SUPPLEMENTAL SMALL BREAK ANALYSIS

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1. Introduction

Babcock & Wilcox has evaluated the effect of a delayed reactor coolant (RC) pump trip during the course of a small loss-of-coolant accident. The results of this evaluation are contained in Section II of the report entitled "Analysis Summary in Support of an Early RC Pump Trip."[1] (Letter R.B. Davis to B&W 177 Owner's Group, "Responses to IE Bulletin 59-05C Action Items," dated August 21, 1979.) The above letter demonstrated the following:

a. A delayed RC pump trip at the time that the reactor coolant system is at high void fractions will result in unacceptable consequences when Appendix K evaluation techniques are used. Therefore, the RC pumps must be tripped before the RC system evolves to high void fractions.

b. A prompt reactor coolant pump trip upon receipt of the low pressure ESFAS signal provides acceptable LOCA consequences.

The following sections in this report are provided to supplement the information contained in reference 1. Specifically discussed in this report are:

a. The analyses to determine the time available for the operator to trip the reactor coolant pumps such that, under Appendix K assumptions, the criteria of 10 CFR 50.46 would not be violated.

b. The RC pump trip times for a spectrum of breaks for which the peak cladding temperature, evaluated with Appendix K assumptions, will exceed 10 CFR 50.46 limits.

c. A realistic analysis of a typical worst case to demonstrate that the consequences of a RC pump trip at any time will not exceed the 10 CFR 50.46 limits.

2. Time Available for RC Pump Trip Under Appendix K Assumptions

A spectrum of breaks was analyzed to determine the time available for RC pump trip under Appendix K assumptions. The breaks analyzed ranged from 0.025 to 0.3 ft^2. As was demonstrated in reference 1, the system evolves to high void fractions early in time for the larger sized breaks. Values in excess of 90% void fraction were predicted as early as 300 seconds for the 0.2 ft^2 break. For the smaller breaks it takes much longer (hours) before the system evolves to high void fraction. Therefore, the time available to trip the RC pump is minimum for the larger breaks. However, as will be shown later, for the larger small breaks (>0.3 ft^2), a very rapid depressurization is achieved upon the trip of RC pumps at high system void fraction. This results in early CFT and LPI actuation, and a subsequent rapid core refill. Thus, only a small core uncovery time will ensue. The following paragraphs will discuss the available time to trip the RC pumps for different break sizes. In performing this evaluation, only one HPI system was assumed available rather than the two HPI systems assumed in the reference 1 analyses.

a. 0.3 ft^2 Break - Figures 1 and 2 show the system void fraction and available liquid volume in the vessel versus time for RC pump trips at 95, 83, and 63% void fractions for a 0.3 ft^2 break at the RC pump discharge. For the pump trip at 95% void the system void fraction slowly decreases and then it drops faster following the CFT and LPI actuations. Following the RCP trip, the pressure drops rapidly and CFT is actuated at 250 seconds. The core begins to refill at this time and, with LPI actuation at 300 seconds, the core is flooded faster and is filled to a liquid level of 9 feet (equivalent to approximately 12 feet swelled mixture) at 370 seconds. The total core uncovery time is 170 seconds. Assuming an adiabatic heatup of 6.5°F/sec, as explained in reference 1, the consequences of a RC pump trip at 95% void will not exceed the 2200°F limit.

   As seen in Figure 2 for the RC pump trip at 63% or lower void fractions, the available liquid in the core will keep the core covered above the 11 feet elevation for about 350 seconds, and above 12 feet elevation at all other times. Therefore, tripping the RC pumps at void fractions ≤ 63% will not result in unacceptable consequences as the core will never uncover.

   A RC pump trip at 83% void fraction demonstrates an uncovery time of 350 seconds. However, previous detailed small break analysis (reference 2) have shown that a 10 ft of mixture height in the core will provide sufficient core cooling to assure that the criteria of 10 CFR 50.46 is satisfied. For this case, the 10 feet of mixture height is provided by approximately 1600 ft^3 liquid in the vessel. At this level in Figure 2, the core uncovery time is 220 seconds. Again, even with the assumption of adiabatic heatup over this period, the consequences are acceptable. It should be pointed out that if credit is taken for steam cooling of the upper portion of the fuel pin, the resulting PCT will be significantly lower then that obtained from the adiabatic heatup assumption.

   From Figure 2, it can be concluded that a RC pump trip at 120 seconds will result in little core uncovery. For RC pumps trip at system void fractions

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higher than 95% (at 200 seconds), the system will be at a lower pressure and with the CFT and LPI actuation there will be little or no core uncovery. Although core uncoveries are predicted for trips at 83% and 95% system void fractions, as shown earlier, the consequences are acceptable. Thus, a delayed RC pump trip at anytime for this break will provide acceptable consequences even if Appendix K evaluation techniques are used.

For breaks larger than 0.3 ft^2, a delayed RC pump trip at any time during the transient is also acceptable as the faster depressurization for these breaks will result in smaller delays between the pump trip and CFT and LPI actuation. Therefore, core uncovery times will be smaller than that shown for the 0.3 ft^2 break.

b. 0.2 ft^2 Break - Figures 3 through 5 show the system void fraction and available liquid volume in the vessel versus time for RC pump trips at 98, 73, 60 and 45% void fraction for a 0.2 ft^2 break at the RC pump discharge. As seen in Figure 5, the RC pump trip at 45 and 60% void fraction does not result in core uncovery. The available liquid volume is sufficient to keep the core covered above the 10 ft elevation at all times. For the trip at 98% void fraction in Figure 4, the core is refilled very rapidly with the actuation of CFT and LPI at approximately 420 and 450 seconds, respectively. The core is refilled to an elevation of 9 feet at 460 seconds. The core uncovery time is in the order of 60 seconds, and the consequences are not significant. The RC pump trip at 73% void fraction as seen in Figure 4, results in a 450 seconds core uncovery time. Although a 450 seconds uncovery time seems to result in unacceptable consequences, if credit is taken for steam cooling and using the same rationale as that given for the RC pump trip at 83% system void in section 1.a, it is believed that the consequences will not be significant. Should the RC pumps be tripped at system voids less than 70%, there will be little or no core uncovery. However, for void fractions between 73% and 98%, there is a potential for a core uncovery depth and time which might be unacceptable. Thus, a time region can be defined in which a RC pump trip, evaluated under Appendix K assumptions, could result in peak cladding temperatures exceeding the 10 CFR 50.46 criteria. This window is narrow and extends from 180 seconds (73% void) to 400 seconds (98% void) after ESFAS. A RC pump trip at any other time will not result in unacceptable consequences.

c. 0.1 ft^2 Break - Figures 6 and 7 shows system void fractions and available liquid volume for trips at 90, 60, and 40% system void fractions for a 0.1 ft^2 break at the RC pump discharge. The same discussions as those presented in sections 2.a and 2.b can be applied here. However, due to slower depressurization of the system for this break, complete core cooling is not provided until the actuation of LPI's. As seen in Figure 7, the time to trip the RC pumps without any core uncovery is approximately 250 seconds. In Figure 6, with the RC pumps operating the LPI's are actuated at approximately 2350 seconds. Tripping the RC pumps at any time before 2350 seconds will actuate the LPIs earlier in time. Therefore, unacceptable consequences are predicted for a delayed RC pump trip in a time range of 250 seconds to 2350 seconds. For any other time, all the consequences are acceptable.

d. 0.075, 0.05 and 0.025 ft^2 Breaks - Figures 8 and 9 show a comparison of system void fractions for pumps running and pumps tripped[3] conditions. As seen in Figure 8, with the RC pumps tripped coincident with the reactor trip, in the short term, the evolved system void fraction is greater than that with the RC pumps operative. The two curves cross at about 300 seconds. Before this time, a RC pump trip will not result in unacceptable consequences since the system is at a lower void fraction than RC pumps trip case. Therefore, the time available for RC pumps trip with acceptable results is estimated at 300 seconds. As the system depressurizes and LPI's are actuated, the core will be flooded, and a RC pump trip after this time will have acceptable consequences. From the analyses performed, the LPI actuation time is estimated at approximately 3000 seconds. Therefore, the region between 300 and 3000 seconds defines the time region in which a RC pump trip could result in unacceptable consequences.

For a 0.05 ft^2 break, the same argument can be made using Figure 9. As seen from this figure, the time available to trip the RC pumps is approximately 450 seconds. The LPI actuation time for this break size is estimated at approximately 4350 seconds. Therefore, the unacceptable times for RC pump trip is defined between 450 and 4350 seconds.

As discussed in reference 1, the system evolves to high void fractions very slowly for 0.025 ft^2 or smaller breaks. The system depressurization is very slow and it takes on the order of hours before the LPI's are actuated. A RC pump trip at 2400 seconds for the 0.025 ft^2 break results in a system void fraction below 50% and the core remains completely covered. A study of the 0.025 ft^2 break with 2 HPI's available shows with the RC pumps operative the system void fraction never exceeds 61%. The CFT is actuated at approximately 4800 seconds and the system void starts to decrease and available liquid volume in the RV starts to increase. Thus, the core will remain completely covered for any RC pump trip time and, thus, will result in acceptable consequences. With one HPI available, a slower depressurization is expected but the system evolution to high void fraction will still be very slow. Thus, the conclusion that a RC pump trip at any time yields acceptable consequences for the 0.025 ft^2 break holds whether one or two HPI's are assumed available.

The LPI actuation time for the 0.025 ft^2 break can be extrapolated using the available data of the other breaks. Figure 10 shows the extrapolated LPI actuation time at approximately 8000 seconds. Thus, a conservative unacceptable time region for pump trip can be defined between 2500 and 8000 seconds for the 0.025 ft^2 break under Appendix K assumptions.

3. Critical Time Window for RC Pumps Trip

As discussed in section 2, there is a time region for each break size in which the consequences of the RC pump trip could exceed the 10 CFR 50.46 LOCA limit. These critical time windows were defined in section 2. Figure 11 shows a plot of the break size versus trip time RC pump which results in unacceptable consequences. The region indicated by dashed lines represent a boundary in which unacceptable consequences may occur if the RC pumps are tripped. However, this region is defined using Appendix K assumptions. It should be recognized that this region, even under Appendix K assumptions, is smaller than what is shown in Figure 11 as the 0.2 and 0.025 ft^2 breaks may not even have an unacceptable region. The time available to trip the RC pumps can be obtained from the lower bound of this region and is on the order of two to three minutes after ESFAS.

4. "Realistic" Evaluation of Impact of Delayed RC Pump Trip for a Small LOCA

a. Introduction

As discussed in the previous sections, there exists a combination of break sizes and RC pump trip times which will result in peak cladding temperatures in excess of 2200F if the conservative requirements of Appendix K are utilized in the analysis. The analysis discussed in this section was performed utilizing "realistic" assumptions and demonstrates that a RC pump trip at any time will not result in peak cladding temperatures in excess of the 10 CFR 50.46 criteria.

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b. Method of Analysis

There are three overriding conservatisms in an Appendix K small break evaluation which maximizes cladding temperatures. These are:

(1) Decay heat must be based on 1.2 times the 1971 ANS decay heat curve for infinite operation.

(2) Only one HPI pump and one LPI pump are assumed operable (single failure criterion).

(3) The axial peaking distribution is skewed towards the core outlet. The local heating rate for this power shape is assumed to be at the LOCA limit value.

In performing a realistic evaluation of the effect of a delayed RC pump trip following a small LOCA, the conservative assumptions described above were modified. The evaluation described in this section utilized a decay heat based on 1.0 times the 1971 ANS standard and also assumed that both HPI and LPI systems were available. The axial peaking distribution was chosen to be representative of normal steady-state power operation.

Figures 12 and 13 show the axial peaking distributions utilized in this evaluation. These axial distributions were obtained from a review of available core follow data and the results of manuvering analyses which have been performed for the operating plants. A radial peaking factor of 1.651, which is the maximum calculated radial (without uncertainty) pin peak during normal operation, was utilized with these axial shapes. As such, the combination of radial and worst axial peaking are expected to provide the maximum expected kw/ft values for the top half of the core for at least 90% of the core life. Since the worst case effect of a delayed RC pump trip is to result in total core uncovery with a subsequent bottom reflooding, maximum pin peaking towards the upper half of the core will produce the highest peak cladding temperatures. Thus, this evaluation is expected to bound all axial peaks encountered during steady-state power operation for at least 90% of core life.

The actual case evaluated in this section is a 0.05 ft^2 break in the pump discharge piping with the RC pump trip at the time the RC system average void fraction reaches 90%. As discussed in reference 1, RC pump trips at 90% system void fraction are expected to result in approximately the highest peak cladding temperatures. The CRAFT2 results for this case and the evaluation techniques utilized are discussed in section II.B.5 of reference 1. A realistic peak

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cladding temperature evaluation of this case, which is discussed below, is expected to yield roughly the highest peak cladding temperature for any break size and RC pump trip time. As shown in reference 1, maximum core uncovery times of approximately 600 seconds occur over the break size range of 0.05 ft^2 through 0.1 ft^2 using 1.2 times the ANS curve. Break sizes smaller than 0.05 ft^2 and larger than 0.1 ft^2 will yield smaller core uncovery times as demonstrated in reference 1 and the preceeding sections. Use of 1.0 times the ANS decay heat curve would result in a similar reduction in core uncovery time, approximately 200 seconds, for breaks in the 0.05 through 0.1 ft^2 range. Thus, the core refill rate, uncovery time, and peak cladding temperatures for the 0.05 ft^2 case is typical of the worst case values for the break spectrum.

c. Results of Analysis

Figure 4 shows the liquid volume in the reactor vessel for the 0.05 ft^2 break with a RC pump trip at the time the system average void fraction reaches 90%. The core initially uncovers and recovers approximately 375 seconds later. Using the previously discussed realistic assumptions the peak cladding temperature for this case is below 1900F. Therefore, the criteria of 10 CFR 50.46 is met.

The temperature response given above was developed in a conservative manner by comparing adiabatic heat up rates to maximum possible steady-state cladding temperatures. First, a temperature plot versus time is made up for each location on the hottest fuel assembly assuming that the assembly heats up adiabatically. Second, a series of FOAM[4] runs are made to produce the maximum steady-state pin temperatures at each location as a function of core liquid volume. FOAM calculates the mixture level in the core and the steaming rate from the portion of the core which is covered. Both the mixture height and steaming rate calculations are based on average core power. Fluid temperatures in the uncovered portion of the fuel rod are obtained by using the calculated average core steaming rate and by assuming all energy generated in the uncovered portion of the hot rod is transferred to the fluid. The surface heat transfer coefficient is calculated, based on the Dittus-Boelter correlation[5], from the fluid temperature and steaming rate and the steady-state clad temperature is obtained. The FOAM data are then combined with the core liquid inventory history (derived from Figure 14) to produce a maximum possible cladding temperature as a function of time. This graph might be termed maximum steady-state cladding temperature as a function of time and decreases in value with time because the core liquid

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inventory is increasing. By cross plotting the adiabatic heat up curve with the maximum steady-state curve a conservative peak cladding temperature prediction is obtained.

5. Conclusions

From this analysis, and the results in reference 1, the following conclusions have been drawn:

a. Using Appendix K evaluation techniques, there exists a combination of break size and RC pump trip times which result in a violation of 10 CFR 50.46 limits.

b. Prompt tripping of the RC pumps upon receipt of a low pressure ESFAS signal will result in cladding temperatures which meet the criteria of 10 CFR 50.4y. The minimum time available for the operator to perform this function is 2 to 3 minutes.

c. Under realistic assumptions, a delayed RC pump trip following a small break will result in cladding temperatures in compliance with 10 CFR 50.46.

REFERENCES

1 "Analysis Summary in Support of an Early RC Pump Trip," Section II of letter R.B. Davis to B&W 177 Owner's Group, Responses to IE Bulletin 79-05C Action Items, dated August 21, 1979.

2 Letter J.H. Taylor (B&W) to Robert L. Baer, dated April 25, 1978.

3 Letter J.H. Taylor to S.A. Varga, dated July 18, 1978.

4 B.M. Dunn, C.D. Morgan, and L.R. Cartin, Multinode Analysis of Core Flooding Line Break for B&W's 2568 MWt Internals Vent Valve Plants, BAW-10064, Babcock & Wilcox, April 1978.

5 R.H. Stoudt and K.C. Heck, THETA1-B - Computer Code for Nuclear Reactor Core Thermal Analysis - B&W Revisions to IN-1445, (Idaho Nuclear, C.J. Hocevar and T.W. Wineinger), BAW-10094, Rev. 1, Babcock & Wilcox, April 1975.

Figure 1 : 0.30 FT^2 BREAK @ P.D., SYSTEM VOID FRACTION VS TIME

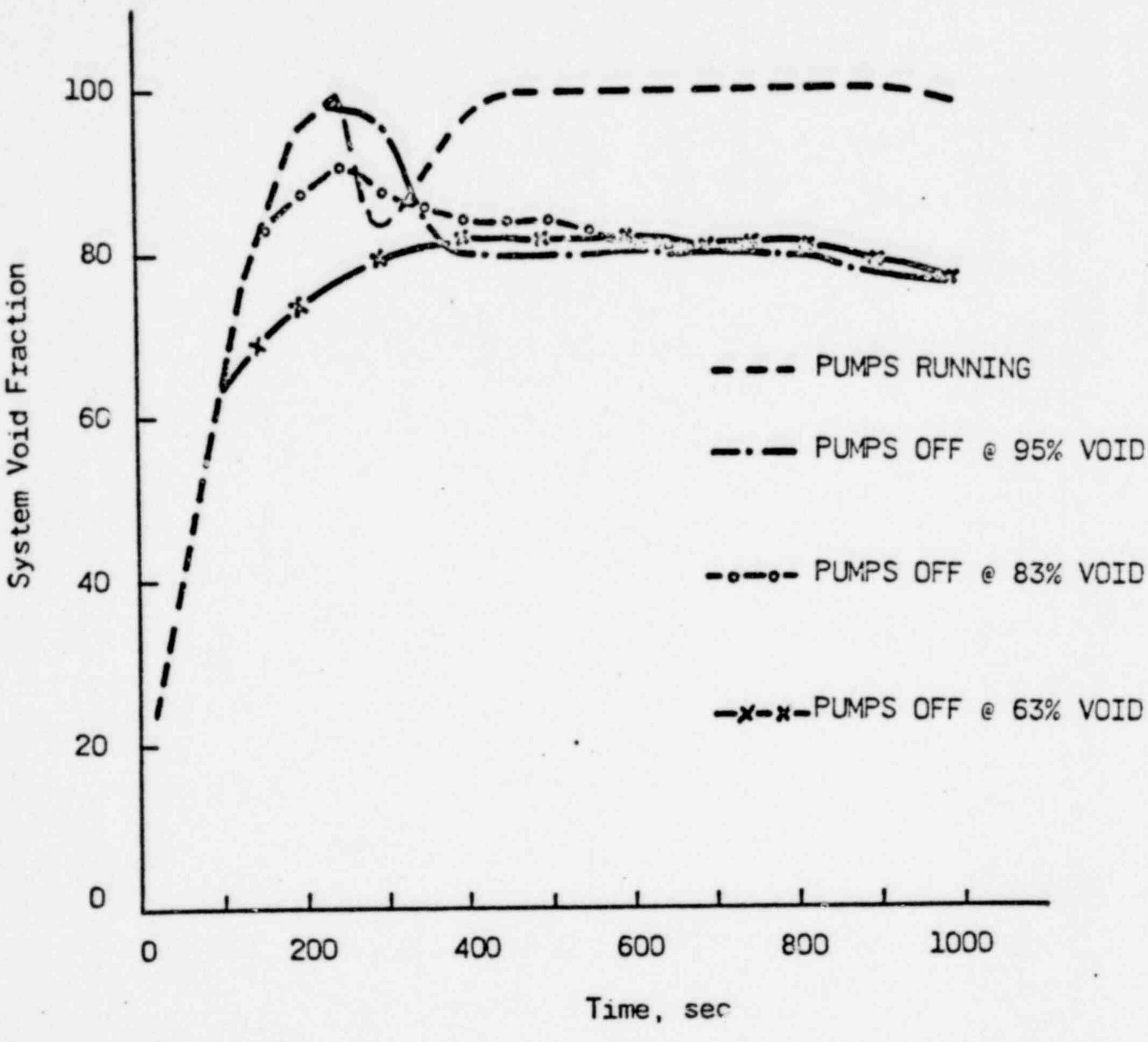

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Figure 2: 0.30 FT² BREAK @ P.D., AVAILABLE LIQUID VOLUME IN RV VS TIME, 1 HPI AVAILABLE

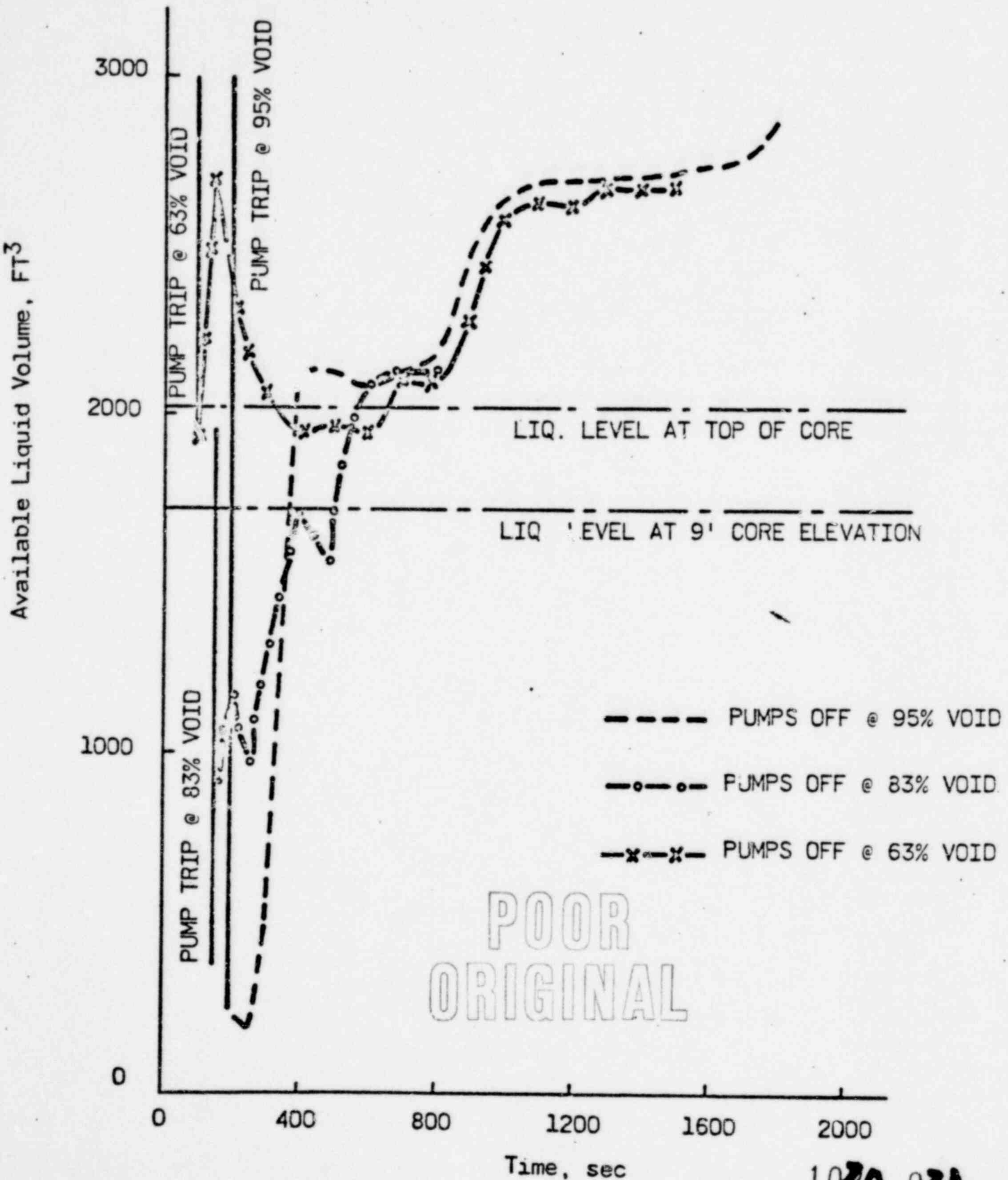

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Figure 3: 0.20 FT^2 BREAK @ P.D., SYSTEM VOID FRACTION VS TIME

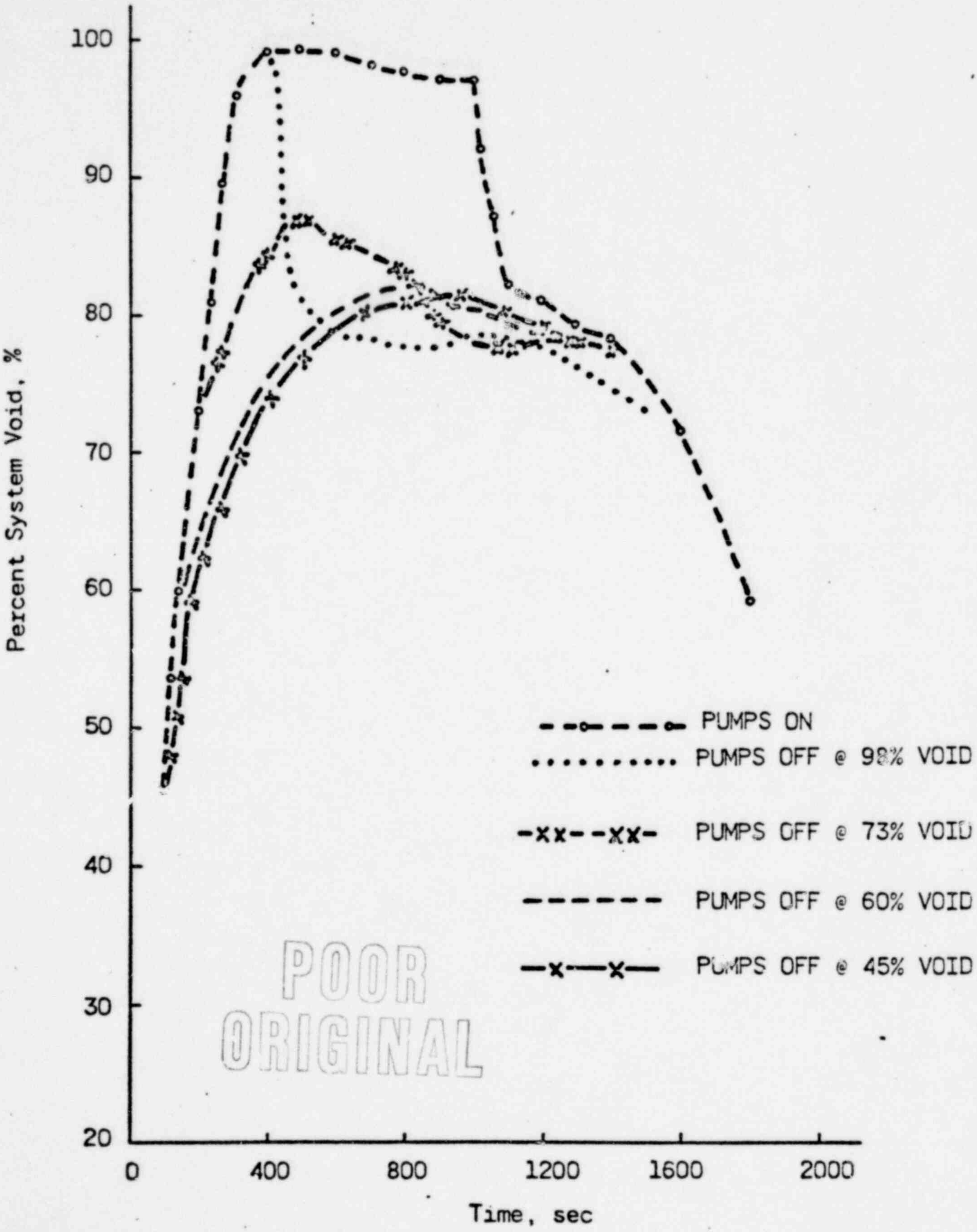

Figure 4 : 0.20 FT^2 BREAK @ P.D., AVAILABLE LIQ. VOL. IN RV VS TIME 1 HPI AVAILABLE

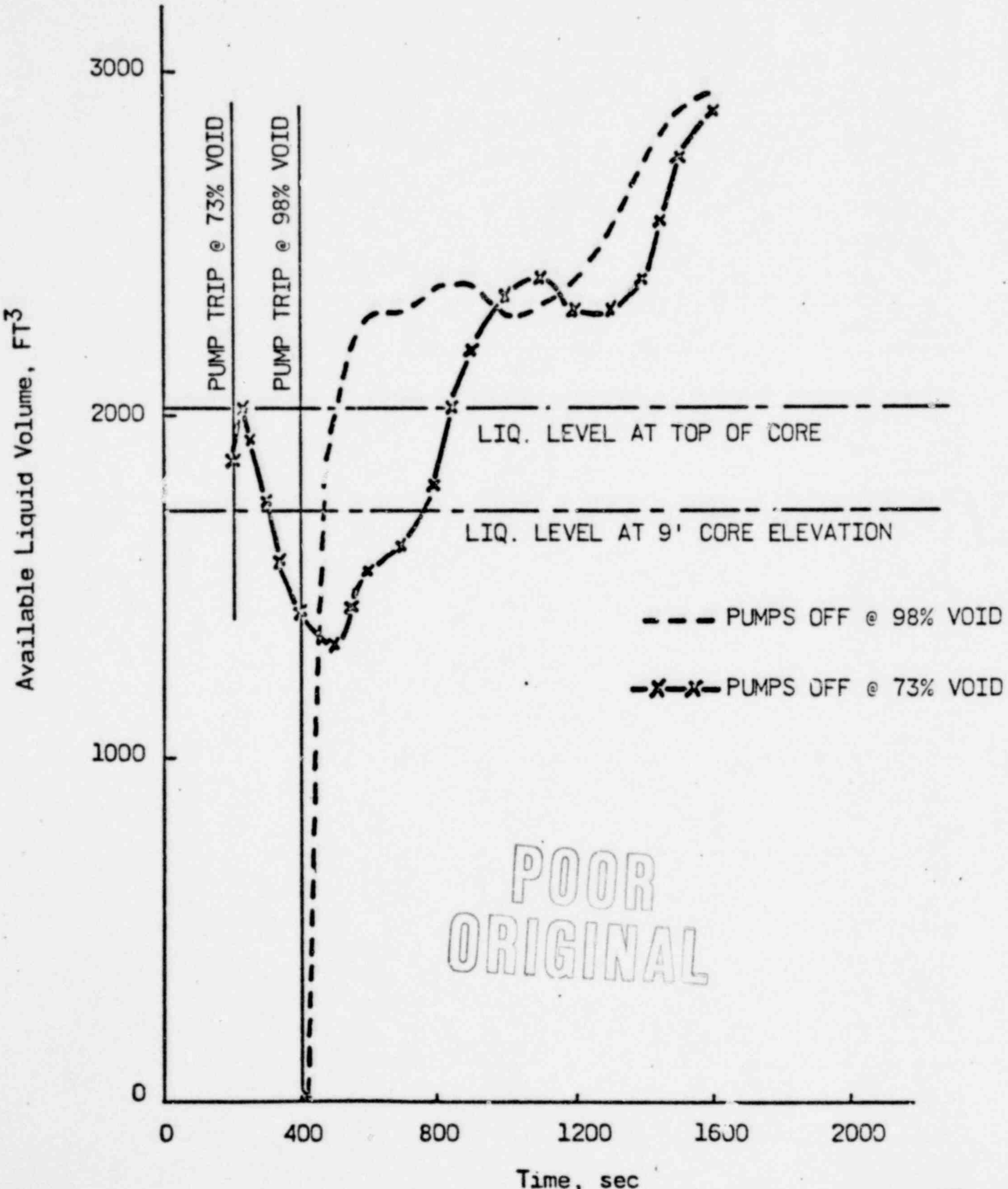

Figure 5 : 0.20 FT^2 BREAK @ P.D. AVAILABLE LIQ. VOL. IN RV VS TIME 1 HPI AVAILABLE

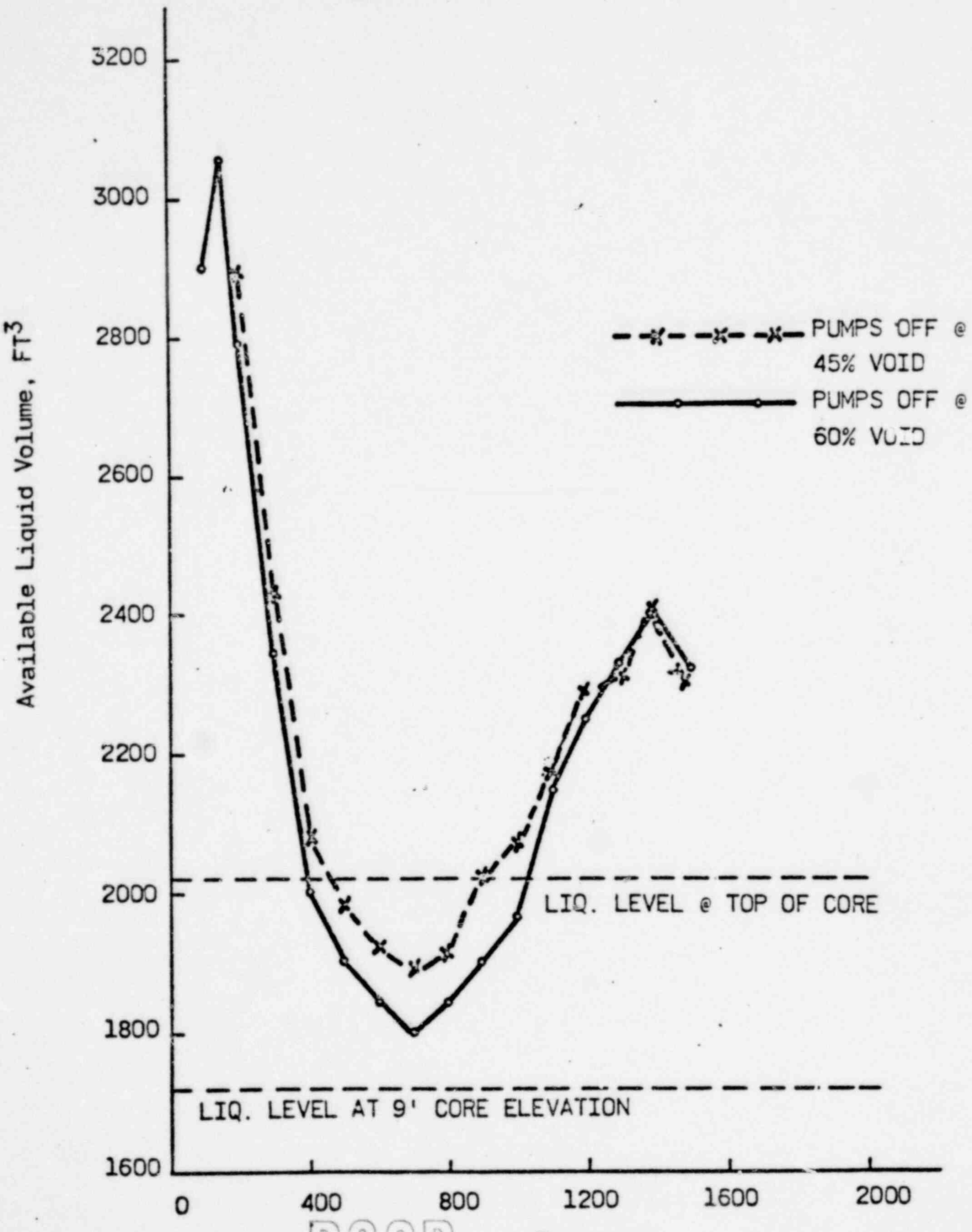

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Figure 6 : 0.1 FT^2 BREAK @ P.D., AVAILABLE LIQUID VOLUME IN RV VS TIME, 1 HPI AVAILABLE

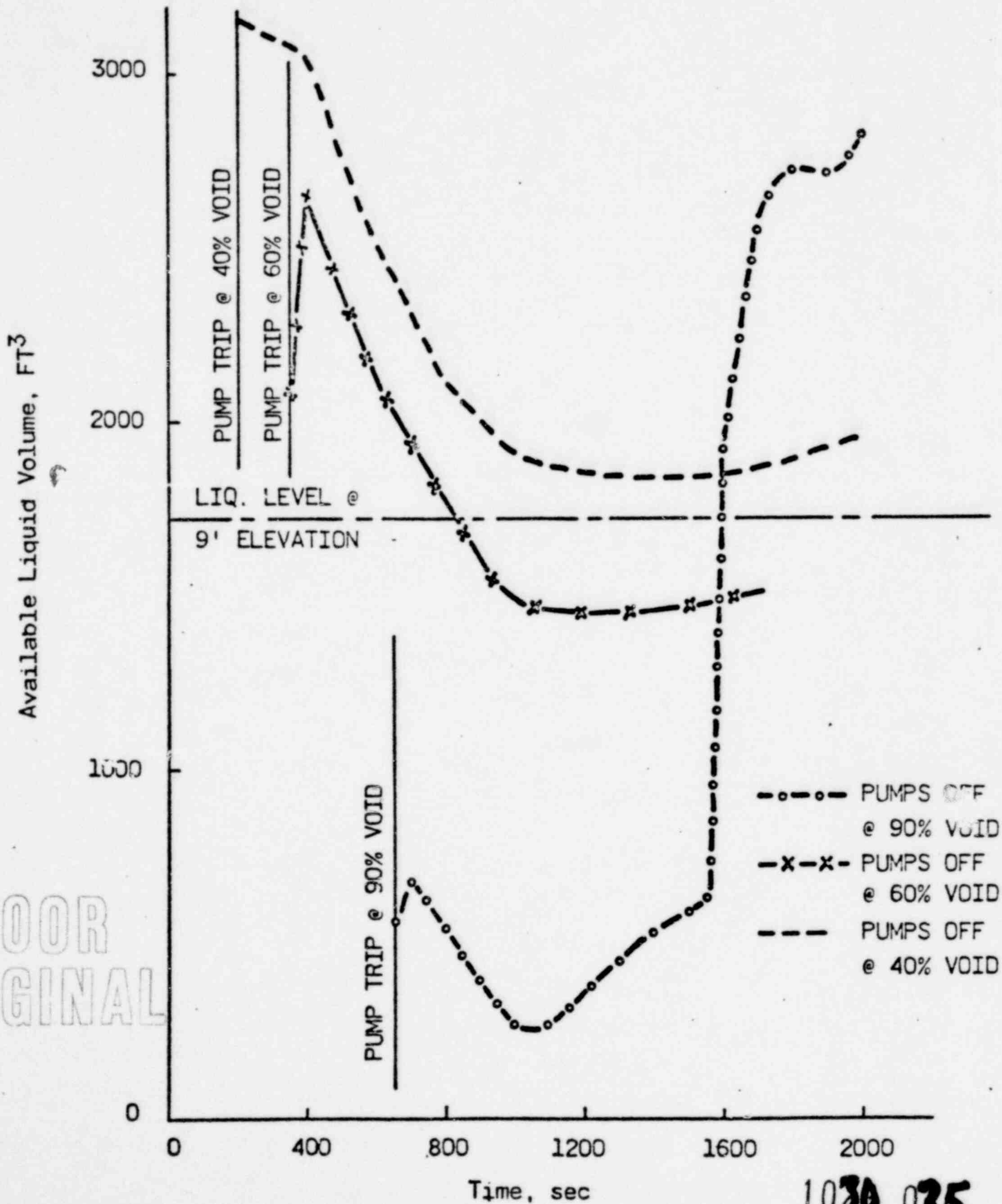

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Figure 7: 0.1 FT^2 BREAK @ P.D., SYSTEM VOID FRACTION VS TIME

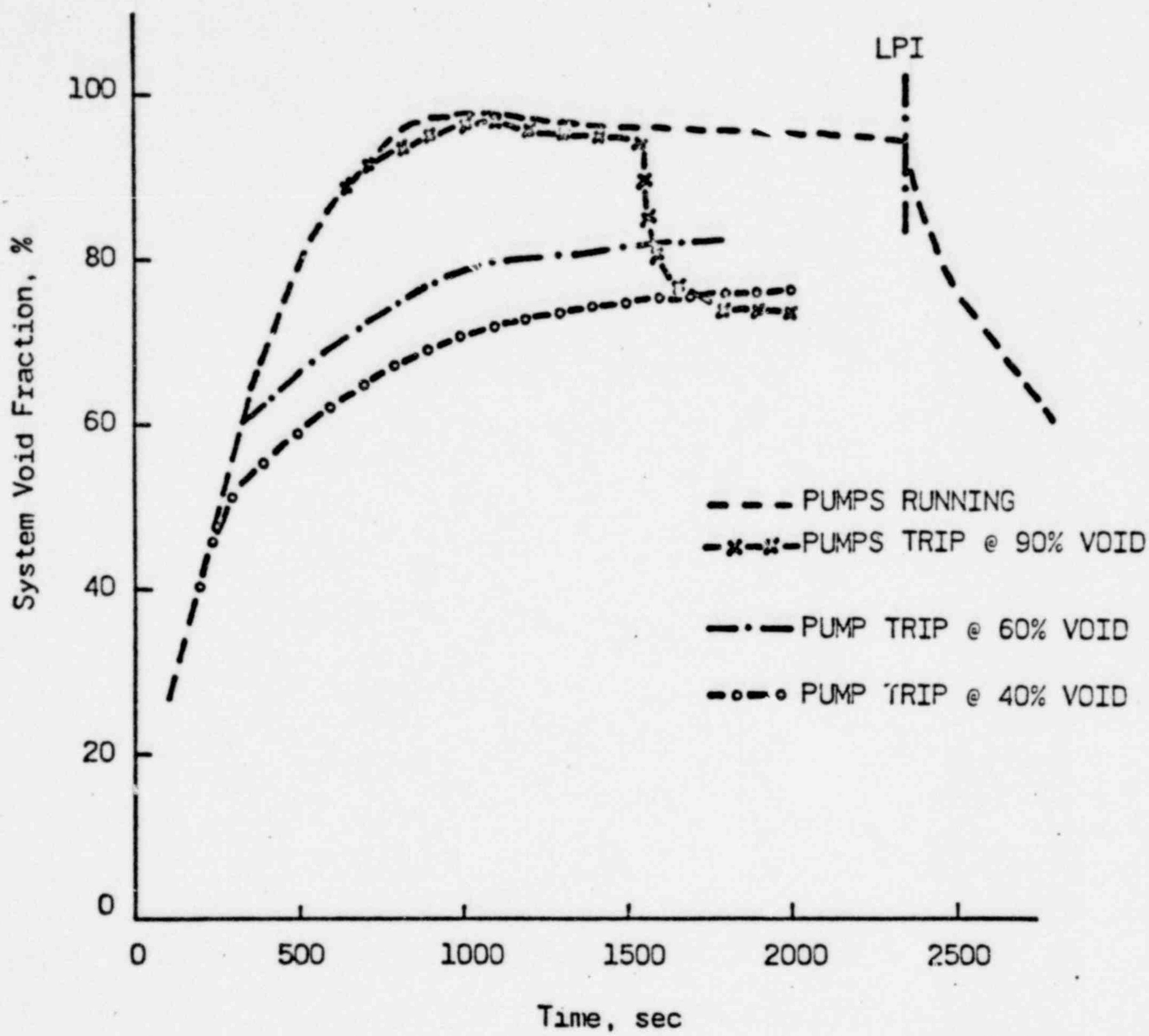

Figure 8: SYSTEM VOID FRACTION VERSUS TIME

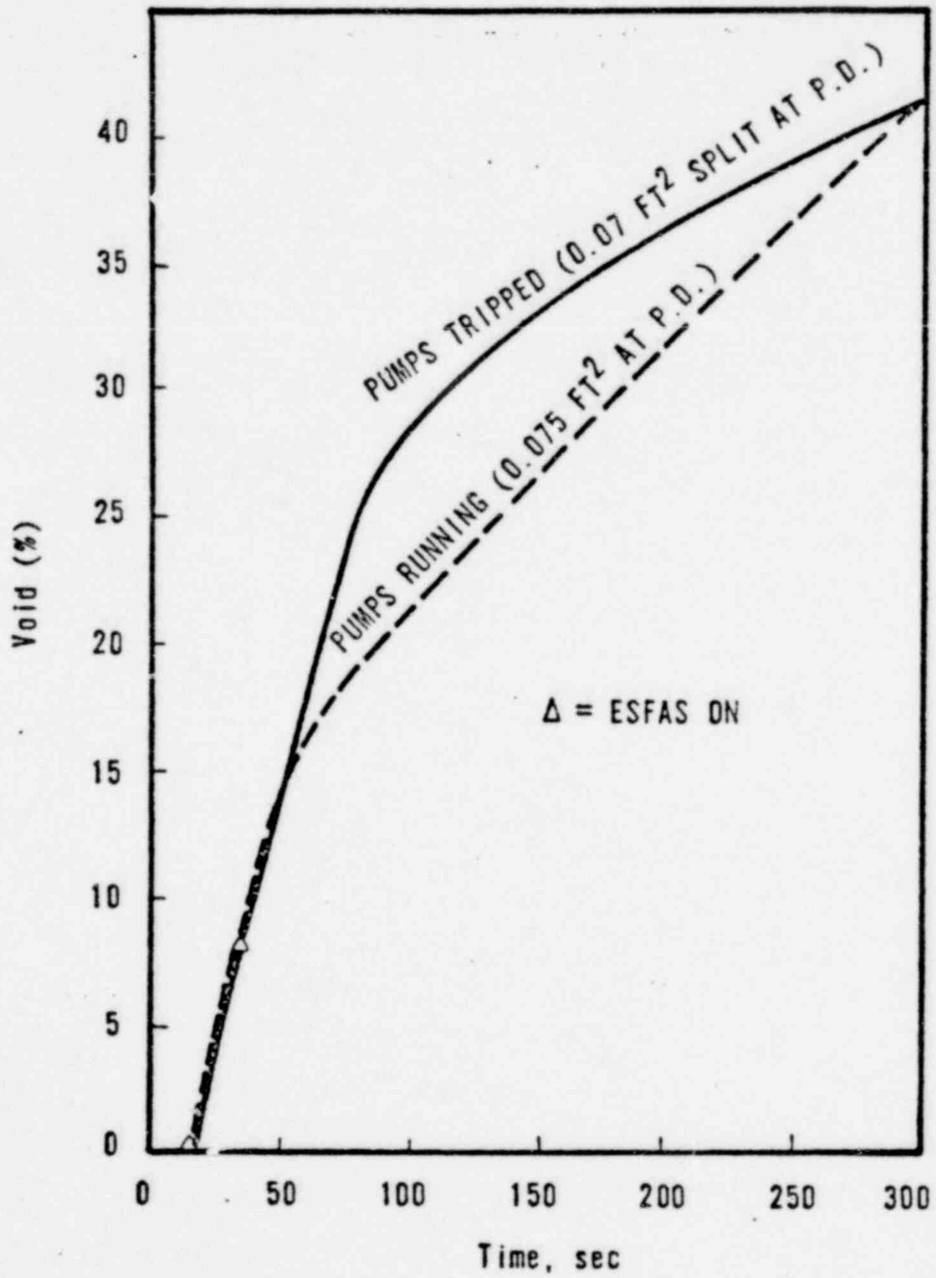

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Figure 9 : SYSTEM VOID FRACTION VERSUS TIME
PUMPS RUNNING AND PUMPS TRIPPED MODEL

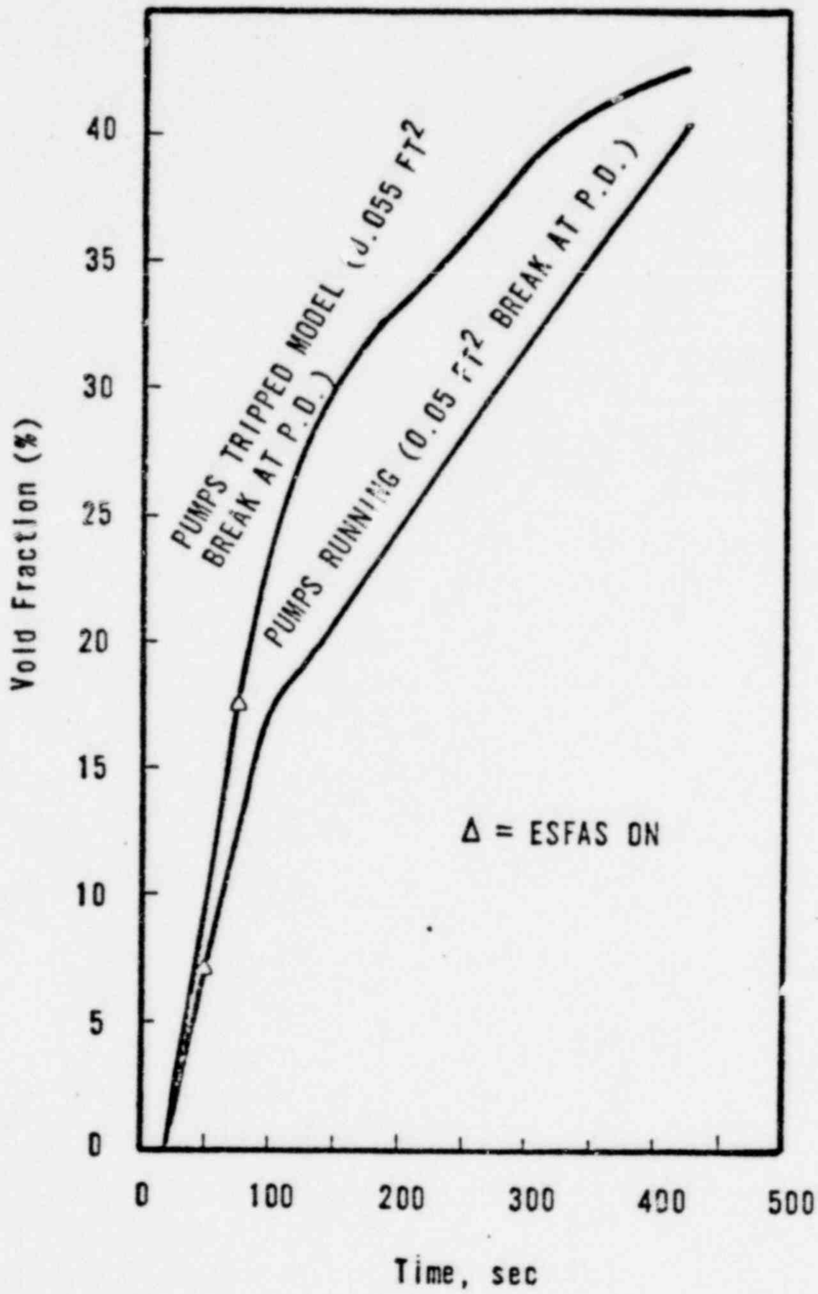

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Figure 10 : BREAK SIZE VS LPI ACTUATION TIME

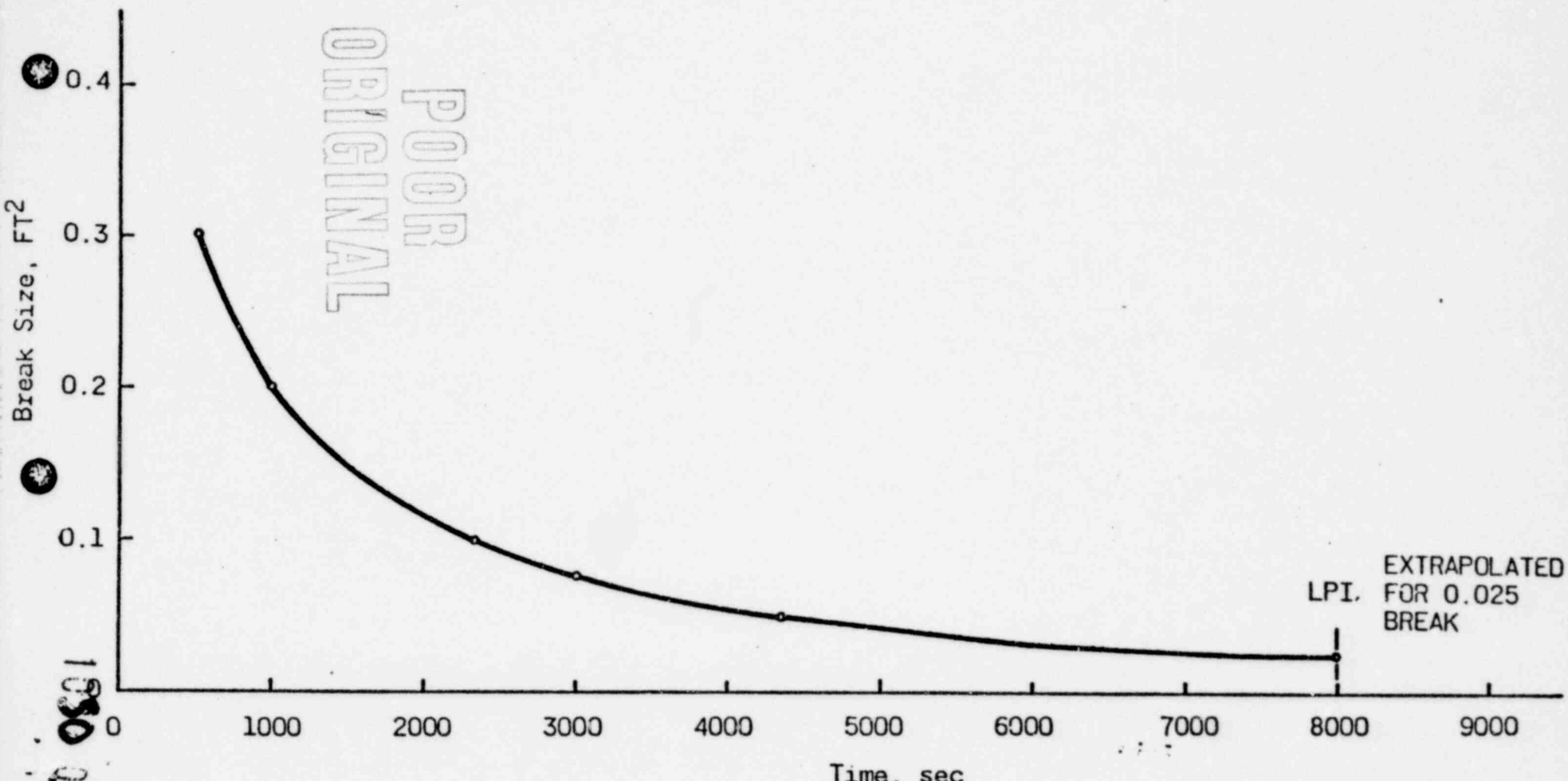

Figure 11 : CRITICAL REGION FOR RC PUMPS TRIP, BREAK SIZE VS TIME

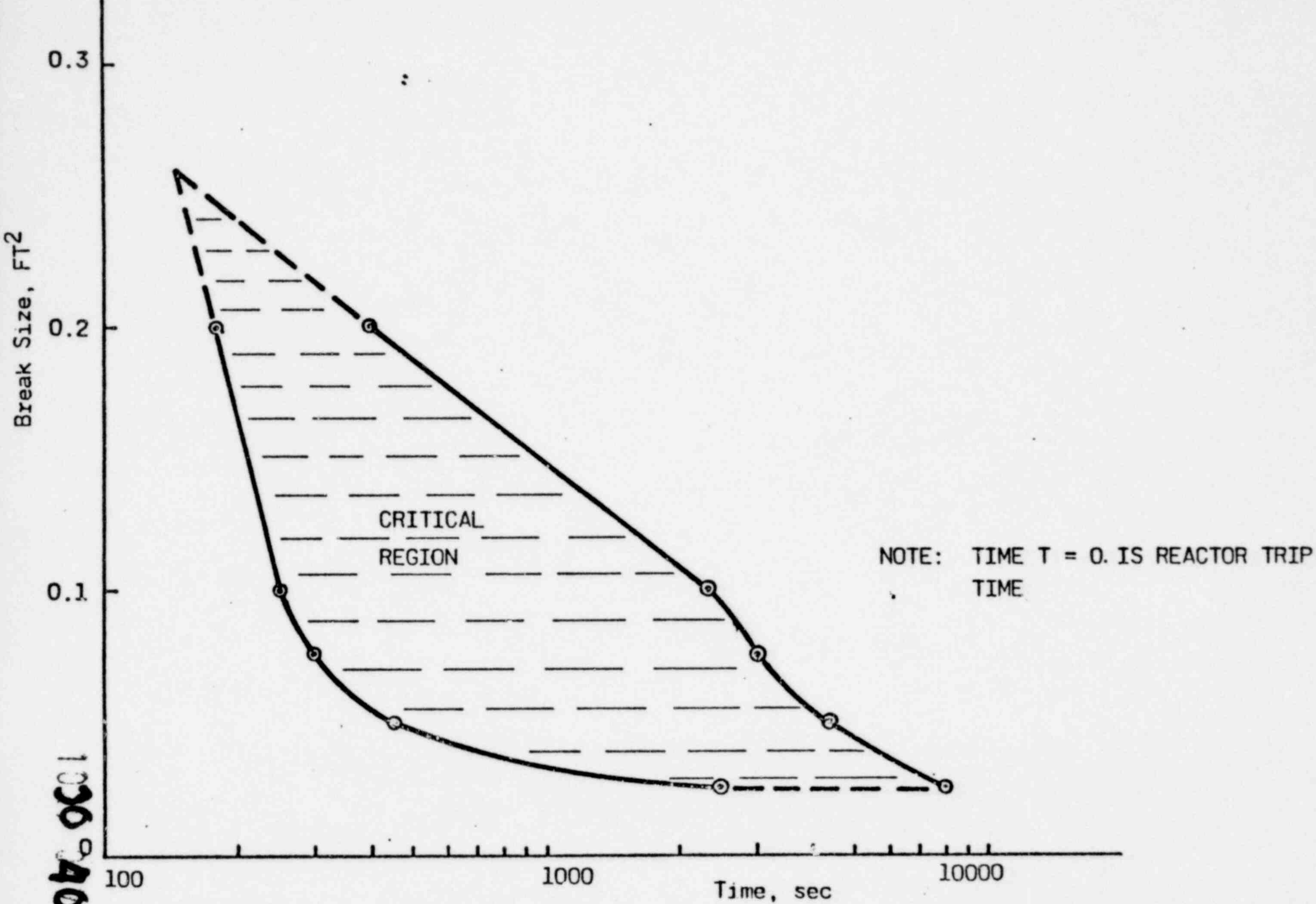

Figure 12: "REALISTIC" CORE AXIAL PEAKING DISTRIBUTION-CASE 1

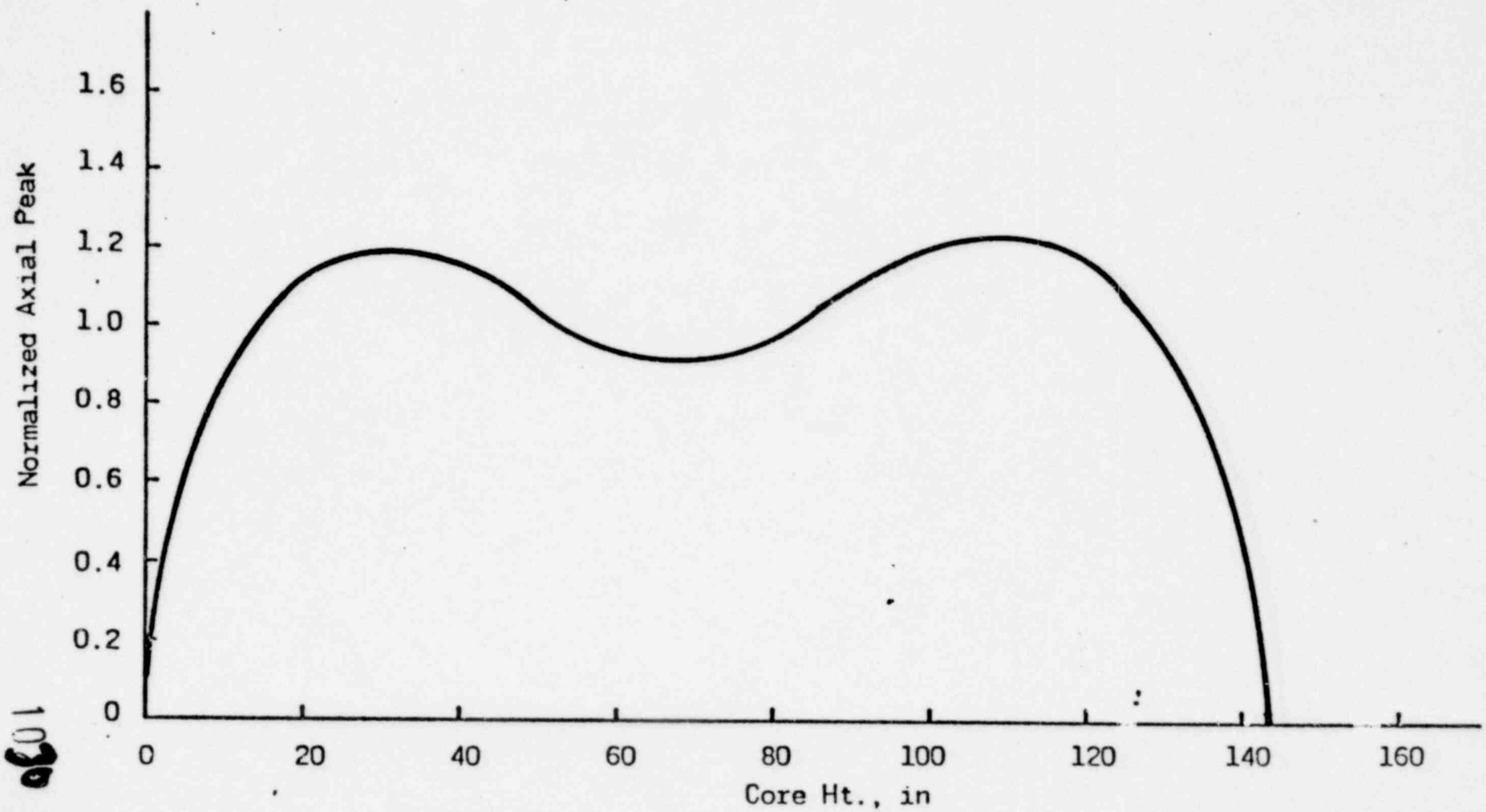

Figure 13: "REALISTIC" CORE AXIAL PEAKING DISTRIBUTION-CASE 2

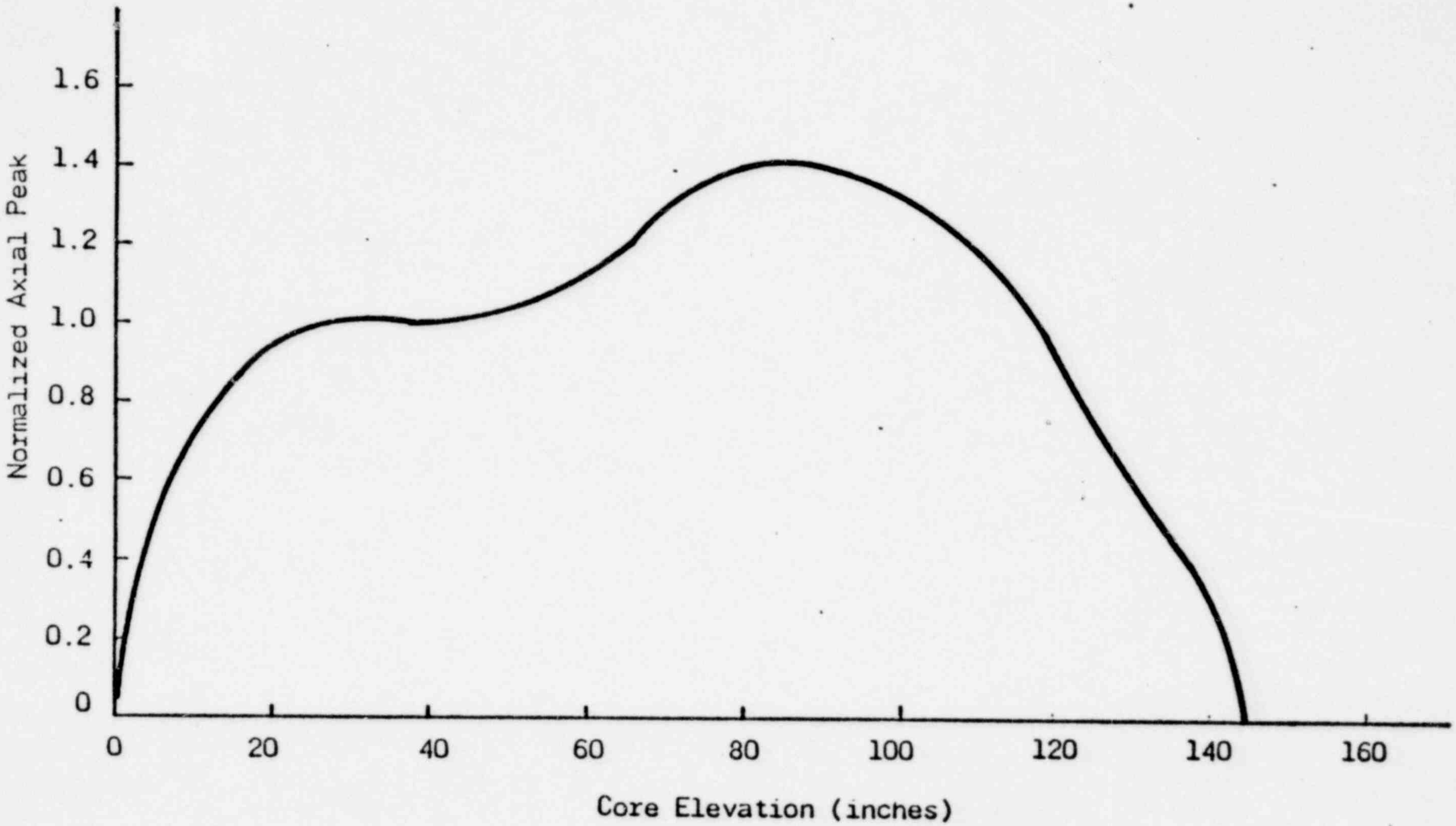

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Figure 14 : AVAILABLE LIQUID VOLUME VS TIME FOR 0.05 FT^2 BREAK WITH 1.0 ANS DECAY CURVE