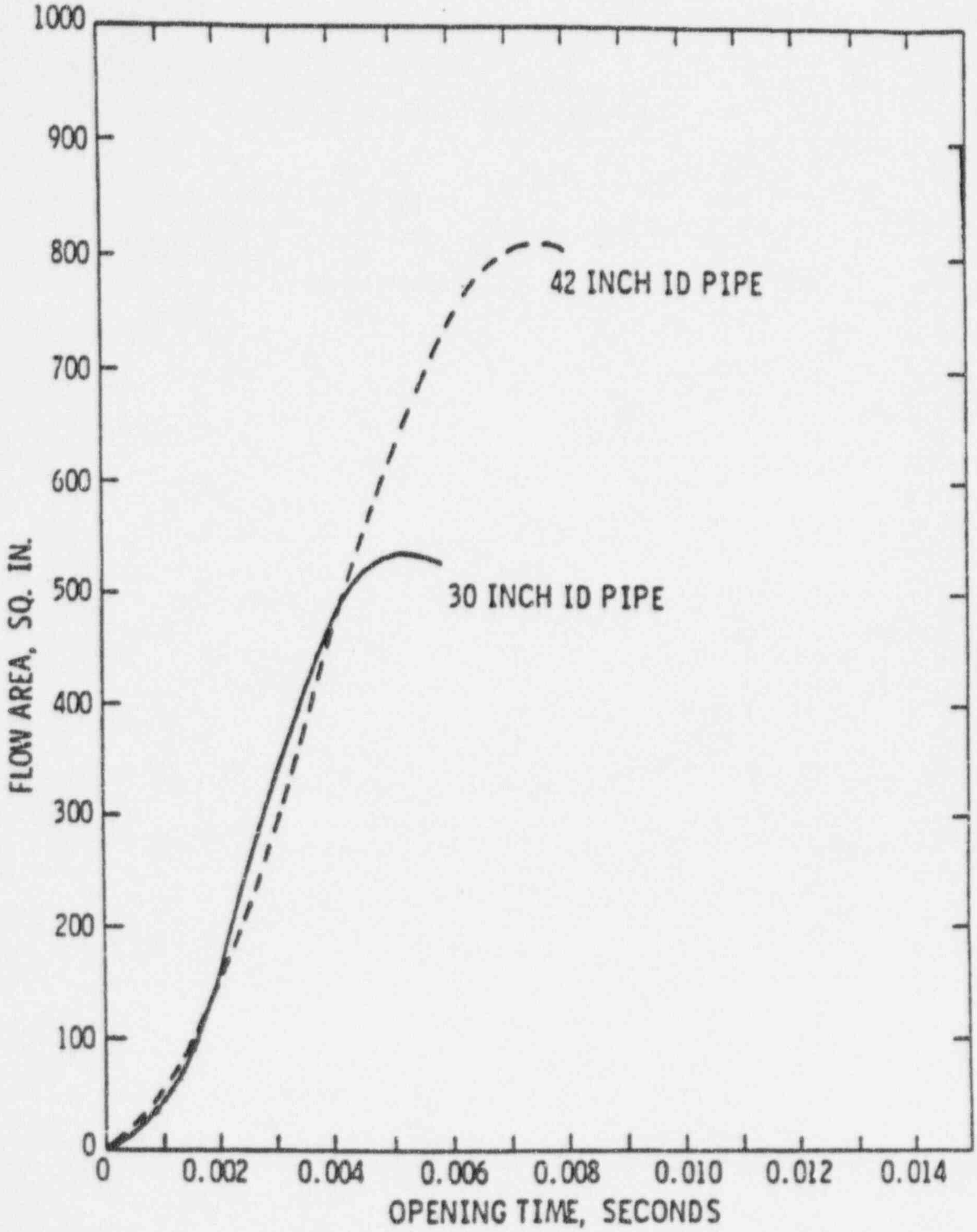

Figure 5-7 Combustion Engineering Calculations of Longitudinal Break Area Versus Time

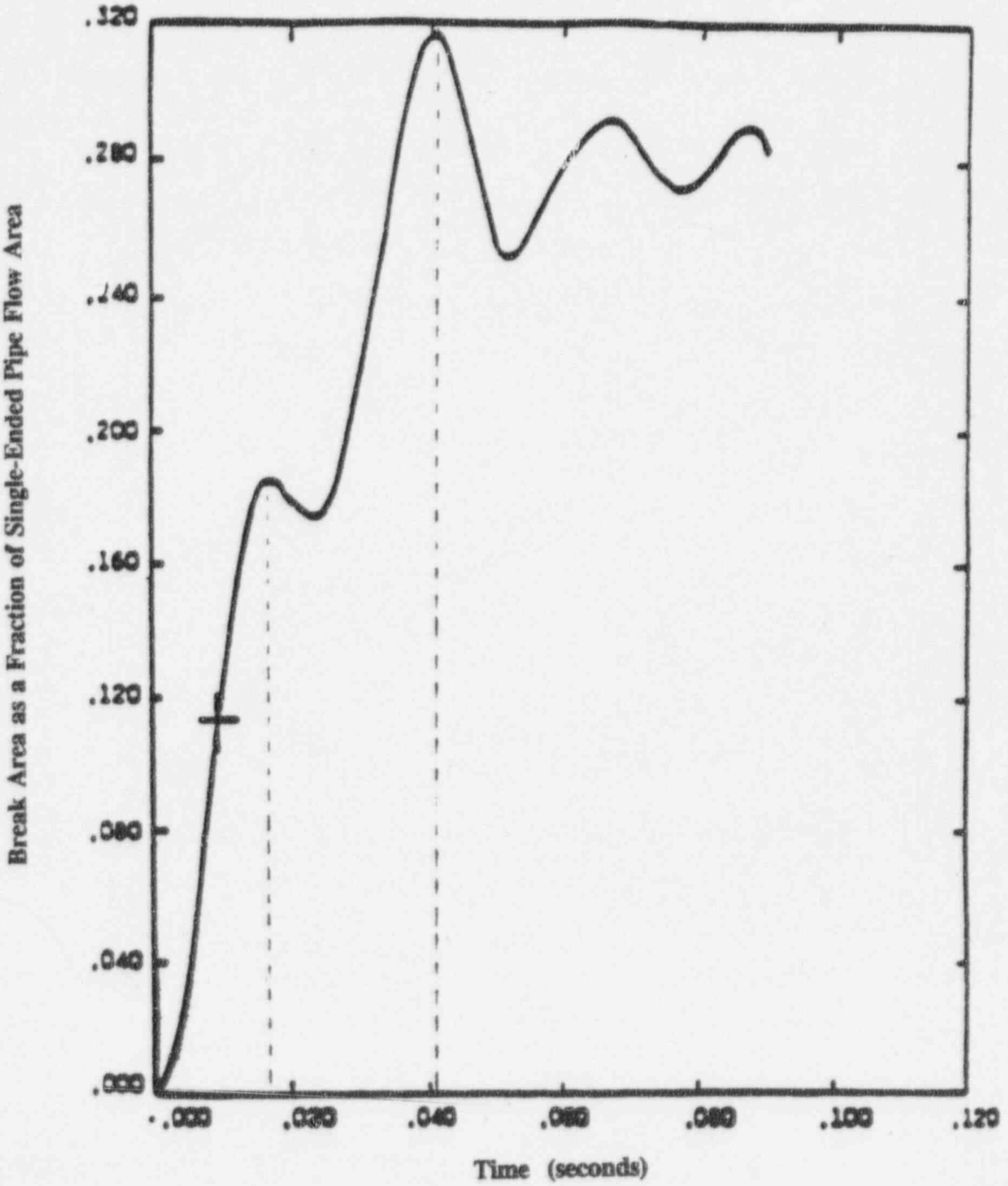

Figure 5-8 Babcock & Wilcox Calculations of Break Area Versus Time at the Reactor Vessel Outlet Nozzle

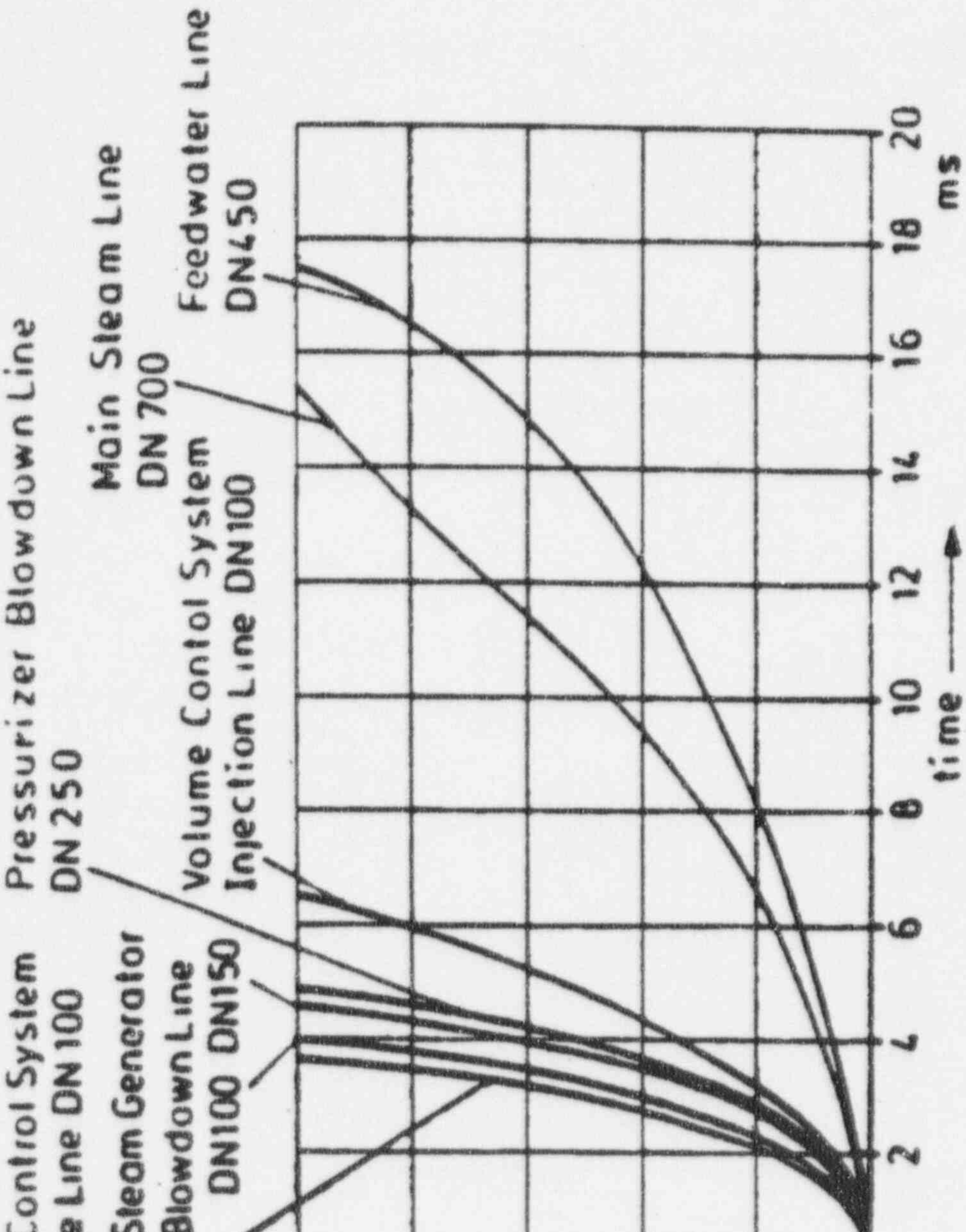

Figure 5-9 Circumferential Break Opening Predictions Presented in Reference 17 for Several PWR Systems

6 COMPARISONS WITH NRC LOCA LOAD CALCULATIONS

Reference 18 describes a study of the sensitivity of 3-loop reactor internals LOCA forcing functions (THF) to BOT. This work was performed in support of the NRC review of the MULTIFLEX computer program. Of interest for present purposes are the calculated effects of BOT on reactor internals loads, and the comparison between Westinghouse load calculations using MULTIFLEX and NRC calculations using the WHAM/MOD-007 program.

6.1 SENSITIVITY OF TOTAL HORIZONTAL VESSEL WALL FORCE (THF) TO BREAK-OPENING TIME

In addition to varying BOT, the Reference 18 study included variations in other parameters. These are identified below:

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]^{a,c,e}

Broadly speaking, the sensitivity study indicated decreased thrust loads (THF) as BOT was increased, but with THF reductions being larger for MULTIFLEX calculations in which core barrel flexibility was not included. The results are summarized in Table 6-1; the column entitled "% Reduction" refers to the percentage THF reduction relative to the 1.0 msec calculation for the same case. All THF values are normalized to the highest THF calculated, which happens to be Case C with a BOT of 1.0 msec.

While the "rigid" MULTIFLEX cases show a greater and more consistent benefit of larger BOT, the load reductions in the "flexible" cases are significant. For a BOT of [ ]^{a,c,e}, however, only Case E, i.e., the smallest break, gives a significant reduction. Whether this can be considered a trend is not clear. [

]^{a,c,e} It is less obvious why the ultimate break size makes a difference. It should be recognized, however, that the depressurization rate for a small break with a given BOT will be less than that of a larger break with the same BOT, and also that saturated conditions (and, therefore, void formation and collapse) will be reached much more rapidly for large breaks – sometimes before the break is fully open. One or both of these factors

may help to explain the larger load reduction benefits of increased BOT for the smallest [ ]^{a,c,e} break cases D and E in Table 6-1.

In substance, Table 6-1 clearly shows that increasing BOT ultimately leads to reductions in core barrel THF loads. What it also shows, however, is that including phenomena like core barrel motion in the calculations tends to make a broad interpretation of BOT-increase benefits more difficult. The possibility of resonant amplification, for instance, may conceivably yield the highest thrust loads for values of BOT which provide the best match with core barrel mode frequencies.

6.2 COMPARISON OF WESTINGHOUSE AND NRC CALCULATIONS

Predictions of THF by Westinghouse, using MULTIFLEX, were compared with calculations performed by the NRC using two WHAM/MOD-007 models: a) one model (WMOD) based on the Westinghouse 3-loop plant MULTIFLEX model, and b) another model (NMOD) developed independently by the NRC for the same plant. Both break size and BOT were parameters in this study, the results of which are illustrated in Figures 6-1 and 6-2.

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]^{a,c,e}

This demonstrated conservatism of MULTIFLEX predictions relative to other calculational methods indicates that comparisons of the type described by the NRC in Reference 13 are not necessary. Furthermore, there do not appear to be any experimental data which can be used to make such comparisons, i.e., which adequately characterize the effects of break opening time on LOCA-induced loads. It is therefore considered that the conservatism inherent in the MULTIFLEX calculational methodology which has been demonstrated in this section adequately satisfies the essential intent of the U.S.N.R.C. remarks in Reference 13.

a,c,e

a,c,e

Figure 6-1 Comparison of W and NRC Computed Rigid Barrel Results

a,c,e

Figure 6-2 Comparison of W and NRC Computed Results

7 ESTABLISHMENT OF A REALISTIC BREAK OPENING TIME DESIGN BASIS

Sections 1 to 5 have presented and reviewed the available information on LOCA break opening time which may be used to justify larger break-opening times in LOCA-load calculations. The arguments which, individually and/or in toto, support such increases are summarized below.

- Break-opening experiments indicate that [ ]^{a,c,e} is a realistic break opening time for longitudinal breaks and is conservatively low for circumferential breaks in piping similar to RCS piping (Section 4.0).

- Circumferential break opening time calculations by Westinghouse for a number of plants yield an average BOT of [ ]^{a,c,e}. The BOT-values from which this average is derived are based on the maximum break areas calculated from the piping transient analysis following rupture. Extrapolations to full single and double ended break areas lead to BOT values which are well in excess of [ ]^{a,c,e}. It is also noted that these estimates of BOT do not include the crack propagation time, which would also increase the overall BOT (Section 5.1).

- The two domestic NSSS suppliers, Combustion Engineering and Babcock & Wilcox, both perform piping dynamics calculations similar to those performed by Westinghouse. These calculations are used to support the use of BOT values of [ ]^{a,c,e} in LBLOCA calculations (Sections 5.2 and 5.3).

- The German RSK guidelines permit the use of a 15.0 msec BOT for LBLOCA calculations without requiring analytical or experimental proof. A 5.0 msec BOT is also allowed for piping diameters of 50-250 mm (Section 5.4).

- The Framatome design basis employs a 1.0 BOT for reactor internals loads and a 10-25 msec BOT for RCS piping loads. Larger break opening times than 1.0 msec are, however, permitted for reactor internals loads if they can be justified. A [ ]^{a,c,e} has, in fact, been used for determining LBLOCA loads on reactor internals (Section 5.5).

- Comparisons of Westinghouse calculations using MULTIFLEX, with NRC calculations using WHAM/MOD-007 - both for a 3-loop plant - indicate that MULTIFLEX calculations of LOCA horizontal thrust forces inside the reactor vessel are conservatively high, even when larger values of BOT are used in the Westinghouse calculations. It is therefore concluded that MULTIFLEX calculations with realistic break opening times will also yield conservatively high loads (Section 6.0).

The above provide ample justification for the use of a [ ]^{a,c,e} in LBLOCA calculations. There may, however, be instances in which: a) the use of even larger BOTs , may become desirable, and b) the use of BOTs in excess of 1.0 msec may be desirable for evaluating loads resulting from smaller RCS breaks, and from breaks in auxiliary lines. A proposed approach to such extensions is outlined below.

7.1 ESTABLISHING BREAK-OPENING TIME FOR GENERAL BREAKS

The information described in Sections 2 to 6 provides a good starting point for formulating a broader, more realistic, approach to BOT design basis assumptions. In this vein, it is also well to consider proposals which have been made by others, consistent with the requirements of Reference 16, for a BOT design basis which reflects the realities of break-opening dynamics. One of these is Schramm, who, in Reference 17, advocates a basis which depends on pipe diameter; this paper and the criteria presented therein are described in Section 5.4. Another general proposal is provided by Evans et al in Reference 19, Section 5.0 of which is reproduced in Appendix A. This proposal is based on much of the same experimental and analytical data described in Sections 2 to 6 of the present report.

The BOT design basis proposed below differentiates between longitudinal and circumferential breaks, since the break opening dynamics of the two cases are significantly different.

7.1.1 Longitudinal Breaks

The Reference 19 (Appendix A) recommendation to use the (Battelle) correlation model of Reference 9 for longitudinal breaks is also recommended here. This is based on test data on piping quite similar to RCS piping and, because of the large initial flaws created in the pipe wall, should yield conservatively high estimates of break area. The Battelle data on crack propagation also suggest that this correlation should also be adequate for carbon steel piping. The correlation model is shown in Figure 4-5 and repeated in Equation 1 below.

$$A = 4.43t\left[\sqrt{\frac{t^2 + 1.96}{1.213}} - 1.27\right] \quad (1)$$

where:

[A] = square inches

[t] = msecs

In Figure 4-5, the terms "single pipe area" and "double pipe area" refer to the pipe tested - 24-inch Schedule 100. For RCS cold leg (27.5 inch ID) and hot leg (31 inch ID) piping, "single" and "double" pipe areas will clearly not correspond to the values in Figure 4-5, but will be higher.

The treatment of longitudinal breaks in MULTIFLEX is described in Reference 20, which defines the largest possible longitudinal break as one in which "the open area is twice as large as the pipe flow area". [

]^{a,c,e} In the past, the steam generator intrados (item 7 in Figure 5-1) longitudinal break, using the MULTIFLEX "split" break model, has not been limiting. However, this conclusion may have to be revisited when break opening times in excess of 1.0 msec are employed.

Except for the initial flaw, the effects of crack propagation speed on BOT are contained in Equation (1). The test from which Equation (1) was derived had an initial flaw length of 11.6 inches which, at a crack propagation speed of 370 ft./sec., yields a crack propagation times of 2.61 msecs. This is a small contribution relative to an overall BOT of [ ]^{a,c,e} and is conservatively neglected in Equation (1).

7.1.2 Circumferential Breaks

Unlike longitudinal breaks, the dynamics of circumferential break opening have a significant dependence on the piping system dynamics. For Westinghouse plants, a [ ]^{a,c,e} is conservative for double-ended guillotine (DEG) RCS primary piping. For other PWR piping systems, however, experimental and analytical data are in short supply. The calculations of Schramm (Reference 17 and Figure 6-2) are probably the only data from the open literature which are available on the subject. These data, therefore, provide the best basis for establishing BOT for non-primary piping.

As discussed in Section 5.4, Schramm has determined from his studies that a quadratic dependence of break opening area with time is a good approximation for circumferential breaks.

$$\frac{A(t)}{2A_P} = \left(\frac{t}{t_B}\right)^2 \tag{2}$$

(See Section 5.4 for definitions of terms.)

[

]^{a,c,e}

7.1.3 Additional Break-Opening Time Margin

Sections 7.1.1 and 7.1.2 provide a methodology - based on the experimental and analytical data available in the literature - for estimating BOT without a demonstration of inherent conservatism. This methodology provides conservative estimates of break opening time for longitudinal and circumferential breaks. It may become desirable, in some applications, to increase margin even further by using larger break opening times than those prescribed above. References 13 and 16 describe two methods for justifying increases in BOT which are NRC-approved:

1. Reference 13 indicates that the NRC will consider "longer (than 1.0 msec) break opening times if the proposed BOT with the current equivalent pipe network adequately predicts the results of applicable experimental data".

2. Reference 16 (NUREG-0800) allows a longer rise time if "a combined propagation time and break-opening time greater than 1 msec can be substantiated by experimental data or analytical theory based on dynamic structural response".

It is proposed that either of these two approaches may be used to justify break-opening times larger than those presented in Sections 7.1.1 and 7.1.2.

8 CONCLUSIONS AND RECOMMENDATIONS

The following summarize the salient conclusions and recommendations of the present study:

1. A design basis of [ ]^{a,c,e} break-opening time for Westinghouse primary coolant piping in LBLOCA applications is thoroughly justified by the results of analyses and tests performed by Westinghouse, other NSSS vendors, and independent technical organizations. Sections 2 to 6 discuss the technical sources which support this conclusion for both longitudinal and circumferential breaks.

2. For general circumferential breaks, a methodology for conservatively estimating break-opening time is presented in Section 7, which is similar to the German RSK guidelines (Reference 17).

3. Larger break-opening times than those derived from (1) or (2) above can be justified by: 1) demonstrating by analysis or test that subsequent LOCA load predictions will be conservative, or 2) demonstrating by analysis or test that the selected break-opening time is justified. These criteria are based on U.S.N.R.C. stipulations in References 13 and 16.

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APPENDIX A

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5.0 POSTULATED BREAK OPENING TIME

5.1 Introduction

5.1.1 Background

In evaluating nuclear power plants for possible interactions resulting from postulated pipe ruptures, it becomes necessary to determine the blowdown force caused by the fluid escaping from the ruptured pipe. Basic to the determination for a blowdown force time history is a realistic estimate of the time required for crack propagation into a full break opening of the type to be postulated.

It has long been a concern that in the absence of costly and time consuming analyses or experimental evaluation, an unrealistic value of one millisecond must be used to satisfy the regulatory requirements.

5.1.2 Discussion

For the purpose of analysis, it is required that all pipe breaks be assumed to open to their defined sizes in one (1) millisecond after break initiation, regardless of the pipe failure type and size. The requirement for the assumption can be found in either the NRC Standard Review Plan (Reference 5.6.1), ANS (N176) (Reference 5.6.2), or many other nuclear industry pipe rupture design criteria. This approach, however, is extremely conservative compared with available analytical and experimental data (References 5.6.3, 5.6.4, and 5.6.5). It is noted that a longer break opening time associated with a pipe break could change the initial condition of the time history thermal-hydraulic blowdown.

In the blowdown analysis, the effect of the break opening time on the pressure transient is a relatively insensitive parameter after the system blows down to the corresponding saturation pressure. However, a long break opening time will affect the initial condition of the blowdown thrust load which is formed by the product of the transient pressure P(t) and the transient flow area A(t), plus a momentum thrust term $F_m(t)$ where both A(t) and $F_m(t)$ are functions of the break opening time.

A longer and more realistic time duration for propagation to a full break will reduce the design impact loading considerably in pipe rupture restraint design, especially for designs which allow only a small gap between the pipe and the pipe rupture restraint.

5.2 Current Approach

The general attitude of the industry concerning this problem is that unwarranted conservatism results from the one millisecond requirement. Isolated efforts to gain much needed relief have occurred for very limited cases for certain primary coolant piping however, no blanket amnesty has resulted. Consequently, virtually all blowdown force time histories are computed using one millisecond as the time required from the instantaneous crack formation until the full opening occurs, regardless of the type of break considered.

Test data and state-of-the-design analyses both show great variations in break opening times but the one millisecond opening time appears to be extremely unrealistic. Experience in analyzing and designing mitigative devices for this requirement have resulted in massive hardware which occupies volume needed for pressure suppression, blocks flow paths needed for venting, interferes with maintainability of equipment, and may even act to increase the probability of the event for which the mitigative devices are designed. Yet, with all of these negative aspects, when given the costs and probable plant delays in performing the customized analyses to justify longer break opening times, the industry (including TVA) has reluctantly accepted the one millisecond opening time and all of the accrued inherent penalties.

5.3 Impact of Current Approach

Within the scope of this effort, it is not possible to quantitatively assess the total cost to industry for the one millisecond opening time for postulated pipe ruptures. If it could be done, it is believed that it would be a staggering amount. This is especially significant when considered in conjunction with the anticipated low probability of the occurrence of a crack break. Then, the additional probability of propagation into a full rupture in such an unrealistically short opening time, coupled with all the other assumptions cascades the conservatisms tremendously. The short opening time, is simply an extremely conservative and expensive requirement.

5.4 Recommendations

It is recommended that a program of analyses, supported by tests, be undertaken to better define realistic times for the propagation of cracks into large breaks for representative pipe materials and conditions.

Two possibilities are foreseen. In the order of preference they are:

A. Estimate a single enveloping break opening time and rate to be used for all conditions and pipe sizes. This would greatly simplify the overall problem but may result in a level of conservatism comparable to that of the present method.

B. Develop a parameterized break opening time which takes into account the participating factors (at this point undefined) affecting the opening time.

The following discussion is offered as a current typical general approach to an analytical solution for a given set of parameters.

The break opening area time history resulting from the pipe failure has in general been determined using finite element dynamic analyses methods based upon the following assumptions:

A. An initial crack of total final length is assumed to occur instantaneously.

B. The final, fully developed length of a circumferential rupture is defined to be completely around the circumference, a longitudinal split is assumed to be twice the length of the inside diameter of the pipe.

C. Using the displacements of the ends of the broken pipe computed by the dynamic analyses, the circumferential rupture flow areas are calculated for combined axial and radial motions. For longitudinal splits, the circumferential deflection at the center of the crack is computed and defined to be the minor axis of an ellipse to compute the resultant break opening area.

   Initially, the various time-history hydraulic loads acting on the system are computed by assuming a break opening area and break opening time. When these loads are applied, an area time history can be determined for use in new force calculations, replacing the original assumed flow area and assumed opening time. This process is repeated until the resultant area converges to a stable value.

Instead of using a nonlinear mathematical model, an arbitrary linear ramp opening time of ten (10) milliseconds is also recommended for pipe break areas equivalent to one pipe cross-sectional flow area (reference 5.6.6). This assumption is based on the empirical data on break opening times obtained by BMI (reference 5.6.5), and results of dynamic analyses of pipe separation times for circumferential ruptures (reference 5.6.3).

For longitudinal splits, an acceptable design model of a break opening time-area relationship is defined as follows (reference 5.6.2):

$$A_b = 4.43t\left[\sqrt{\frac{t^2 + 1.96}{1.213}} - 1.27\right]$$

Where: A_b = break opening area, in^2 or the largest piping cross-sectional flow area at the point of the break, and t = time from break opening initiation, milliseconds.

5.5 Anticipated Benefits

Benefits which may occur by implementation of the recommendations are:

A. Elimination of individual efforts by individual utilities attempting to gain waivers or acceptance of alternative approaches to break opening times.

B. Elimination of, or a great reduction in, the number of individual dynamic fracture mechanics analyses performed by utilities or NSSS suppliers.

C. Longer time for realistic break opening will result in lower loads and fewer design problems, less restraint material tonnage, fabrication, and installation.

D. Less lead time for fabrication and installation of restraints.

E. Less in-service inspection interference.

F. Relief in critically of compartment pressurization from less flow blockage of venting paths.

G. Reduction in normal maintenance time for equipment which is sometimes blocked by the restraints.

5.6 References

5.6.1 NRC Standard Review Plan, Section 3.6.2, Determination of Break and Dynamic Effects Associated with the Postulated Rupture of Piping, November 24, 1975.

5.6.2 "Design Basis for Protection of Nuclear Power Plants Against Effects of Postulated Pipe Rupture," ANS-58.2 (N176), American Nuclear Society, January 1978.

5.6.3 "LOCA Pipe Break Criteria for the Design of Babcock & Wilcox Nuclear Steam System" TR BAW-10127, Babcock & Wilcox, December 1976.

5.6.4 "Design Basis Pipe Breaks, Design Base Pipe Breaks for the Combustion Engineering Two-Loop Reactor Coolant System," Evaluation of CENPD-168 A, Revision 1, CE Power Systems, Combustion Engineering, Inc., June 1977.

5.6.5 Eiber, R. J. et al., "Investigation of the Initiation and Extent of Ductile Pipe Rupture." BMI-186, Battelle Memorial Institute, July 1969.

5.6.6 "Reactor Coolant System Hydrodynamic Loadings During a LOCA," TR BAW-10132, Babcock & Wilcox, November 1977.