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THE B&W **OWNERS GROUP**

ANALYSIS COMMITTEE

EVALUATION OF POTENTIAL BORON DILUTION FOLLOWING SMALL BREAK LOSS-OF-COOLANT ACCIDENTS

FINAL REPORT

FRAMATOME
TECHNOLOGIES

EVALUATION OF POTENTIAL BORON DILUTION FOLLOWING SMALL BREAK LOSS-OF-COOLANT ACCIDENTS

FINAL REPORT

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Abstract

Boric acid is a critical component in the reactivity control of pressurized water reactors—generally being necessary to maintain a plant subcritical. In 1995, the B&W Owner's Group recognized a possible mechanism for the accumulation of low boron concentration coolant (deborate), potentially complicating recovery from certain small break LOCAs. The BWOG established a program to quantify concerns and determine prudent procedure or equipment adjustments.

This report is the final report in a series dealing with the issue of boron dilution. Results of earlier studies and BWOG actions taken are reviewed. Analytical results, developed during the past year, on vent valve performance and long-term SBLOCA recovery are presented.

The potential for rapid core reactivity insertion, by restart or bump of the main coolant pumps forcing deborate into the core, is shown to be procedurally restricted to safe conditions. Natural circulation restart is shown to provide insufficient core reactivity insertion rates, removing concerns over core or plant damage. It is demonstrated that vent valves remain open and flowing during both system refill and the restart of natural circulation. Vent valve operation mixes highly borated water with deborate at the downcomer entrance, again mitigating core reactivity insertion concerns. It is concluded that: issues regarding deborate accumulation within the reactor coolant system during small break LOCA are resolved; B&W-designed plants may operate without expectation of difficulties during SBLOCA recovery.

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1. Introduction

Boric acid is a critical component in the reactivity control of a modern pressurized water reactor (PWR). Except near the end of a fuel cycle, the control rods are not sufficient to maintain the plant in a subcritical condition without the presence of boron. Therefore, events, accidents, or scenarios that postulate the possible removal or depletion of the boron within the reactor coolant system (RCS) have been extensively studied. In 1995, the B&W Owner's Group (BWOG) recognized a possible mechanism for the accumulation of low boron concentration coolant (deborate) within the RCS that was associated with recovery from certain small break loss-of-coolant accidents (SBLOCA). Since that time, the BWOG has conducted a comprehensive program to evaluate the inherent SBLOCA boron dilution event. Because the goals were to quantify related concerns and determine what adjustments to plant procedures or equipment might be prudent, the evaluations were carried similar to risk determinations using realistic or best estimate assumptions. Most important of these are the use of a realistic decay heat correlation similar to the ANS 1979 standard and the use of full ECCS injection capabilities. This report is the final report in a series dealing with the issue. The report reviews the results of earlier studies and actions taken by the BWOG, presents analytical results on vent valve performance and long-term recovery obtained over the last year, and summarizes the results and conclusions of the entire program.

The possibility of adverse consequences from an inherent boron dilution event was documented by Framatome Technologies Incorporated (FTI) in 1995 as PSC 1-95. The concern relates to the potential effect of the accumulation of stagnant pockets of deborated coolant within the RCS following the occurrence of an SBLOCA. There is a potential for a reactivity transient if that coolant is carried to the reactor core following resumption of either forced flow or natural circulation. During an SBLOCA, a plant may spend time in the boiler-condenser mode of operation, with water being boiled in the core and steam being condensed in the steam generator. Because boron is not readily volatile, this process concentrates boron in the core region and accumulates essentially boron-free water, deborate, in the steam generator and pump suction piping. As long as there is no bulk flow in the reactor coolant system, there is no concern for core criticality because the core fluid, concentrated in boron, does not leave the core. However, if a bulk flow initiates, by restart of a reactor coolant pump or by restart of natural circulation, the core and steam generator fluid would exchange places. If, when the flow is induced, there is little or no mixing between the fluid regions (an extremely conservative assumption), the displacement of borated core water by deborated water has the potential to lead to a substantial positive reactivity insertion.

In January 1996 the BWOG released Reference 1, a preliminary report of findings on PSC 1-95. The report focused on the identification of possible scenarios and the establishment and reporting of basic phenomena. The volatility of boric acid was found sufficiently low that condensate formed from boiled RCS coolant would contain low boron concentrations. In conjunction with the report a survey of the world industry experience and opinion on the inherent dilution event was obtained. Concerns were organized around two differing methods of restarting bulk circulation of water within the RCS, RC pump restart or initiation of natural circulation. Of these two, the restart of natural circulation, because it would occur slowly and involve substantial system mixing opportunities, was considered significantly less problematic than the restart of the reactor coolant pumps. In fact, the predominant industry opinion was that the restart of natural circulation was not of concern.

In September of 1996, the BWOG issued guidance on the acceptable conditions for the restart of reactor coolant pumps. In essence, the guidance delays the starting or bumping of a RC pump until the boron distribution within the RCS is known sufficiently to assure that no criticality issue would ensue from a pump start. As an example, if the plant is in natural circulation with sufficient core exit subcooling and no core criticality transient has occurred, the boron distribution in the plant is sufficient to prevent criticality transients. The guidance, underlying studies, and utility implementation programs were documented in 1998 in References 2 and 3.

Following this, the BWOG turned its attention to the determination of the result of a system refill followed by an initiation of natural circulation. Integral system experiments, which had achieved a refill and resumption of natural circulation, were investigated but found to be somewhat limited in the range of conditions simulated. The results available did support a conclusion that a restart of natural circulation would involve sufficient system mixing of borated and deborated coolant to prevent a core criticality. However, because the system behaviors during these experiments could not be proven to bound possible plant behaviors, further analytical investigations were necessary. In Reference 2, the BWOG released the results of the first of these studies as a status report. The report concluded that analysis of the restart of natural circulation based on reasonable mixing assumptions showed a substantial increase in the boron concentration of the coolant entering the core. Although, a worst case deficit of about 300 ppm in boric acid concentration remained, several analytical conservatisms embodied in the analytical approach used were identified that would offset the deficit. The report concluded that it was unlikely that a restart of natural circulation would result in a reactivity insertion sufficient to raise the plant to a critical condition and even more unlikely that a prompt criticality would result. The report, however, did not contain a determination of risk for the event.

In September of 1998, the BWOG produced a report, Reference 3, based on the evaluation approach documented in the June 1998 report, which contained the event frequency for restart of natural circulation and consequence information necessary to evaluate risk. No actual risk evaluation was included. Rather, the probability and frequency of the events and conditions necessary to restart natural circulation following a SBLOCA were determined. In addition a consequence evaluation, a calculation of the outcome of a restart of natural circulation with a boron deficiency of up to 300 ppm, was performed. This calculation showed that the plant would experience a rapid power increase but one that was slower and more controlled then the classic rod ejection accident. After an initial prompt critical condition suppressed primarily by Doppler feedback, core reactivity was held to a supercritical condition, about 0.3 \$, through the combination of slow reactivity insertion being compensated by both Doppler and

Moderator feedback. The peak enthalpy for the fuel was limited to less than 90 cal/gram with the increase spanning at least 15 seconds. Such a result indicates no instance of cladding failure and thus no adverse consequence for the event. Finally, Reference 3 identified several additional conservatisms that could be incorporated into the analysis procedure. These conservatisms were evaluated as sufficient to prevent any criticality excursion whatsoever by a factor of more than two. The September, 1998 report concluded, therefore, that the possibility of a criticality incident during recovery from SBLOCA was extremely small and that even if one were to occur it would be limited and pose no threat to the continued recovery of the plant.

To further establish the conclusions reached in the Reference 3, the BWOG initiated analyses to quantify the effect of vent valve operation on the downcomer boric acid concentration during natural circulation restart. The largest, unevaluated conservatism embodied in the September, 1998 consequence analysis, was the assumption that the vent valves closed upon the initiation of circulation flow toward the reactor vessel. It has been demonstrated in several analyses, Reference 3 included, that the vent valves will allow single- or two-phase fluid to circulate between the core and downcomer under any condition for which an RCS refill is imminent. Such a circulation mixes borated core coolant with the downcomer coolant and assures that both the core and downcomer are sufficiently borated. During fully developed natural circulation as might follow a SBLOCA recovery, the vent valves will be closed because insufficient pressure drop between the upper plenum and the downcomer exists. However, the vent valves will close as a function of the development of natural circulation. If the valves are open while the deborate is passing the vessel inlet, they will borate the incoming coolant sufficiently to prevent a criticality concern.

The main purpose of this report, in addition to the summary of previous studies, is to document the results of the BWOG evaluation of system and vent valve performance during long-term SBLOCA recovery. The results of these studies show:

1. That the vent valves are open, passing liquid, and promoting vessel mixing throughout system refill,

2. That, when the system does not evolve to natural circulation post refill, the vent valves remain open to promote vessel mixing and the loop flows are small such that high pressure injection (HPI) boration is very effective, and

3. That, when the system does evolve to natural circulation, the initial loop circulation flows remain small enough that the HPI provides a substantial increase in boron concentration and the vent valves remain open more than twice as long as required to borate the coolant entering the downcomer.

Therefore, the core boron deficit modeled in the September, 1998 report, Reference 3, does not exist and natural circulation may be restarted following SBLOCA without concern.

In conclusion, the concerns over the buildup of low boron concentration coolant within the RCS during a SBLOCA have been resolved through a combination of improved plant-operating instructions and analysis to demonstrate plant safety. Coolant of low boron concentration can accumulate within the RCS pump suction piping during certain SBLOCAs. Although the size range of these events is limited, the probability of accidents in this size range cannot be eliminated. The consequences of a rapid insertion of significant deborate into the core, three to five times faster than natural circulation, remains undefined but may comprise a significant hazard to safe plant operation. The only potential means of achieving such an insertion, restart or bump of RC pumps, has been procedurally restricted, allowing pump activity only when plant conditions will not induce core criticality. The restart of natural circulation has been shown to involve sufficiently slow reactivity insertion rates to remove concern over core damage and plant safety. Further, as documented herein, vent valve operation mixes high boration coolant with deborate at the downcomer entrance, eliminating concerns over this method of plant recovery. If the long-term cooldown of the plant evolves to single-pass cooling, the deborate is either flushed directly from the system or passed benignly to the core with the vent valves in operation. Therefore, the concerns of deborate pockets building within the RCS have been resolved and plants may operate without expectation of difficulties during SBLOCA recovery.

2. Long-Term Cooling Mechanisms and Vent Valve Effects

Reference 3 presented an analysis of the restart of natural circulation based on the following scenario:

1. An SBLOCA of concern occurs and proceeds through to initial equilibrium.
2. As decay heat drops, break quality drops and the system depressurizes.
3. Eventually leak discharge quality is low enough to commence an RCS refill.
4. Refill of the cold legs raises the downcomer and upper plenum water levels initiating two-phase vent valve flow.
5. Plant refill continues, flow from the core through the vent valves borates the downcomer and pump discharge piping.
6. Hot downcomer liquid is pushed over cold ECCS flow to fill cold legs and steam generators.
7. Hot legs fill from the core.
8. Deborate is pushed back into the steam generators until liquid spills over the hot leg U-bend.
9. Fully developed natural circulation initiates instantaneously and the reactor vessel vent valves close and remain closed.
10. Deborate flows to the core, mixing in the steam generator outlet plenum, the cold legs, the downcomer, and the reactor vessel lower plenum.

The resultant calculations showed a core inlet boron concentration that peaked in severity some 300 ppm below the concentration required to maintain the core subcritical. Therefore, the calculations in Reference 3 involved the occurrence of a prompt critical condition. Included in the report, however, was a listing of the conservatisms embodied in the analytical approach that if included would preclude a prompt critical occurrence. Step nine, instantaneous initiation of full natural circulation flow and vent valve closure, is the most significant of these. Had the vent valves been accurately modeled, they would have remained open during the restart of natural circulation, mixing core liquids with the coolant entering the downcomer from the cold legs. Because core liquid is highly borated, this provides a significant additional process by which the boron concentration of the deborate can be increased. This section documents the results of the BWOG studies on SBLOCA long-term cooling mechanisms and vent valve performance. The results of these studies show that the vent valves are open and allow flow throughout system refill, that they stay open when the system does not evolve to natural circulation (single-pass cooling), and that if natural circulation initiates the valves are open more than twice as long as required for the deborate to enter the downcomer.

2.1 Description of Long-Term Operational Modes

The SBLOCA transients of concern for inherent boron dilution issues are those with break areas large enough to evolve past natural circulation to boiler-condenser operation yet small enough to remain there for some time. These breaks establish an initial quasi-steady condition with two-phase flow at the break. Energy is transported from the core to the break via liquid and steam. Relatively cold liquid enters the vessel from the cold leg where it mixes with and condenses any vent valve steam flow. The coolant is then transported down the downcomer and into the core where it is heated, and some portion is boiled. The fluid then passes to the upper plenum and via the hot leg nozzles or the vent valves to the break. In either case, the break passes liquid and steam in quantities that maintain an approximate system mass and energy balance for this first post condensation quasi-equilibrium condition.

As the decay heat drops, the evolution will be toward lower system pressures, decreasing break flow quality, and increases in system average levels. With time, the system can reject decay heat as liquid-only break flow. At this point, the break fluid will start to become subcooled, and it will be possible for a system refill to occur. The rate of refill will be controlled by the imbalance between the injection flow (ECCS) and leak flow rates and the ability of the RCS to condense or vent the steam trapped above the break. As a refill of the system is attempted, there will be a manometric balance between the hot leg levels and the levels in the primary side of the steam generators. This requires liquid flow from the reactor vessel or pump discharge piping over the pump to the pump suction piping. The liquid level in the pump discharge piping is, therefore, above the pump overflow, and the downcomer level will be at or above the top of the inlet nozzle. A water level this high in the downcomer ensures that the vent valves are in a liquid flow condition and that inner vessel circulation is active. (References 2 and 3 discuss this point in more detail.)

The rate of system refill is controlled by the ability to clear the steam space above the break. During the first phase of refill this can be accomplished via condensation in the steam generators, opening of the RCS high point vents, or slowly by condensation and heat release through the primary piping. For the final stage of refill it is likely that only the high point vents or condensation on the RCS piping walls are credible. Which of these finishing mechanisms is effective depends on the specific actions taken by plant operators. If the high point vents are utilized, the refill can be expected within the first 22 hours following the accident. If only heat transfer through the piping walls is available it is probable that refill will occur at times beyond one day.

Post refill the plant takes on one of two modes. If a system energy balance can be achieved with an upper plenum temperature below the saturation temperature of the steam generators, the simulation evolves to a direct cooling mode with relatively stagnant loop flows. In this mode coolant enters the RCS relatively cold, is heated directly from the core or by inner-vessel circulation through the vent valves, and flows out the break. Nearly all of the system energy loss is via the break. The steam generator is either removing very little energy or, most likely, acting as an energy supply. Some small loop flows are possible in either the forward or backward direction but their magnitude is on the order of the ECCS and break flows. This mode is termed single-pass cooling. If system energy flow can not be accommodated by the break without the upper plenum temperature exceeding the steam generator saturation temperature, the plant stabilizes with flowing loops. This mode is termed natural circulation because some of the system energy is being relieved through the steam generators. Water is injected by the ECCS systems, heated in the core, and flows both to the break and around the loops to the steam generators. Either one or both generators may be involved. Inner vessel circulation continues only so long as a temperature difference between the downcomer and the core outlet of more than 40 F can be maintained. Because a substantial amount of loop circulation and energy rejection can be supported by a loop temperature differential of 40 F or less, it is unlikely that inner vessel circulation is maintained after natural circulation fully develops. Loop flows are substantially above the magnitude of the ECCS or break flows.

2.2 Analytical Model

It has been demonstrated in several analyses, Reference 3 included, that the vent valves will allow single or two-phase fluid to circulate between the core and downcomer under the conditions necessary for an imminent RCS refill. Such a circulation mixes borated core coolant with the downcomer coolant and assures that both the core and downcomer are sufficiently borated. It can also be shown that the vent valves are closed under conditions of low power fully developed natural circulation. Under such conditions there is simply not enough differential pressure across the vent valves to hold them open. In fact the vent valves close during the natural circulation restart transient as a function of the developing circulation. To determine the timing of these events, the RELAP5/MOD2 simulations used to determine buildup of deborate within the RCS in Reference 3 were extended to simulate plant refill and the establishment of a stable long-term cooling. The RELAP5 model was based on the RELAP5 SBLOCA lowered-loop evaluation model inputs, Figures 1 and 2, with some notable exceptions. The evaluations being conducted herein are to determine realistic expectations for plant behavior. Therefore, the decay heat correlation was adjusted to best estimate levels and the ECCS was modeled at its full capability. Further details of the model are provided in Appendix A. A model of the lowered-loop plant was selected over the Davis-Besse design because the raised-loop embodies a smaller volume within which deborate can accumulate and would, therefore, experience less severe deborate induced transients. As will be discussed in Section 3, the results obtained bound the Davis-Besse plant and can be applied directly albeit with some added conservatism.

2.3 Results of Long-Term Cooling RELAP5/MOD2 Simulation

For the long-term cooling studies, six RELAP5/MOD2 calculations, one hot leg break and five cold leg breaks, were conducted. Because the primary goal of these studies was to determine the nature and timing of system evolution once a system refill occurred, the RELAP5 modeling was adjusted individually within the runs to enhance certain physical phenomena. An example of this is the placement of the high pressure injection (HPI) location in the highest control volume of the pump discharge piping. At this location the injection is modeled about one and a half feet above its actual position. The alteration was necessary to facilitate the removal of steam trapped in the RC pump and immediate pump discharge volumes. Steam trapped in the upper portions of the pump discharge piping will be readily condensed because of the splash of the HPI stream against the wall of the RCS pipe as it is injected. RELAP5/MOD2, however, does not have the ability to simulate this occurrence where it would cross a node boundary. Raising the injection location slightly accomplishes the proper condensation simulation for the region. Another example is the cold leg nozzle elevation. RELAP5/MOD2 lacks the ability to simulate separated liquid-vapor regions within control volumes. For several of the cases run, this resulted in a suppressed downcomer level because the condensation of steam in the nozzle belt area required an interface region. With the original modeling, that region occupied one-half of a cold leg nozzle, excessively limiting the downcomer level. For the analysis of Section A.5 in Appendix A, the interface level was restricted to the upper three inches of the cold leg nozzle. These and other special process modeling efforts are described further in Appendix A along with the results of each simulation.

Case results can be divided into two general categories: those for which loop flow was relatively stagnant and those resulting in a robust natural circulation. The differentiating factor for the two lay in the ability of the steam generators to remove system energy. If a system energy balance could be achieved with an upper plenum temperature below the saturation temperature of the steam generators, the simulation evolves to a single-pass cooling mode with relatively stagnant loop flows. Else wise, the system would reinitiate a bulk natural circulation of liquid within one or two loops.

Stagnant Loops - Single-pass Cooling

Figure 3 shows the temperature of the fluid in the upper plenum in comparison with the steam generator saturated temperature for the hot leg break. With the resultant temperature distribution, there is no need for energy transport to the steam generators, no such transport ensues, and no significant loop circulation initiates. The long-term coolant flow path for this case comprised a split in the net flow at the injection location. Most of the coolant passes through the reactor core to the break but some travels backward in the loop over the hot leg bend to the break. Figures 4 and 5 show the upper plenum temperature comparisons and the loop flow rate for the cold leg break documented in Section A.5 of Appendix A. This case simulated a late steam generator depressurization in an effort to induce natural circulation. The results show that the case is close to initiating natural circulation and could possibly achieve circulation had the simulation continued. Figure 4 shows that, by the end of the run, the intact loop steam generator temperature has dropped below the upper plenum temperature but the broken loop steam generator temperature remains above the upper plenum temperature. Figure 5 shows that loop flow may just be initiating within the intact loop at the end of the case. However, a substantial plug of cold water has accumulated within the suction piping and is seriously retarding the development of circulation. Figure 5 also shows that vent valve flow has been continuous throughout the simulation.

In addition to vent valve flow a common factor within the stagnant loop results was the presence of inter-cold leg circulation. This type of circulation occurs when the flow of one cold leg in a single loop is backward and the other is forward. Although inter-cold leg circulation has been observed experimentally, the system conditions necessary for initiation have not been extensively formulated. One requirement is that no dominant bulk circulation is present within the loop. A dominant loop circulation washes out the small imbalances in individual cold leg densities that are the likely precursors to inter-cold leg circulation. Therefore, inter-cold leg circulation is only present when the loop flows are essentially stagnant. When occurring, inter-cold leg circulation is significant in mixing of cold leg and downcomer fluids and providing a substantial influence on the coolant temperatures and boron concentrations within the cold leg suction piping and the steam generator lower plenum.

Deborate control for these cases was provided by direct flow of the deborate to the break or by continuous vent valve flow in combination with low loop flow rates and boration via HPI. For the hot leg break, Section A.1, reverse heat flow in the steam generators heated the coolant in the primary side of the steam generators such that the generators filled before the hot legs. This resulted in a reverse flow condition that flushed the deborate directly to the break. A similar situation happened for some of the cold leg breaks. Where small positive loop flows resulted, the continued vent valve flow results in a mixing volume comprised of the reactor vessel outlet plenum, the two horizontal hot leg sections, the core, the vessel lower plenum/lower head, the downcomer, and the four pump discharge pipes. This is a volume of approximately 4000 ft^3 which is gradually to be mixed with up to 2000 ft^3 of low boron coolant. The loop flows achieved in the simulations only approach the HPI and break flows. Therefore, the boron concentration within the coolant after passing the HPI injection location would be, at a minimum, the average between the HPI (assuming the system has evolved to sump recirulation and 2000 ft^3 of deborate has been stored in the RCS $\approx$ 2400 ppm) concentration and the deborate concentration ($\approx$ 200 ppm from 10 % carry over) or 1300 ppm. If none of the other loop mixing effects applied in Reference 3 are credited, the mixed mean boron concentration after vent valve induced mixing is approximately 1850 ppm, substantially bounding the minimum for criticality concentration of 1500 ppm from Reference 3. If credit is given for the loop mixing processes described in Reference 3 the minimum core inlet boron concentration increases further. Thus, the deborate is flushed through the system and mixed with borated coolant and HPI to the extent that its boron concentration is increased well beyond concern.

Significant Flow in Loops – Natural Circulation

If natural circulation develops, the vent valves will eventually close and success at borating the incoming core flow depends on when that happens. The final case, Section A.6 of Appendix A, of the six calculations performed initiated an earlier steam generator depressurization. This case achieved sufficiently low steam generator temperatures near the time of system refill to induce natural circulation in the RCS. Figure 6 shows the upper plenum temperature and the steam generator saturation temperatures versus time. Figure 7 displays the loop and vent valve flows. Loop flow develops slowly and competes with vent valve flow, gradually decreasing the temperature difference across the reactor vessel. When the temperature difference is no longer sufficient to hold the vent valves open, they close and the loop flow increases. The timing of the vent valve closure is longer than required to mix the deborate. Loop flow is well established and stable by 20700 seconds, 345 minutes, (flow actually started some 500 seconds, 8 minutes, earlier). By 22200 seconds, 370 minutes, all of the deborate has passed into the downcomer and mixed with the vent valve flow. Vent valve flow stops at approximately 24600 seconds, 410 minutes. Thus, the vent valves were open more than twice as long as required to mitigate the maximum accumulation of deborate.

The timing of this transient affirms the theory of vent valve closure timing presented in Section 6 of Reference 3. At the initiation of circulation the vent valves are open and flowing because of elevation head imbalances set up across the reactor vessel prior to and during refill. Until sufficient fluid has been transported from the steam generators and mixed within the reactor vessel to adjust the vessel temperature distribution, the vent valves should continue to be open and flowing. Within Reference 3, the integrated fluid flow required to alter the distribution was estimated at somewhat over twice the integrated flow required to displace the deborate to the downcomer. The timing displayed in the accident simulation of Section A.6 shows vent valve closing at just longer than twice what is required to pass the deborate. The same timing relationship can be expected throughout the spectrum of possible steam generator cooldown and RCS refill rates. Although the transient will develop more quickly if the generator cooldown rate and RCS refill are accelerated to the limits of the EOP guidance (approximately 100 F/hr or 4 times the rate simulated in Section A.6), effective vent valve induced vessel mixing can be expected until the deborate is well into the reactor vessel. Because the loop flows during the restart of circulation are approximately equal to the HPI and break flows, the estimation of core inlet boron concentration is the same as that for the non-circulating system, 1850 ppm (For the circulating case, however, the estimation is substantially more accurate.) Therefore, no criticality transient will result from a restart of natural circulation.

2.4 Summary of Results

The studies documented within this section and in Appendix A demonstrate many possible long-term cooling end states for plant recovery from SBLOCA. Each state involves some degree of unique interaction with the deborate and its elimination from the RCS. Long-term cooling modes can be divided into circulating or non-circulating systems. Analysis of each case shows that the maximum amount of deborate that can be accumulated within the system was either removed from the system without consequence or mixed with highly borated coolant and HPI flow prior to entry into the core. Therefore, all long-term cooling paths have been demonstrated as safe relative to core criticality concerns.

3. Applicability of Analyses

The reference plant for the calculations in this report as well as those in References 2 and 3 is Crystal River, Cycle 11. This is a 24 month cycle and has the highest inherent reactive of any cycle being run by any of the BWOG lower loop plants. The borated water storage tank (BWST) concentration, 2500 ppm, is a compromise amongst the plants and was selected in conjunction with the Crystal River core to achieve an analysis that would be considered reasonable for any of the plants. These selections coincide with the desire to determine the risk to the plant of a prompt critical excursion during recovery from SBLOCA. Other plants within the lower loop category could be expected to have slightly different results if specifically analyzed. However, none would differ sufficiently to eliminate the margins identified by the evaluation conducted herein or in References 2 and 3. The Davis-Besse (DB-1) raised loop design, however, differs sufficiently from the lowered loop design to warrant a deeper consideration of applicability.

A review of the geometric and operational differences between DB-1 and the reference model concludes that the lessons learned and phenomena observed for the safe disposal of the deborate in the analyses of the lowered loop plant can be extended to DB-1. The important plant differences are (1) initial power level, (2) number of vent valves, (3) ECCS flow capacities, (4) pump suction side volume differences, (5) relative elevation differences, and (6) the upper head vent path.

The initial power level for the raised loop plant is about 8% higher than that of the reference lowered loop plant (2772 MWt versus 2568 MWt). This is expected to result in a time shift in the blowdown of the system. The time shift would be on the order of that required to adjust the decay heat downward by about 8 percent. The events that occurred in the lowered loop plant analyses would occur for DB-1 at later times. The following table shows the equivalent times of the two initial power levels.

Decay Heat MW	Time, Hours Lower Loop Plants	Time, Hours Davis Besse	Time Shift, Hours (Davis Besse – LLPs)
24.8	5.0	6.5	1.5
20.0	10.0	12.7	2.7
17.6	15.0	19.8	4.8
16.2	20.0	27.2	7.2
15.5	24.0	32.8	8.8

There are only four vent valves in DB-1 compared to eight valves in the reference plant. This is expected to result in a somewhat reduced total vent valve flow. For the same amount of decay heat, the total vent valve flow (W) is related to the total vent valve area (A) as follows. $(W_{DB}/W_{LL}) = (A_{DB}/A_{LL})^{(2/3)}$, or $W_{DB} = 0.63*W_{LL}$. The predicted vent valve flow is more than 300 lbm/s for the lowered loop plant during natural circulation and before the closure of the vent valves. The corresponding natural circulation flow is about 25 to 50 lbm/s per loop. For the raised loop plant, the expected vent valve flow would be more than 0.63*300, 190 lbm/s. This is still larger than the expected loop natural circulation flow during vent valve operation. Therefore, the mixed boron concentration will remain characteristic of the core concentration and the reduced number of vent valves in the raised loop plant are more than sufficient for safe dispersion and mixing of the deborate.

The ECCS flow capacities differ among the lowered loop plants and between the lowered loop plants and Davis-Besse. The lowered loop plant analyses were done for a representative Crystal River-3, 2-HPI system. For the representative lowered loop plant, the analyzed break size was 0.007 ft^2 and the corresponding quasi-equilibrium condition (break flow and core energy matched by HPIs alone) occurred at a system pressure of about 700 psia. For pressures below 1350 psia, however, the DB-1 raised loop plant has a higher HPI injection rate. For example, the DB-1 HPI would be about 33 to 55 percent more for system pressures between 1000 and 500 psia, respectively. This is expected to result in higher quasi-steady pressures and slightly increased HPI and break flows for the raised loop plant compared to the representative lowered loop plant given the same break size. It does not alter the energy and coolant movement pattern within the system, only the pressure under which that pattern operates. Similar, but much reduced, trends would also be expected for specific lowered loop plants depending on their ECCS flow versus pressure characteristics. Therefore, no ECCS related special consideration is deemed necessary. For events expected to remain in solid natural circulation credit has been given for operator management of the makeup and purification system for DB-1. The basis for this assumption is the reality of expected operator performance and is the same as the lowered loop plant assumption that the operators will activate the HPI system within two minutes of the initiation of the event even without an ESFAS signal.

The pump suction piping volume for the raised loop plant is about 200 ft^3 less per loop than that of the lowered loop plants. This will lower the amount of deborate that can accumulate within the system and lessen its effectiveness in inducing core criticality issues. Thus, deborate consequence calculations for DB-1 would be expected to have less severe results than those for the lowered loop design.

One of the measures of the propensity for natural circulation is the relative elevation of SG secondary set level with respect to core center. For DB-1, the relative elevation is about six feet higher than the lowered loop plants. (The relative elevation ratio for the raised loop design is about 27 percent larger than that of the lowered loop design.) This will promote additional natural circulation in the Davis-Besse plant. The higher natural circulation rate would cause an earlier closure of the RV vent valves. However, the time it takes to buildup natural circulation will remain sufficient to disperse the deborate before the valves close. From a simple elevation head balance, flow proportional to square root of height, the 27 percent relative head ratio amounts to $(1.27)^{0.5} = 1.13$, or 13 percent more flow for the raised loop plant. The added 13 percent loop flow should not have a substantial impact on the ability of the vent valve to provide downcomer mixing for conditions of natural circulation restart.

For the lowered loop plant restart of natural circulation calculations, Section A.6 of Appendix A, the system flow increased from about 25 lbm/s to about 50 lbm/s in a span of about 50 minutes after which the vent valves begin to close. It took an additional 15 minutes before the valves were shut closed. Considering 13 percent more flow potential for the raised loop plant, and the loop flow of 50 lbm/s as the threshold for vent valve closure, the time span before the vent valves begin to close would be about 38 minutes [(50/1.13-25)/(50-25)*50]. Add to this the additional time before the valves would actually close, and the time available for deborate mixing remains substantially greater (more than 50 percent) than the 25 minutes required for mixing in the lowered loop plant. Further, as noted earlier, due to geometric differences, less deborate will be collected in the raised loop plant, and the flow of the deborate to the DB-1 core will be 13 percent faster. Both factors, not accounted for here, would shorten the required mixing time. Therefore, adequate time will be available in a raised loop plant before the vent valves close.

The Davis-Besse plant has a small vent line connecting the reactor vessel upper head and the inlet plenum of one of the steam generators. The vent line will facilitate filling the reactor vessel, making it somewhat easier for DB-1 to establish liquid vent valve flow during refill. Further, as refill nears completion, loop circulation through the vent line will precede circulation through the hot legs. The result will be a predisposition for DB-1 to initiate full circulation in the vent line loop and an expansion or lengthening of the low flow initial circulation phase. The early circulation, induced by the vent line, provides DB-1 with an expanded opportunity for HPI boration and the vent valves to mix and borate the incoming coolant. Therefore the vent line comprises a small but positive difference in the treatment of the SBLOCA inherent dilution event.

In summary, there are attributes about Davis Besse that increase the consequences of the deborate event and there are attributes that lessen the consequences. The possible increase in loop flow is balanced by increased HPI flow such that in combination with the 20 percent decrease in stored deborate volume, the likely core inlet concentration is less reactive (higher relative boron concentration) then has been calculated herein for the lowered loop plants. Therefore, the calculational results presented herein and those developed earlier in the program can be conservatively applied to Davis Besse.

4. Conclusions

The BWOG has completed a major multi-year effort to evaluate and understand the potential safety issues associated with inherent boron dilution events. The deboration of RCS coolant and subsequent movement of that coolant to the core can result in core recriticality. Best estimate evaluations have been conducted for both RC pump restart and the restart of natural circulation subsequent to system refill. Of these only the RC pump restart was found to pose a significant risk to plant safety. Therefore, restart of forced circulation, by either bumping or starting the reactor coolant pumps, has been limited to acceptable conditions by changes to the emergency operating procedures.

The range of applicable break sizes and locations has been identified, and the process for post-LOCA deboration and the resultant conditions prior to a restart of natural circulation have been described within the program. Calculations have been performed that conservatively predict the volume of deborated coolant accumulated and track the progress of the deborate through the system to the reactor core during refill and natural circulation.

An evaluation of the frequency of a small break LOCA that would lead to a possible return to critical has been done and the frequency shown to be small. Only a small fraction of these events have the potential to proceed to core damage. In particular the frequency of the most probable (2 HPI) case is 8.1 E-6, Reference 3. As noted above, this has no potential for core damage. The '1 HPI case' has a frequency of 1.1 E-7. This case has only limited, if any, potential for core damage. The resulting possible overall change in core damage frequency is therefore below the 1.0 E-6 definition of a "very small change."

A conservative consequence evaluation of the impact of natural circulation restart has been conducted and no core damage was predicted. The excursion was self-limiting and the maximum enthalpy of the fuel limited to less than 90 cal/gram. The resulting fuel temperature is less than that experienced during normal operating conditions. More complete calculations, performed to further investigate the role of vent valve flow in long-term cooling, have demonstrated deborate disposition without core criticality. Plant refill without a natural circulation restart leads to removal of the deborate through the break or slow migration to the core with substantial HPI boration and continuous vent valve flow to facilitate mixing. Refill and subsequent restart of natural circulation, although leading to faster core penetration, retains substantial time for HPI boration and the vent valves remain open long enough to assure inner vessel mixing with the deborate.

In conclusion, the potential significant scenarios for inherent boron dilution SBLOCA events have been evaluated. Where potential concerns existed, procedural changes in the emergency operation of the plants have been incorporated to remove the concerns. For other scenarios, analyses have been conducted to show that core recriticality would not result from plant recovery operations. Therefore, the SBLOCA inherent boron dilution event is acceptably mitigated by all BWOG plants and is not a concern for safe operation of the facilities.

5. References

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FIGURE 1. SBLOCA LOOP NODING ARRANGEMENT (177 LL PLANT).

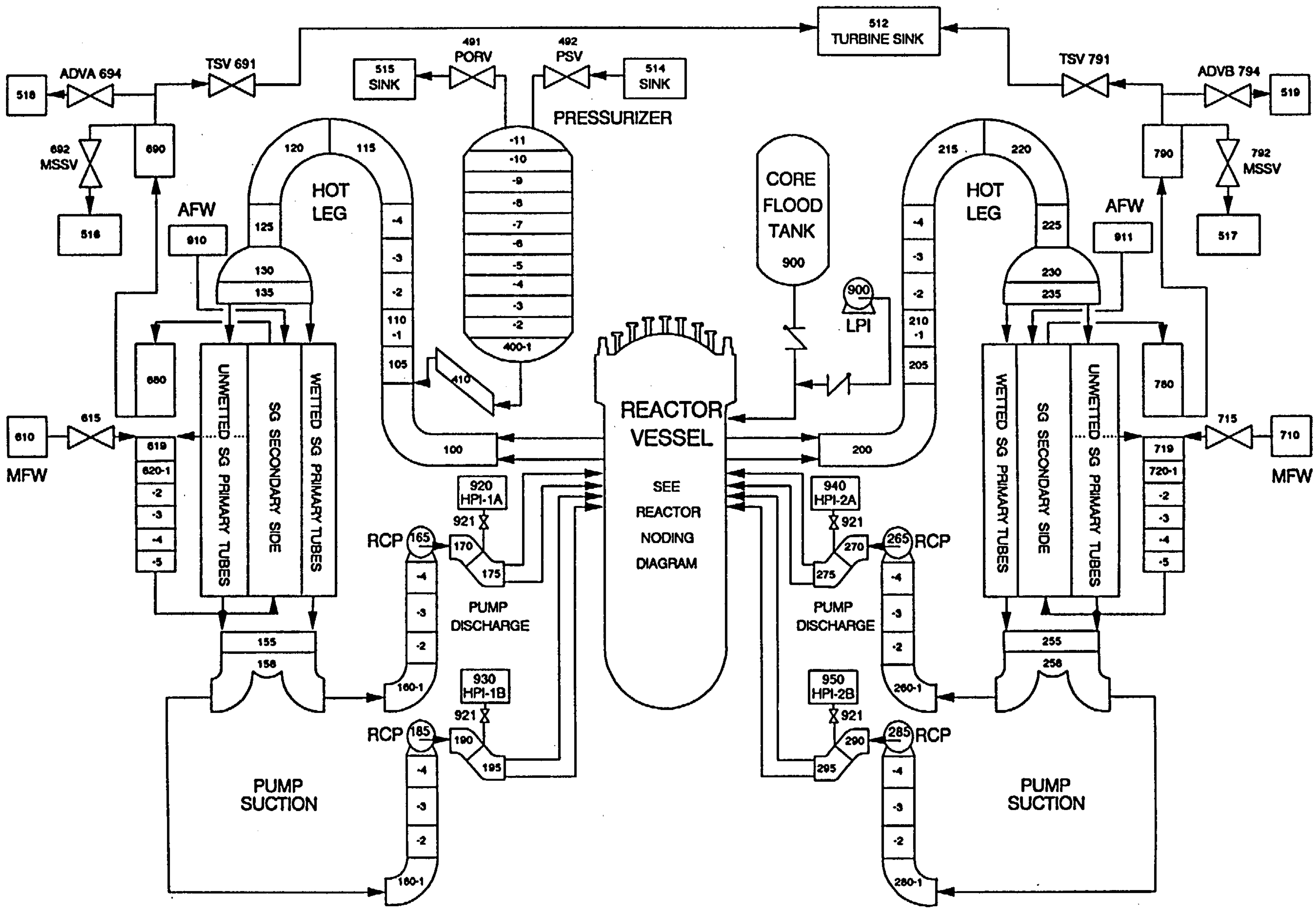


FIGURE 2. SBLOCA REACTOR VESSEL NODING ARRANGEMENT (177 LL PLANT).

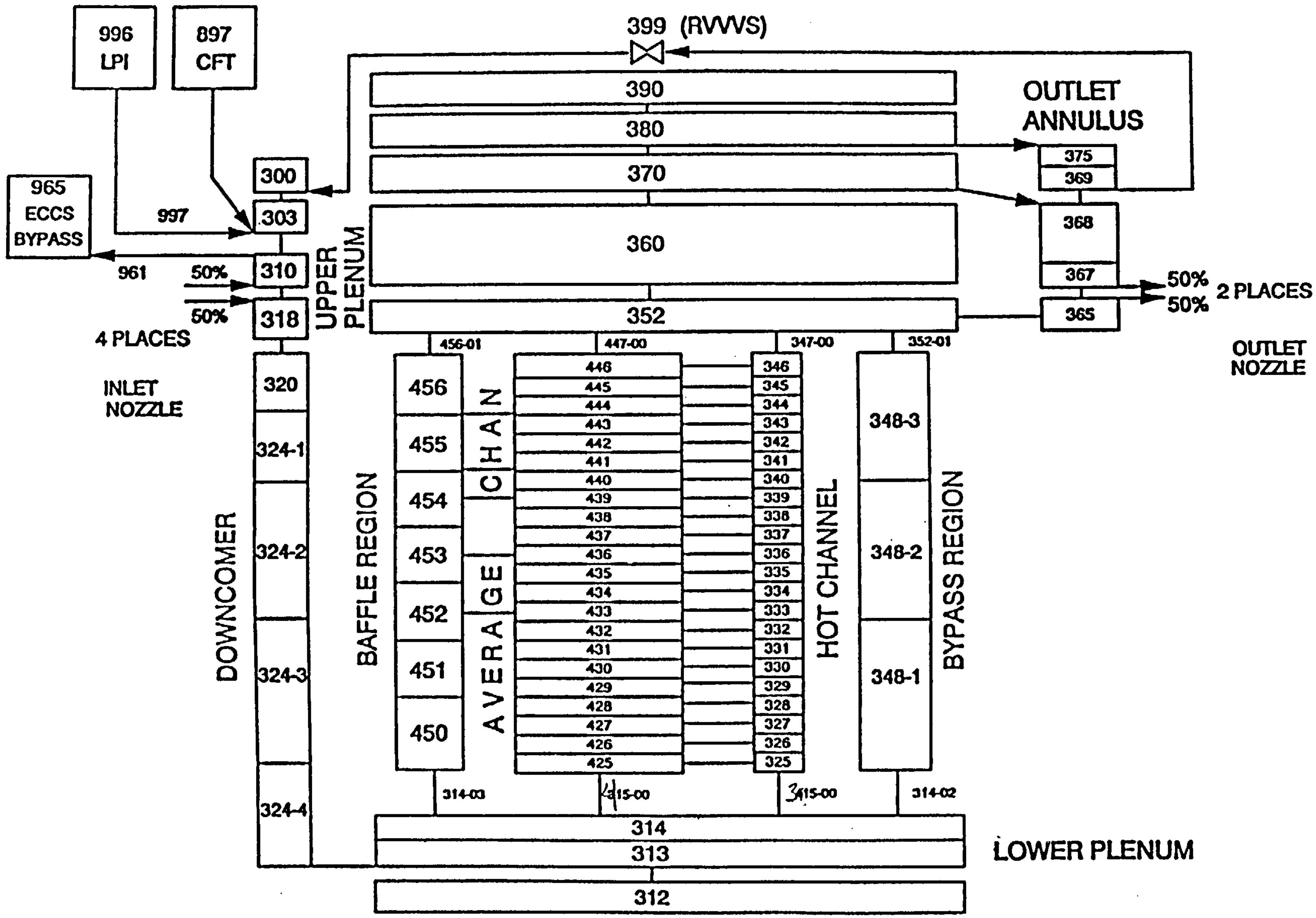


FIGURE 3 : Break, Upper Plenum and Steam Generator Temperatures for Hot Leg Break

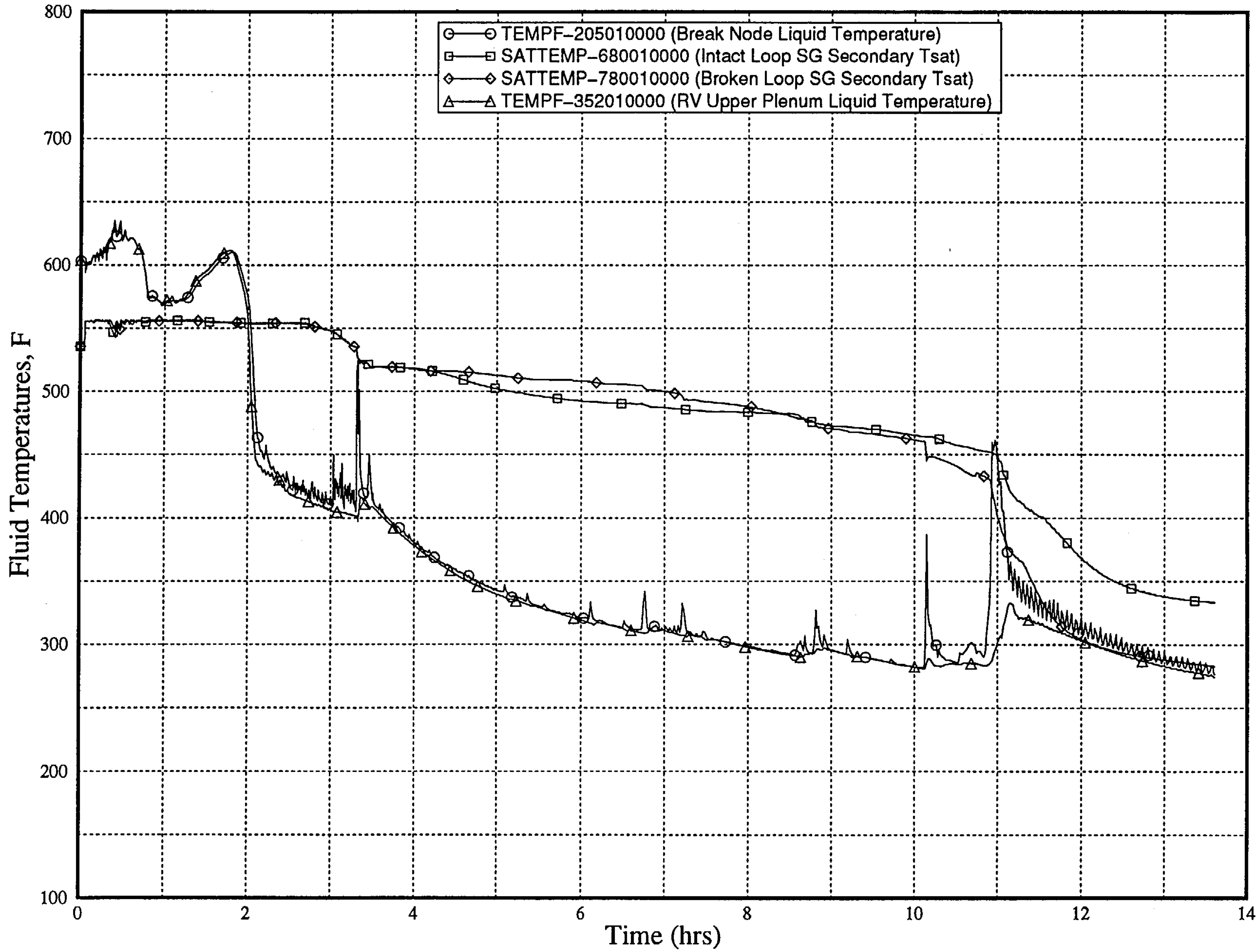


FIGURE 4 : System Temperatures for CLB that Did Not Initiate Natural Circulation

Break, RV Upper Plenum and Steam Generator Temperatures

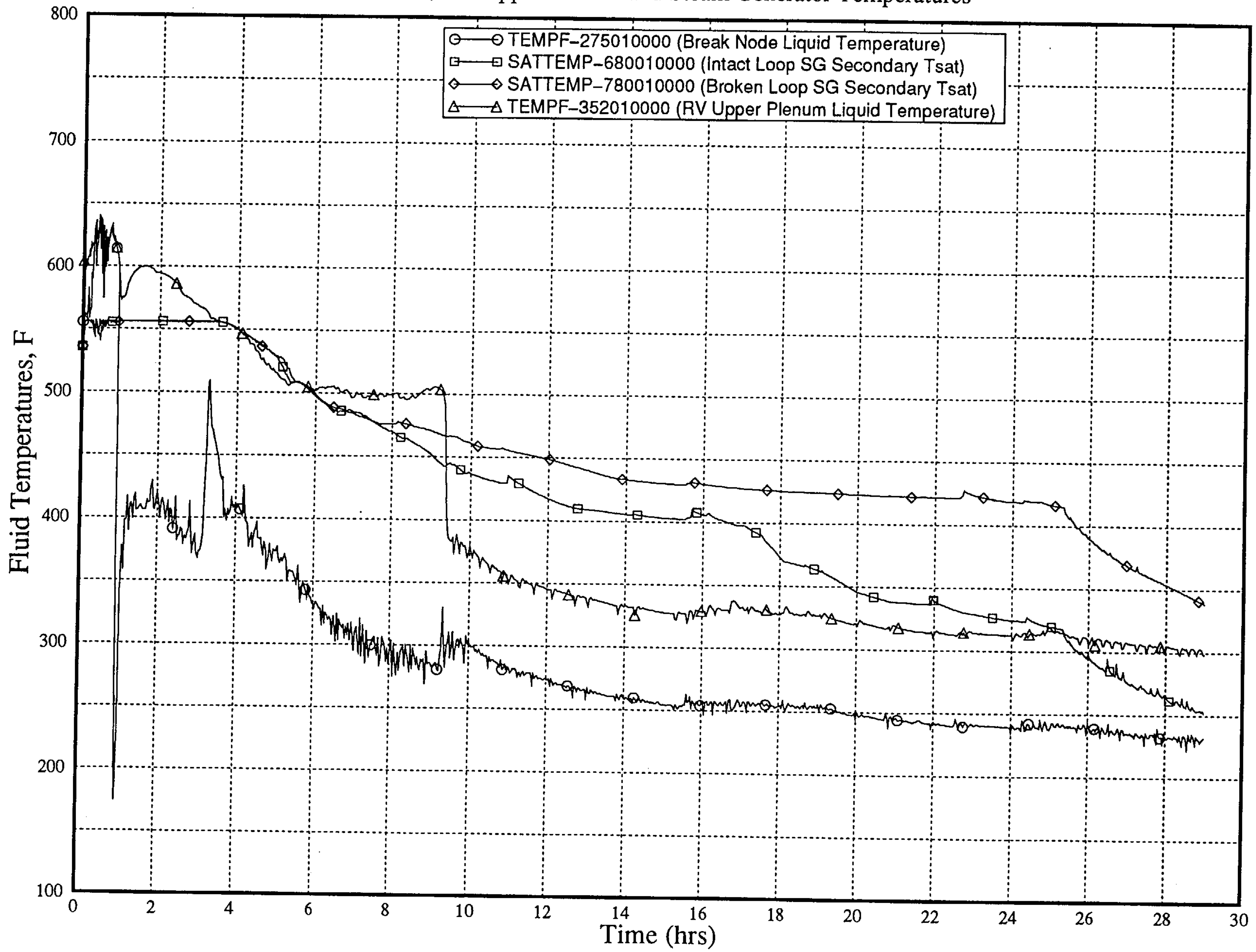


FIGURE 5 : Loop Flows for CLB that Did Not Initiate Natural Circulation

Intact Loop U–Bend, Broken Loop U–Bend, and Vent–Valves Flow Rates

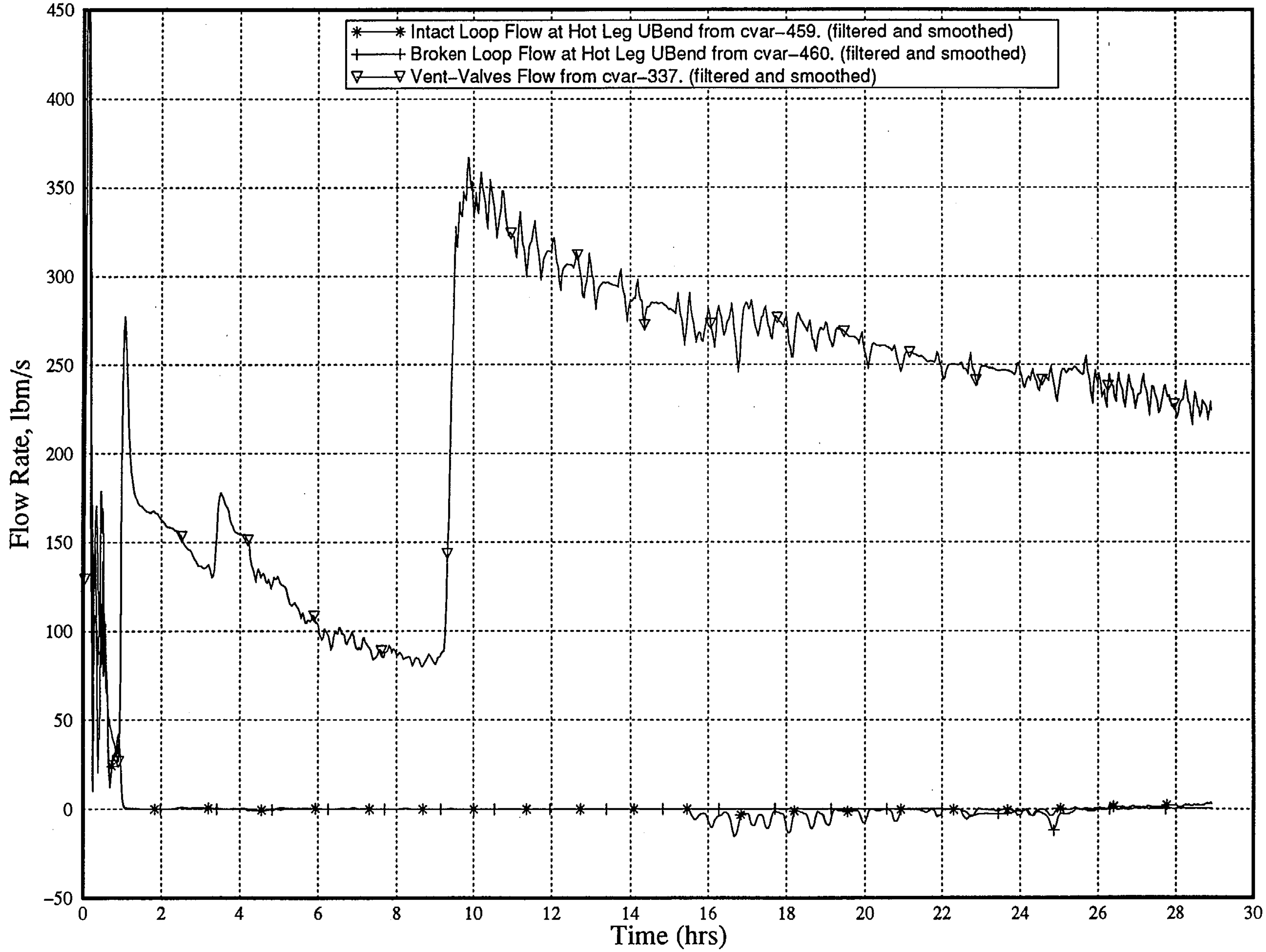


FIGURE 6 : System Temperatures for CLB that Did Initiate Natural Circulation

Break, RV Upper Plenum and Steam Generator Temperatures

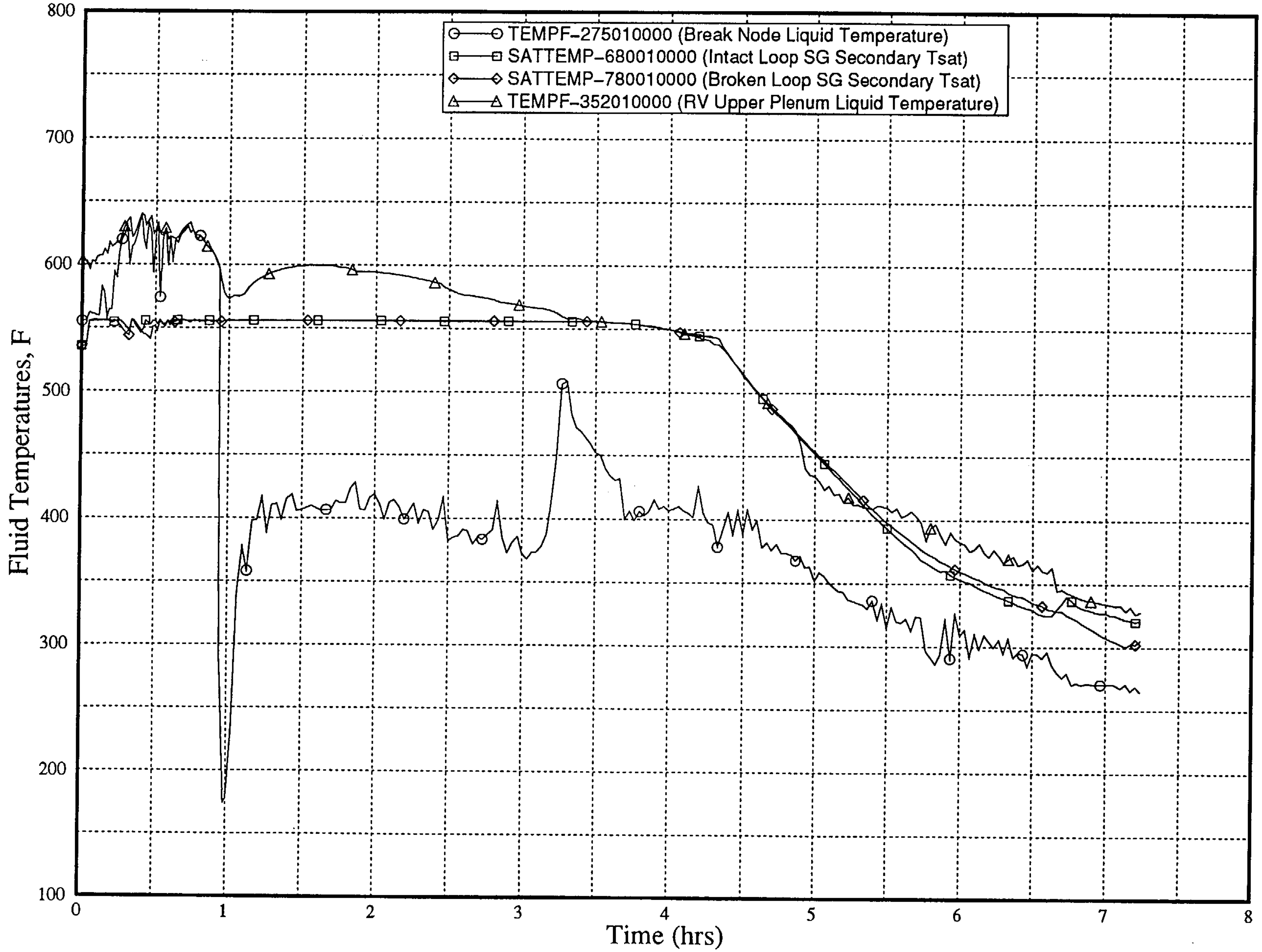
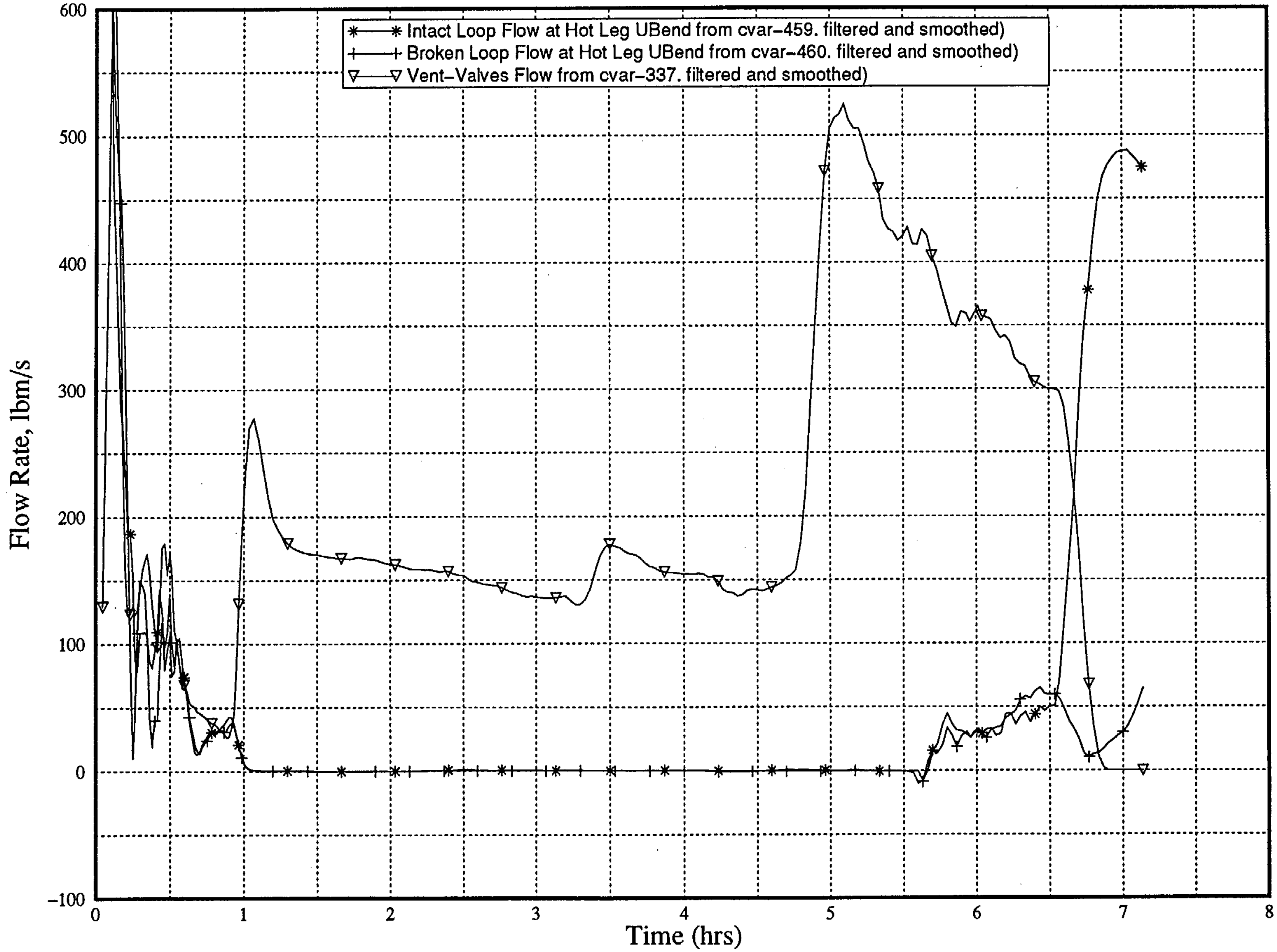


FIGURE 7 : Loop Flows for CLB that Did Initiate Natural Circulation

Intact Loop U–Bend, Broken Loop U–Bend, and Vent–Valves Flow Rates



Appendix A

Analysis of RELAP5/MOD2 Simulation of Long-Term Cooling

To determine the transient response and timing of system refill and possible restart of natural circulation, a series of RELAP5/MOD2 calculations were performed. Of particular interest was the vent valve performance as it evolved during the establishment of bulk loop circulation. The RELAP5 runs used to determine buildup of deborate within the RCS in Reference 3 were extended to simulate plant refill and the establishment of stable long-term cooling. The model is based on the RELAP5 SBLOCA lowered-loop evaluation model inputs, Figures 1 and 2, with some notable exceptions. The evaluations being conducted herein are to determine realistic expectations for plant behavior. Therefore, the decay heat correlation was adjusted to be best estimate and the ECCS was modeled at its full capability.

As the cases evolved, it was discovered that further modifications of the model were necessary. The first of these was the alteration of the HPI injection location to the first control volume downstream of the RC pump. At this location the injection is modeled about one and a half feet above its actual position. The alteration was necessary to facilitate the removal of steam trapped in the RC pump and immediate pump discharge volumes. Steam trapped in the upper portions of the pump discharge piping will be readily condensed because of the splash of the HPI stream against the wall of the RCS pipe as it is injected. RELAP5/MOD2, however, does not have the ability to simulate this occurrence where it would cross a node boundary. Raising the injection location slightly accomplishes the proper condensation simulation for the region. Additional model changes are described on a case-by-case basis. As described in the main, report the model, although specifically for a lowered loop plant, produced results that bound the Davis-Besse plant and can be applied directly with some degree of conservatism.

The cases analyzed comprise a hot leg break and five cold leg breaks. All breaks were 0.007 ft^2 in area. Progressive model improvements and more aggressive operator accident management were inserted into the simulations on a case by case basis. The first four cases did not induce bulk circulation within the RCS. In some of these, a complete refill was not achieved. Only the last combination of these, subsection A.6, was sufficiently aggressive to induce natural circulation.

A.1 Hot Leg Break, No Operator Action

Case Description and Phenomena:

A 0.007 ft^2 hot leg break at the 35-foot elevation was simulated with no operator action. The choice of break elevation, about eight feet above the pressurizer surge line but on the opposing loop, was arbitrary with a view to achieving a simple transient advancement. The simulation successfully executed through system refill and subsequent loop circulation. Refill took almost ten hours on the steam generator sides and about eleven hours on the hot leg sides. Refill was achieved without high point vents. Break flow was subcooled during refill and the vent valves were open with a slowly decaying flow of over 100 lbm/s. Sustained inter-cold leg circulation was evident during refill, as was a substantial subcooling of the pump suction piping. As a result of strong cold leg subcooling and reverse steam generator heat transfer, the steam generators filled faster than the hot legs and established a final RCS flow pattern with net flow through both the steam generators and the core to the break. For the conditions achieved, the deborate would not challenge core criticality because the backward flow in the generator swept most of it directly to the break. The reverse loop flow averaged about 17.5 lbm/s/loop over the first 40 minutes after refill, sufficient for all accumulated deborate to be displaced to the break. It is apparent that the homogeneous modeling of RELAP5/MOD2 accelerated condensation in the upper plant regions beyond what could be reasonably expected and shortened refill. However, the refill time remained within that achievable through high point vent operation and the conditions for high point vent opening were demonstrated. Therefore, the refill process and timing are reasonably modeled.

Parametric Histories and Discussion of Results:

Figure A.1.1 is a plot of system pressures. The primary pressure stabilized around 700 psia during refill while the secondary pressures steadily decreased due to sustained net reverse heat transfer in the steam generators. The secondary side pressures were stable at about 110 psia in the intact loop steam generator and about 50 psia in the broken loop steam generator.

Figures A.1.2 and A.1.3 show the intact loop and broken loop refills. The steam generator side refill time was about 10 hours and the hot leg side refill time was about 11 hours. The steam generator sides refilled faster than the hot leg sides because the steam generator side liquid temperatures were hotter (due to reverse steam generator heat transfer) than at comparable elevations on the hot leg sides. The steam generator heat transfer plot is shown in Figure A.1.4. Primary side liquid temperature distributions for the steam generator side, pump suction piping, and hot leg side of the intact loop are given in Figures A.1.5, A.1.6, and A.1.7, respectively. Similar plots for the broken loop are given in Figures A.1.8, A.1.9, and A.1.10, respectively. Liquid temperatures in the cold legs at the reactor vessel and downcomer, and lower and upper plenums are shown in Figures A.1.11 and A.1.12, respectively. These temperature distributions show that steam generator side liquid temperatures are hotter than corresponding elevation temperatures in the cold legs and hot legs. Figure A.1.12 also demonstrates the condition for high point vent opening, should it be needed, as the upper plenum subcooling was in excess of 100 F after about two hours into the transient.

Figures A.1.13 and A.1.14 show total ECCS and break flows, and break flow temperature, respectively. The break flow became subcooled shortly before 2 hours. At 11 hours, the break and the ECCS injection flows equilibrated, setting up a quasi-equilibrium condition.

Figures A.1.15, A.1.16, and A.1.17, respectively, show total vent valve flow, quality, and liquid temperature. The vent valve flow during refill is subcooled, gradually decreasing from 350 to about 150 lbm/s.

Figures A.1.18 and A.1.19 show steam generator plenum and cold leg flows for the intact loop and the broken loop, respectively. Inter-cold leg flow circulation, meaning flow in one leg being in the opposite direction of the flow in the other leg of the same loop, is evident. The steam generator refill flow is small in comparison to the cold leg circulation flows. Due to the slow refill rates and reverse steam generator heat transfer, the steam generator side liquid temperature column remains relatively hotter than the cold leg and hot leg side temperatures. Upon refill of the steam generator sides of the loops, there was a switch in the direction of the inter-cold leg circulation in the broken loop; the direction of inter-cold leg circulation in the intact loop did not change. However, both loops changed flow direction frequently once the hot leg side refilled. Although inter-cold leg circulation behavior is not well understood at this time, it is important to note that any such circulation would gradually remove the suction side deborate to the reactor vessel which is highly borated.

Figures A.1.20 and A.1.21 show the intact loop and the broken loop flows over the hot leg U-bends. A noticeable reverse flow of about 10 lbm/s began after the steam generator sides were filled. This occurred shortly after 10.5 hours. Significant reverse flow started after the hot legs were filled at around 11 hours. The flow increased from about 10 lbm/s to an average high of about 70 lbm/s and then dropped to an average of 10 lbm/s within 10 to 15 minutes. Roughly estimated, the total back flow was about 10*30*60 = 18000 lbm/loop before 11 hours and 0.5*(10+70)*10*60 = 24,000 lbm/loop in the next 10 minutes, giving a total of 42,000 lbm/loop. This displaces the accumulated deborate, about 40,000 lbm/loop as shown in Figure A.1.22, to the hot leg and the break. The reverse flow, thereafter, should bring in highly borated water to the hot legs.

Figure A.1.23 shows the flow in the lower plenum and in each of the hot leg pipes near the reactor vessel. The intact loop, shortly after refill at 10.5 hours, was negative indicating flushing of the deborate to the upper plenum. The lower plenum flow during the same period was positive indicating no net flow of the upper plenum deborate to the core except through the downcomer via the vent valves. The broken loop hot leg flow from the vessel was in the positive direction indicating flushing of the upper plenum deborate to the break. The deborate coming from the broken side U-bend goes out the break. In short, the backward flow in the generators would sweep most of the deborate directly or indirectly to the break. The deborate that found its way to the upper plenum would mix there and some could flow down the baffle region and then cross-flow to the core. However, due to subcooled core conditions, baffle flow would be small. The combination of the mixing of the deborate in the upper plenum before entering the baffle region and the small cross-flow that carries it to the core is not expected to challenge core criticality.

Figure A.1.24 is a plot of normalized core decay heat. It shows that the core power was about 0.75 percent of the initial power at the time of refill.

Key Results and Observations:

- Loop flows after refill were small with no bulk circulation.
- Break flow was subcooled and the vent-valves were open throughout the simulation, both during and after refill.
- Sustained inter-cold leg circulation was evident throughout the simulation.
- Core criticality was not challenged because the deborate was vented directly to the break.

A.2 Cold Leg Break at RV Inlet, No Operator Action, Downcomer Level Simulation Low

Case Description and Phenomena:

The case input was modified to shift the break location to the pump discharge piping at the reactor vessel inlet. As in the hot leg break, no operator action was simulated. The downcomer cold leg piping elevations from the SBLOCA evaluation model were preserved for this case. Those elevations cause RELAP5/MOD2 to simulate the downcomer liquid level at approximately the elevation of the bottom of the cold leg piping. This is acceptable, even desirable for EM calculations, but it does limit the ability of the model to achieve a proper simulation of a system refill calculation. Later cases made adjustments to the model to raise the downcomer level. The simulation executed beyond system refill. It took almost 20 hours to fill the hot legs. The steam generator primary side filled only to within four feet of the hot leg U-bend. The loop flow after refill was small, about 2 to 7 lbm/s in the normal direction. Break flow was subcooled through out the simulation. The vent valves were open and the flow was highly voided with a slow flow rate of about 15 lbm/s. The core continued steaming during and after refill resulting in two-phase vent valve flow and saturated hot leg temperatures. Therefore, the hot legs were refilled and the steam generator sides were not. Sustained inter-cold leg circulation was evident during refill, as was a substantial subcooling of the pump suction piping. For the conditions achieved, the deborate would not challenge core criticality due to the low loop flow rates and inter-cold leg circulation.

Noteworthy for this case is that substantial flow chattering was observed in the system. The chattering at the core inlet resulted in the heating of the lower plenum water and energy transfer propagated up the downcomer. This resulted from the lower downcomer level modeling and is considered an atypical plant response. The next case partially revised the elevation modeling and achieved results that are more realistic.

Parametric Histories and Discussion of Results:

System pressures are shown in Figure A.2.1. The primary pressure stabilized around 680 psia during and after refill, while secondary pressure steadily decreased due to a sustained net reverse heat transfer in steam generators. The secondary side pressures stabilized around 200 psia.

Figures A.2.2 and A.2.3 show the intact loop and broken loop refills. The hot legs refilled in about 20 hours and the steam generator sides did not refill. The hot leg refilled rather than the steam generator sides because of a core steaming that kept the hot leg temperatures warmer than those at the corresponding steam generator level. Figures A.2.4 and A.2.5, respectively, show total vent valve flow, vent valve quality, and vent valve and upper plenum void fractions. The plots show that the upper plenum and vent valve flows remain two-phase during refill. The vent valve flow gradually decreased during refill and was about 15 lbm/s post-refill.

Figures A.2.6, A.2.7, and A.2.8 show total ECCS and break flows, break flow quality, and break flow temperatures, respectively. The break flow became subcooled shortly after 2 hours and became more subcooled out to around 20 hour. Soon thereafter, the break and the ECCS injection flows remained roughly matched, establishing a quasi-equilibrium condition.

Figures A.2.9 and A.2.10 show cold leg flows for the intact and broken loops, respectively. Inter-cold leg flow circulation is evident. The circulation directions switched during refill but not after. In general, the broken leg flow remained in reverse direction. Although there are concerns on the reliability of this type of circulation, it would gradually remove the suction side deborate to the break or to the highly borated reactor vessel; thus reducing the amount of problematic accumulations.

Figure A.2.11 shows the intact and broken loop flows over the hot leg U-bends. The flow rates were less than 10 lbm/s, mostly 2 to 5 lbm/s. The deborate flow to the vessel is low and should not challenge core criticality.

Figure A.2.12 shows the core inlet flow and Figure A.2.13 shows the reactor vessel liquid temperature distribution in the downcomer and lower plenum. The core inlet flow chatter is representative of chatter seen at other locations in the system. Due to core inlet chatter, there is a net energy transfer to the lower plenum, heating it up unrealistically. The chattering suggests that the RELAP5 model may need to be adjusted for low power, slow flow simulations. The flow pattern shown near the end of refill and thereafter is not representative of the calculations due to plot point editing that was inappropriately phased with the intermediate flow oscillations calculated by RELAP5.

Figure A.2.14 is a plot of normalized core decay heat. It shows that the core power was about 0.63 percent of the initial power at the time of refill and out to about 20 hour into the transient.

Figure A.2.15 is a plot of deborate accumulation due to steam condensation in the steam generators.

Key Results and Observations:

- The case exhibited atypical flow and energy exchange between the core region and the downcomer.
- Prolonged inter-cold leg circulation was observed.
- The deborate did not challenge core criticality due to low loop flow rates and prolonged inter-cold leg circulation.

A.3 Cold Leg Break at RV Inlet, Mid-Level DC Stratification

Case Description and Phenomena:

The downcomer cold leg noding was modified to produce a transient downcomer liquid level near the middle of the cold leg nozzle. As discussed in the Section A.2, EM modeling produces nonphysical behavior during and after system refill. The adjustment was made by raising the cold leg node elevations such that the modeled elevations correspond to the plant physical elevations (the modeled elevation is slightly depressed in the EM model). The case was simulated with no operator action. The case was executed for 24 hours of transient simulation but only partial refill was achieved. The refill process started at about 4 hours but the levels stagnated just above the steam generator upper tube sheet elevation at 20 hours. The stagnation is attributed to the model not containing a provision for atmospheric pipe heat losses. Steam in the upper regions of the loop has no condensing mechanism other than mixing with the nodal liquid. If the system inventory stagnates, when a level is at or near a node crossing or the nodal liquid becomes saturated, the RELAP5/MOD2 simulation lacks surface condensation potential to remove trapped steam. The potential for such a result was present in the previous cases but not realized. The break flow was subcooled during refill and stagnation, and after stagnation it remained matched to the ECCS injection. The còre was steaming during refill and stagnation resulting in a two-phase flow through the vent valves. Vent valve flow was voided with a moderate flow rate of about 35 lbm/s. Reflecting the alteration of the downcomer level, this flow is about twice that achieved in case A.2. Sustained inter-cold leg circulation was evident during refilling, as was a substantial subcooling of the pump suction piping. For the conditions achieved, the deborate did not challenge core criticality because the deborate in the steam generators could not move due to stagnation. Substantial deborate was dissipated by inter-cold leg circulation. Had a refill occurred, deborate behavior similar to that of case A.2 would have removed any potential for a core criticality excursion.

Parametric Histories and Discussion of Results:

Figure A.3.1 shows a plot of system pressures. The primary pressure stabilized around 680 psia during refilling and stagnation. The secondary side pressures were about 250 to 310 psia at the end of the run.

Figures A.3.2 and A.3.3 show the intact loop and broken loop liquid levels. The hot leg and steam generator side levels stagnated at about 8 to 11 feet below the hot leg U-bend spillover elevation. Figures A.3.4 and A.3.5, respectively, show total vent valve flow, and vent valve quality and vent valve and upper plenum void fractions. The plots show that the upper plenum and vent valve flows remain two-phase during refill and stagnation. The vent valve flow gradually decreased and stabilized at 35 lbm/s.

Figures A.3.6, A.3.7, and A.3.8 show total ECCS and break flows, break flow quality, and break flow temperatures, respectively. The break flow became subcooled shortly after one hour and remained so for the rest of the transient, increasingly becoming more subcooled. The break and ECCS injection flows remained roughly matched after about 10 hours, setting a quasi-equilibrium or stagnation condition.

Figures A.3.9 and A.3.10 show cold leg flows for the intact and broken loops, respectively. The inter-cold leg flow circulation is evident. The circulation directions remained stable after about one hour.

Figure A.3.11 shows the intact and broken loop flows over the hot leg U-bends. The flow rates were almost nil during refilling. Hence, the deborate should not challenge core criticality as long as stagnation persists.

Figure A.3.12 shows the core inlet flow and Figure A.3.13 shows the reactor vessel liquid temperature distribution in the downcomer and lower plenum. The upper downcomer temperature is slightly higher due to mixing and condensation of vent valve two-phase flow.

Figure A.3.14 is a plot of normalized core decay heat. It shows that the core power was about 0.61 percent of the initial power at the end of the case, 24 hours into the transient.

Figure A.3.15 is a plot of deborate accumulation due to steam condensation in the steam generators.

Key Results and Observations:

- The case did not achieve a refill after 24 hours.
- Break flow remained subcooled during refill.
- Core steaming persisted during and after the partial refill.
- The vent-valves were open continuously throughout the run.
- Inter-cold leg circulation persisted throughout the run.
- The deborate did not challenge core criticality.

A.4 Cold Leg break at RV Inlet, Refill with HPV Operation

Case Description and Phenomena:

To induce loop refill, the previous cold leg break case was modified to include an operator action to open high point vents (HPV) at ten hours into the transient. The HPVs were kept opened for about 45 minutes, with a steam escape rate of about 1.3 lbm/s, and then closed. The case was run to 20 hours.

The broken loop refilled first after about 11 hours and a slow circulation was established in the normal flow direction until about 12 hours. After flow reversals, the flow dropped to near zero at 13.5 hours. The circulation between 11 and 12 hours was sufficient to displace the entire broken loop deborate. Vent valve flow was continuous at about 40 lbm/s. The displaced deborate would be borated in the upper downcomer by the vent valves. Parts of the mixed deborate would discharge out the break.

The intact loop refilled by 13.5 hours. Flow, however, remained small or near zero except for several flow spikes at 14 and 15.5 hours. Only about 40 percent of the deborate in the intact loop would be displaced by the conditions achieved. Inter-cold leg circulation, frequently oscillating after about 12 hours, would mix any remaining deborate.

The break flow remained subcooled during and after refill. It roughly matched the ECCS injection flow rate after 13 hours. The core was steaming during and subsequent to refill. The upper plenum was 5 percent voided after 12 hours.

Parametric Histories and Discussion of Results:

Figure A.4.1 shows a plot of system pressures. The primary pressure stabilized around 680 psia during loop circulation. The secondary side pressure was about 300 psia and gradually decreased at the end of the run, 20 hours.

Figures A.4.2 and A.4.3 show the intact and broken loop liquid levels. The broken loop hot leg was liquid full by about 11 hours and the intact loop in about 13.5 hours. The steam generator side levels mostly remained about one foot below the U-bends. However, for up to an hour after the hot leg refilled, the broken loop steam generator side was also liquid full. Figures A.4.4 and A.4.5, respectively, show total vent valve flow, and vent valve quality and vent valve and upper plenum void fraction. The plots show that the upper plenum and vent valve flows remain two-phase during refill and loop circulation. The vent valve flow gradually decreases during refill and stabilized to about 35 to 40 lbm/s during loop flow.

Figures A.4.6, A.4.7, and A.4.8 show total ECCS and break flows, break flow quality, and break flow temperatures, respectively. The break flow became subcooled shortly after one hour and remained so for the rest of the transient, increasingly becoming more subcooled. The break and ECCS injection flows remained roughly matched after about 12 hours. The break flow, however, was highly oscillatory due to oscillatory inter-cold leg circulation.

Figures A.4.9 and A.4.10, respectively, show the cold leg flows for both loops. The inter-cold leg flow circulation is evident. In the intact loop circulation direction switches at 10 and 11 hours and becomes quite oscillatory after 12 hours. The broken loop simulates this behavior but does not achieve the switch at 11 hours and while the magnitude of flow oscillates after 12 hours the directing is stable.

Figure A.4.11 shows the intact and broken loop flows over the hot leg U-bends. The broken loop refilled first after about 11 hours and flow was established in the normal (forward) direction in the U-bend. The flow quickly rose to about 80 lbm/s, gradually decreasing to about 17 lbm/s after 11.5 hours. The flow reversed shortly after 12 hours, returned to the forward direction after 12.5 hours, and finally dropped to near zero after 13.5 hours. The circulation was sufficient to displace all 46,000 lbm of the broken loop deborate in less than 40 minutes. The displaced deborate would mix with the highly borated HPI injection in the pump discharge piping and the reactor vessel water in the nozzle belt region. Parts of the mixed deborate discharge out the break. The intact loop hot leg refilled by 13.5 hours. The system flow, however, was small or near zero except for spikes of about 60 lbm/s and 30 lbm/s at 14 and 15.5 hours, respectively. This would displace about 40 percent of the 48,600 lbm of deborate in the intact loop. The inter-cold leg circulation should displace most, if not all, of the remaining deborate.

Figure A.4.12 shows the core inlet flow and Figure A.4.13 shows the reactor vessel liquid temperature distribution in the downcomer and lower plenum. The upper nozzle belt temperature is slightly higher due to mixing and condensation of vent valve two-phase flow.

Figure A.4.14 is a plot of normalized core decay heat. It shows that the core power was about 0.63 percent of the initial power at the end of the case, 20 hours.

Figure A.4.15 is a plot of deborate accumulation due to steam condensation in the steam generators.

Key Results and Observations:

- The break flow remained subcooled during and after refill.
- The core was steaming throughout the run. The upper plenum was 5 percent voided after 12 hours.
- The vent valves were open throughout the run.
- Inter-cold leg circulation persisted throughout the run.
- The deborate does not challenge core criticality.

A.5 Cold Leg Break at RV Inlet, SG Blowdown after Refill, High DC Stratification Level

Case Description and Phenomena:

Although the transient downcomer level in the previous analyses had been increased to the middle of the cold leg nozzles, at that height it remained unrealistically low compared to the liquid levels in the cold legs. To better represent the downcomer liquid level, the node elevations for the downcomer nozzle belt nodes and the cold leg pump discharge nodes were increased to provide a downcomer level within a few inches of the top of the cold leg piping. To limit the possibility that the inter-cold leg circulation was being driven by injection of the HPI high in the pump discharge volume, the HPI injection level was shifted to the design location after cold leg refill. In an attempt to induce natural circulation, an operator action was invoked to slowly blowdown the steam generators after loop refill. The operator action was credited at about 25.3 hours into the transient. Both the steam generators were blown down at a rate of about 20 F/hr. The case was run to 29 hours.

The case successfully ran through system refill and subsequent loop circulation. It took almost 16 hours to fill the intact loop and about 22.5 to 25 hours to fill the broken loop. In both cases steam generator sides refilled before the hot leg sides. Loop circulation flows, after refill, were small (about 3 to 6 lbm/s) and in the reverse direction. With the operator action at 25.3 hours to blowdown the steam generators, loop flow adjusted to the normal direction. By 29 hours, the intact loop flow was about 3 lbm/s and slowly increasing. The broken loop flow was about 0.5 lbm/s and steady. After the operator action, secondary side cooling led the primary in the steam generator regions. However, the secondary did not cool sufficiently to become a major energy sink and natural circulation had not started by the end of the run.

Due to the higher downcomer stratification level, the intra-vessel flow circulation improved resulting in a subcooled core. The upper plenum, vent valve region was subcooled after about 11.5 hours. The upper head filled just before 13 hours with a subcooling of over 100 to 150 F thereafter. The vent valves were open during loop refill and steam generator blowdown. Once the vent valve region was subcooled, the vent valve flow increased to about 350 lbm/s and then slowly decreased to about 225 lbm/s by 29 hours.

Inter-cold leg circulation was evident in both the loops during the time when the upper plenum was two-phase. Circulation in the intact loop was suppressed after approximately 6 hours. Broken loop inter-cold leg circulation, however, remained active.

Parametric Histories and Discussion of Results:

Figure A.5.1 shows a plot of system pressures. The primary pressure stabilizes around 670 psia while secondary pressures decrease steadily to about 90 psia for the intact loop and 290 psia for the broken loop before operator action is taken at 25.3 hours. After that, the secondary side pressure decreased rapidly to 30 psia in the intact loop and 115 psia in the broken loop.

Figures A.5.2 and A.5.3 show the intact and broken loop refills. In both loops, the steam generators fill before the hot legs. It takes about 14.5 to 16.7 hours to fill the intact loop and about 22.5 to 25 hours to fill the broken loop.

Figures A.5.4 and A.5.5 show the total vent valve flow, the vent valve quality, and the vent valve and upper plenum void fractions. The plots show that the upper plenum and vent valve flows were liquid-only (subcooled) halfway through refill. Once the vent valve region becomes subcooled, at about 11.7 hours, the vent valve flow increases to about 350 lbm/s and then slowly decreases to about 225 lbm/s by 29 hours.

Figures A.5.6, A.5.7, and A.5.8 show total ECCS and break flows, break flow quality, and break flow temperature. The break flow becomes subcooled shortly before an hour and highly subcooled for the remainder of the transient. The break flow and the ECCS injection flow remain closely matched after about 19.5 hours.

Figures A.5.9 and A.5.10 show cold leg flows for the intact and broken loops. Inter-cold leg circulation is evident. Inter-cold leg circulation gradually removes the suction side deborate to the break or to the highly borated reactor vessel, thus, reducing the amount of deborate.

Figure A.5.11 shows the intact and broken loop flows over the hot leg U-bend. The loop flows, after refill, are small (about 3 to 6 lbm/s) and in the reverse direction. However, with operator action at 25.3 hours to slowly blowdown the steam generators, the loop flows readjust and start flowing in the normal direction. By 29 hours, the intact loop flow is about 3 lbm/s and slowly increasing; the broken loop flow is about 0.5 lbm/s and steady. Before operator action, the steam generators are cooled by the primary. However, after operator action, secondary side cooling leads the primary, resulting in a primary column cold enough to change loop flow to the normal direction.

The Figure A.5.12 shows the core inlet flow, and Figure A.5.13 shows the reactor vessel liquid temperature distribution in the downcomer and lower plenum. The whole inner vessel becomes subcooled after about 10 hours.

Figure A.5.14 is a plot of normalized core decay heat. It shows that the core power is about 0.8 percent when the inner vessel becomes subcooled and about 0.6 percent at the end of the transient.

Figure A.5.15 is a plot of deborate generation due to condensation in the steam generators.

Key Results and Observations:

- The high stratification in the downcomer resulted in a subcooled upper vessel and a substantial increase in vent valve flow after RV refill. The vent valves remained open after RCS refill with a flow rate of approximately 225 to 250 lbm/s.

- The case executed through system refill and subsequent low-level loop circulation but did not restart natural circulation.

- Break flow was subcooled during and after refill.
- The deborate did not pose a challenge to core criticality.

A.6 Cold Leg Break at RV Inlet, Operator Intervention (HPV Opening, SG Blowdown)

Case Description and Phenomena:

The previous case of late operator action was replaced by an earlier intervention to simultaneously open the high point vents and initiate steam generator blowdown at 4.3 hours. This case is of particular importance because it resulted in a restart of natural circulation and the closure of vent valves. As in the previous case, downcomer and cold leg noding elevations were set to provide a reasonable representation of the downcomer liquid level. HPI injection level was similarly shifted to the design location after cold leg refill. The case was run to over 7 hours. Steam generator blowdown was fixed at a steam flow of 5 lbm/s/generator. This resulted in a cooldown rate of about 120 F/hr that slowed gradually to around 50 F/hr. Two hours after initiation of operator action the core exit to steam generator temperature difference was about 25 F, less than the operation guidelines of 50 to 100 F. The existing operator action guidelines suggest opening of the PORV followed by steam generator blowdown before HPVs are opened. However, for analysis convenience, the PORV was not opened. Timing of the operator action was chosen based on existing plant operation guidelines.

The upper plenum and vent valve region became subcooled by about 5 hours, shortly after the beginning of operator actions. The upper head refilled about an hour later. When the upper plenum became subcooled, the vent valves flow increased from about 150 lbm/s to about 500 lbm/s. The flow then gradually decreased to 300 lbm/s by about 6.5 hours when the vent valves closed rapidly.

Both the loops refilled by around 5.75 hours, about 1.5 hours after the initiation of operator intervention. The hot legs filled slightly ahead of the steam generators. Loop circulation was established in the normal flow direction at about 25 to 50 lbm/s before the beginning of vent valve closure. As the vent valves started closing, the intact loop flow increased to more than 450 lbm/s. Circulation was sufficient to displace all the system deborate to the downcomer within 25 minutes after loop refill. The displaced deborate would mix with the highly borated flow from the vent valves in the downcomer nozzle belt region. Some portion of the deborate would also be discharged out the break.

The operator actions resulted in a moderate degree of primary and secondary cooldown and initiation of natural circulation. Displacement of the deborate occurred safely before the vent valves closed. The deborate does not challenge core criticality. The time margin available after the refill to displace the deborate and before the vent valve closure was a factor of two. If operator action was more aggressive, in keeping with existing guidelines, there would still be sufficient time to dispose of the deborate before the vent valves closed.

Parametric Histories and Discussion of Results:

Figure A.6.1 provides a plot of system pressures. The primary pressure dips below the core flood tank actuation pressure briefly during refill before stabilizing around 600 psia. The secondary side pressure steadily decreases to about 90 psia in the intact loop and to about 75 psia in the broken loop at the end of the transient, about 7.25 hours.

Figures A.6.2 and A.6.3 show intact and broken loop refills. Both loops fill by about 5.75 hours, the steam generators filled at approximately the same time as the hot legs.

Figures A.6.4 and A.6.5 show total vent valve flow, vent valve quality, and vent valve and upper plenum void fractions. The plots show that the upper plenum and vent valve flows are liquid-only (subcooled) by 5 hours. The upper head becomes solid shortly before 6 hours. After becoming subcooled, the vent valve flow increases to over 500 lbm/s and then slowly decreases to about 300 lbm/s at 6.5 hours, just before the valves close.

Figures A.6.6, A.6.7, and A.6.8 show the total ECCS and break flows, break flow quality, and break flow temperature. The break flow becomes subcooled shortly before an hour and continues to be subcooled for the remainder of the transient. The break and the ECCS injection flows remain stable after about 6.6 hours, differing only by an amount equal to the high point vent discharge.

Figures A.6.9 and A.6.10 show cold leg flows for the intact and broken loops. Inter-cold leg circulation is evident after about 3.1 hours.

Figure A.6.11 shows the intact and broken loop flows over the hot leg U-bends along with the total vent valve flow. Natural circulation begins at about 5.75 hours with a moderate flow of about 25 lbm/s/loop, gradually increasing to about 50 lbm/s at 6.5 hours. As the vent valves close, the intact loop flow rapidly increases to around 450 lbm/s. The broken loop flow decreases at first but is starts to increase at transient termination. Once the loop is refilled, natural circulation is strong enough to displace the deborate in 25 minutes, well before vent valve closure. The deborate will mix with HPI injection at the pump discharge and with the vent valve flow in the downcomer nozzle belt region. Some of the deborate will discharge out the break.

The Figure A.6.12 shows the core inlet flow, and Figure A.6.13 shows the reactor vessel liquid temperature distribution in the downcomer and lower plenum. The inner vessel becomes subcooled after about an hour, even before operator intervention.

Figure A.6.14 is a plot of normalized core decay heat. It shows that the core power was about 1.0 percent when operator action was initiated, 4.3 hours, and about 0.9 percent by the end of the transient, 7 hours.

Figure A.6.15 is a plot of deborate generation from condensation in the steam generators.

Figure A.6.16 is a plot of reactor vessel upper plenum liquid temperature at the core exit and steam generator temperature. Between the initiation of circulation and the start of vent valve closure, 5.5 to 6.5 hours, the core exit-to-steam generator temperature differential varies from 19 to 28 F.

Key Results and Observations:

- Steam generator cooldown stabilized at about 50 F/hr. The core exit to steam generator temperature difference was maintained at about 25 F.

- The upper plenum and vent valve region became subcooled by about 5 hours. Vent valve flow was about 500 lbm/s decreasing to 300 lbm/s just prior to valve closure.

- Both loops refilled. Before the vent valves begin to close, loop circulation was established in the normal direction at about 25 to 50 lbm/s. Circulation was sufficient to displace all the system deborate in about 25 minutes. The amount of time available for mixing prior to vent valve closure was about 50 minutes. Therefore, the deborate will not challenge core criticality.

- Inter-cold leg circulation continued through system refill but stopped when full natural circulation commenced at about 7 hours.

FIGURE A.1.1 : 0.007 ft^2 Hot Leg Break.

System Pressures

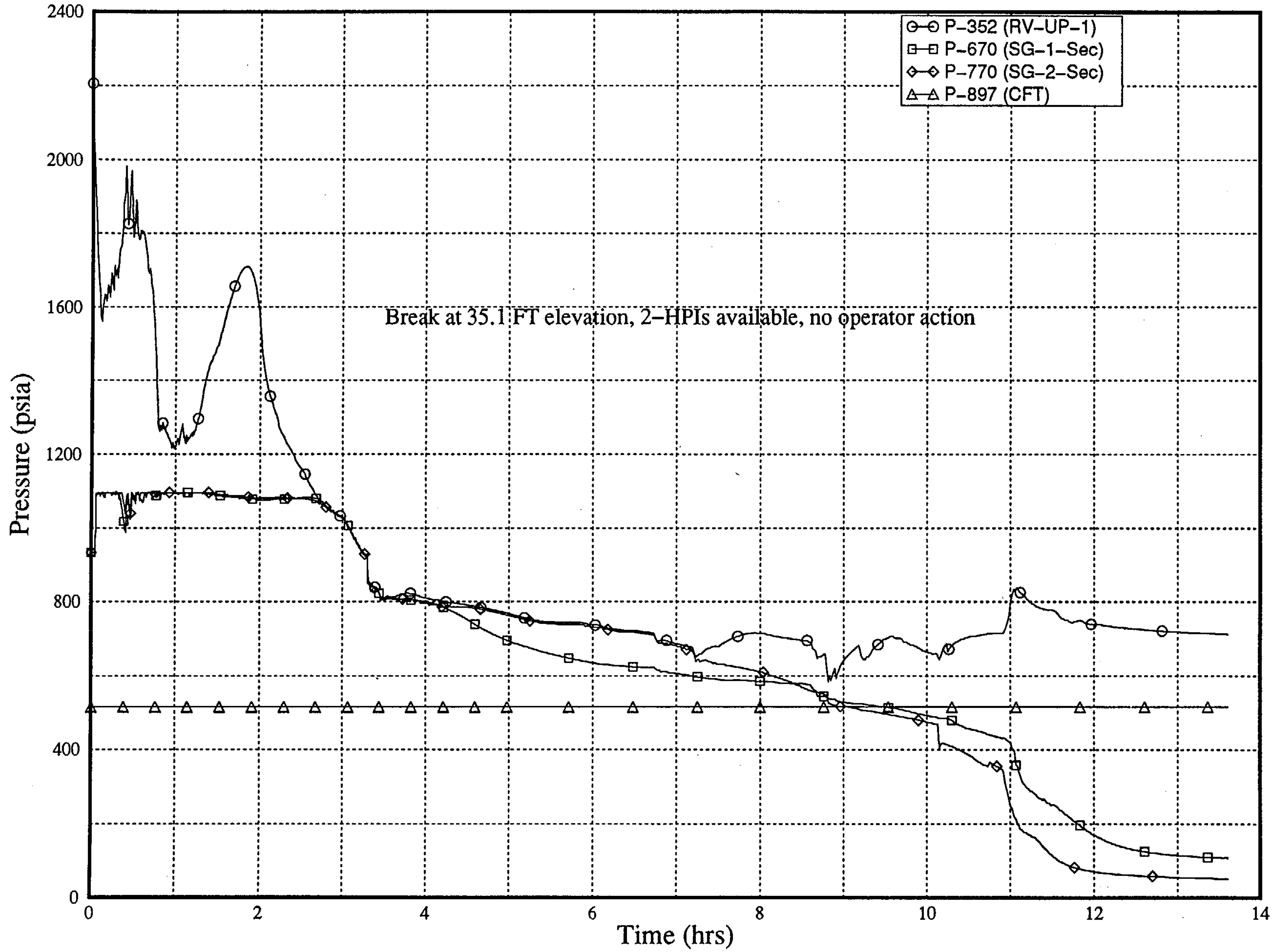


FIGURE A.1.2 : 0.007 ft² Hot Leg Break.

Intact Loop Collapsed Liquid Elevations

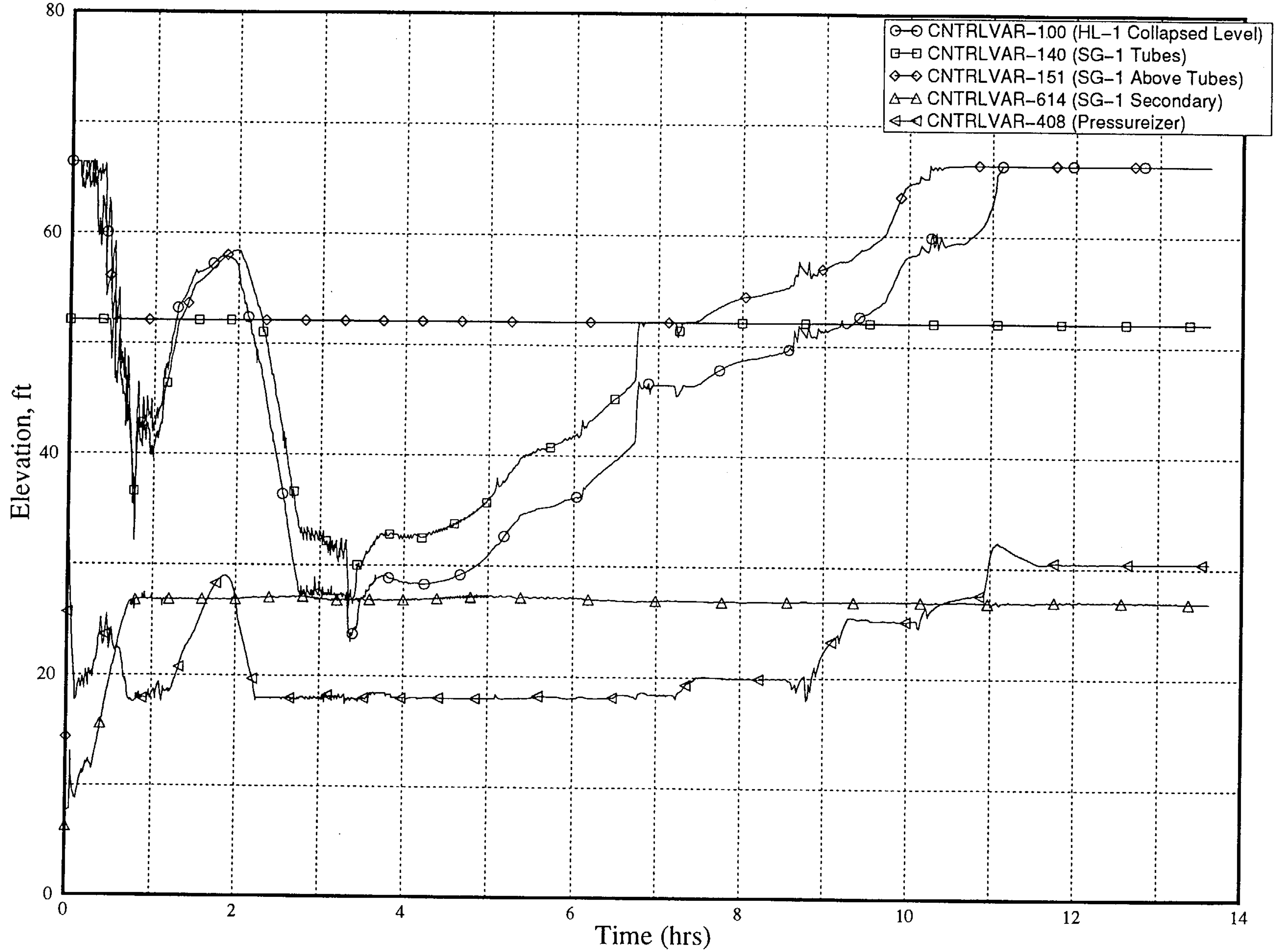


FIGURE A.1.3 : 0.007 ft^2 Hot Leg Break.

Broken Loop Collapsed Liquid Elevations

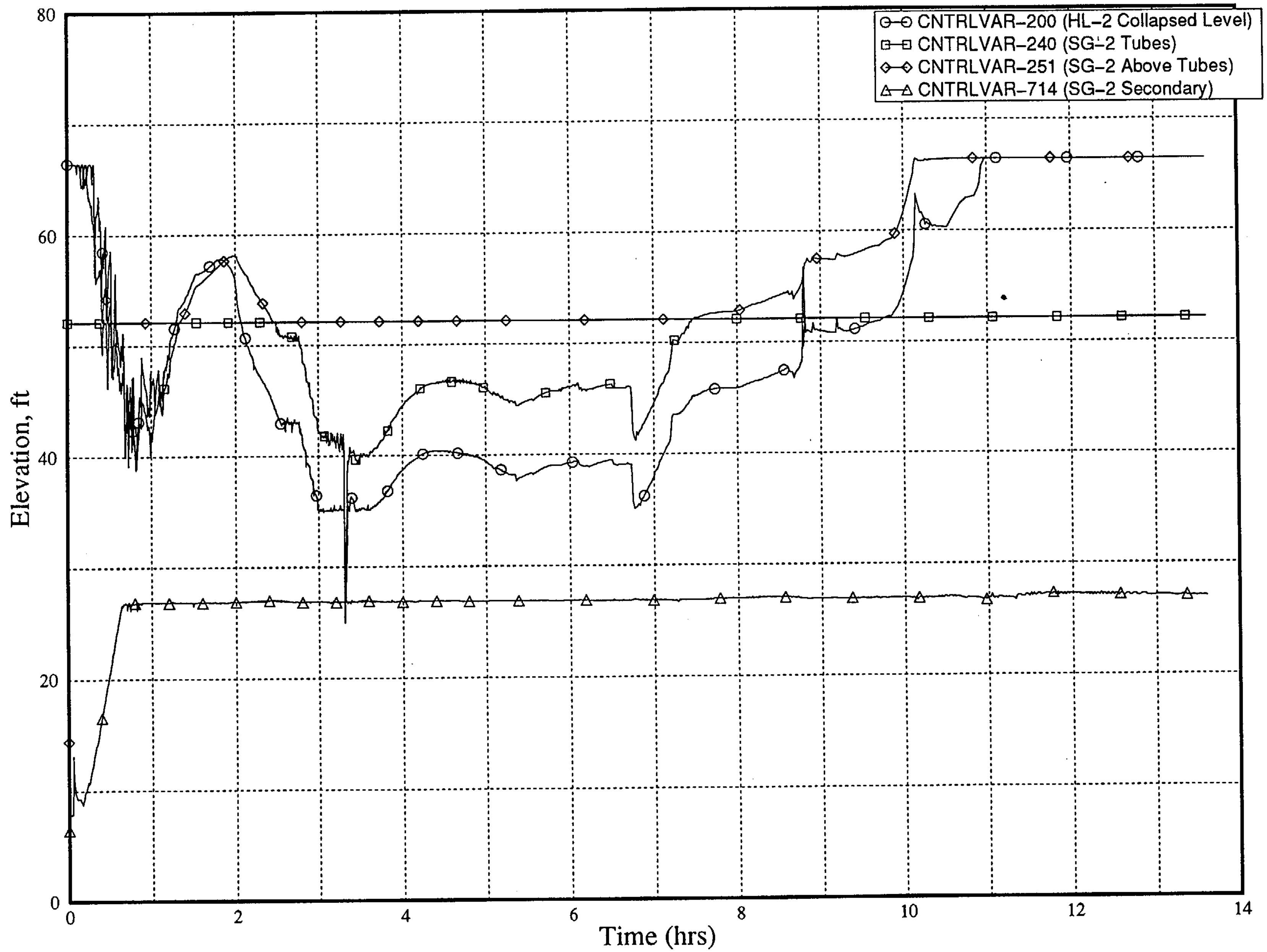


FIGURE A.1.4 : 0.007 ft^2 Hot Leg Break.

Steam Generator Heat Transfer

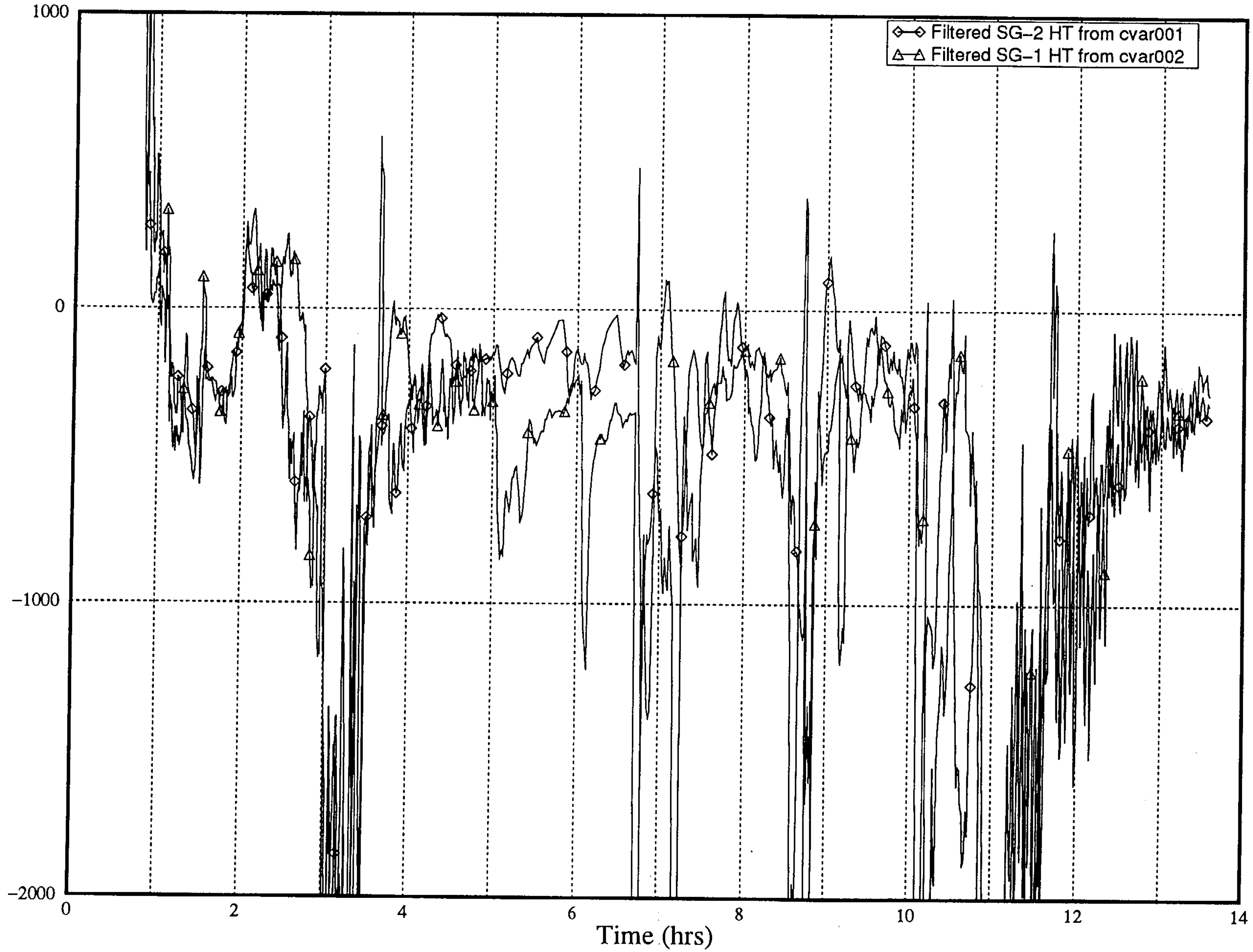


FIGURE A.1.5 : 0.007 ft² Hot Leg Break.

Intact Loop SG–side Liquid Temperatures

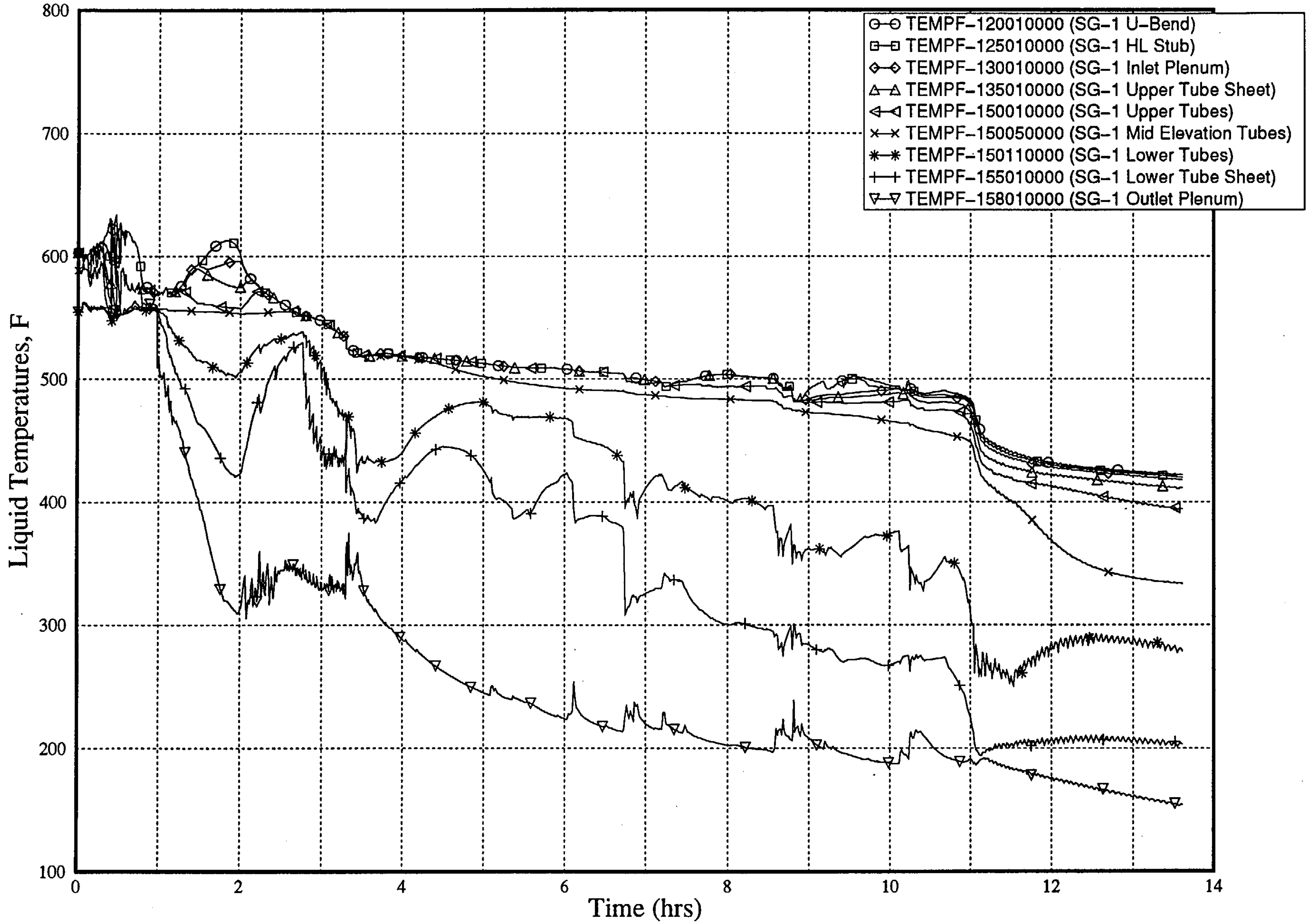


FIGURE A.1.6 : 0.007 ft^2 Hot Leg Break.

Intact Loop SG OP and Pump Suction Liquid Temperatures

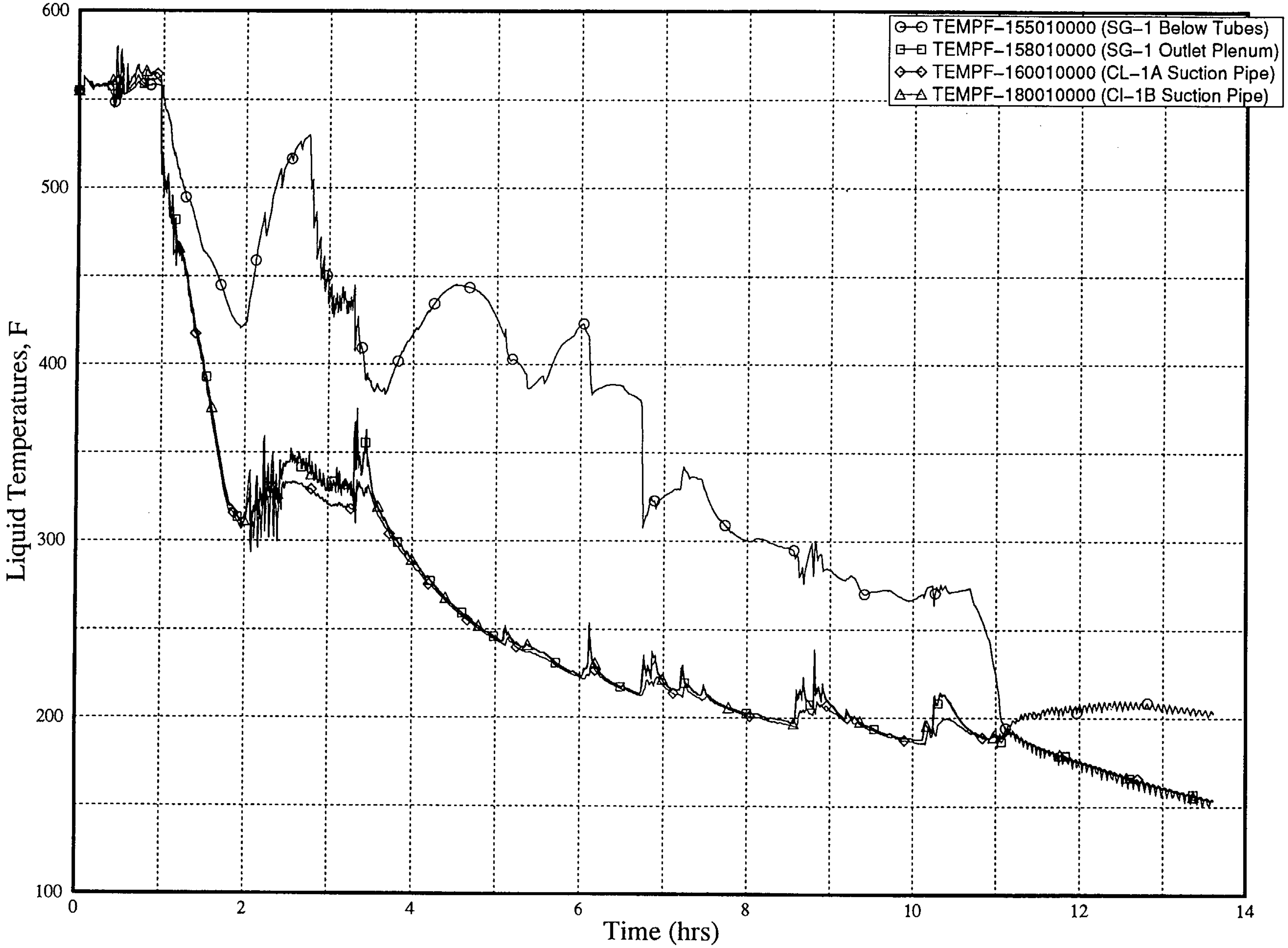


FIGURE A.1.7 : 0.007 ft^2 Hot Leg Break.

Intact Loop Hot Leg Temperatures

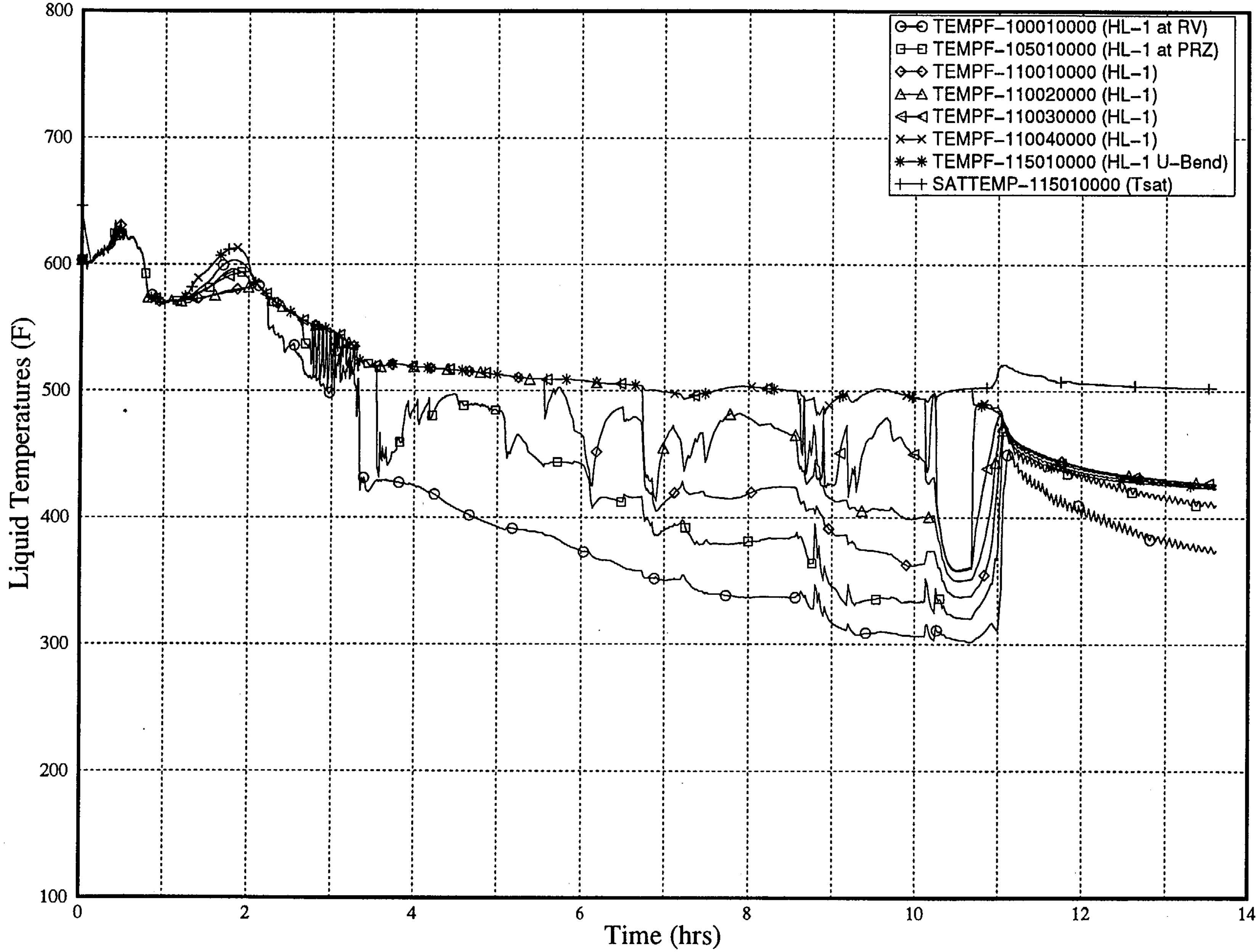


FIGURE A.1.8 : 0.007 ft^2 Hot Leg Break.

Broken Loop SG–Side Liquid Temperatures

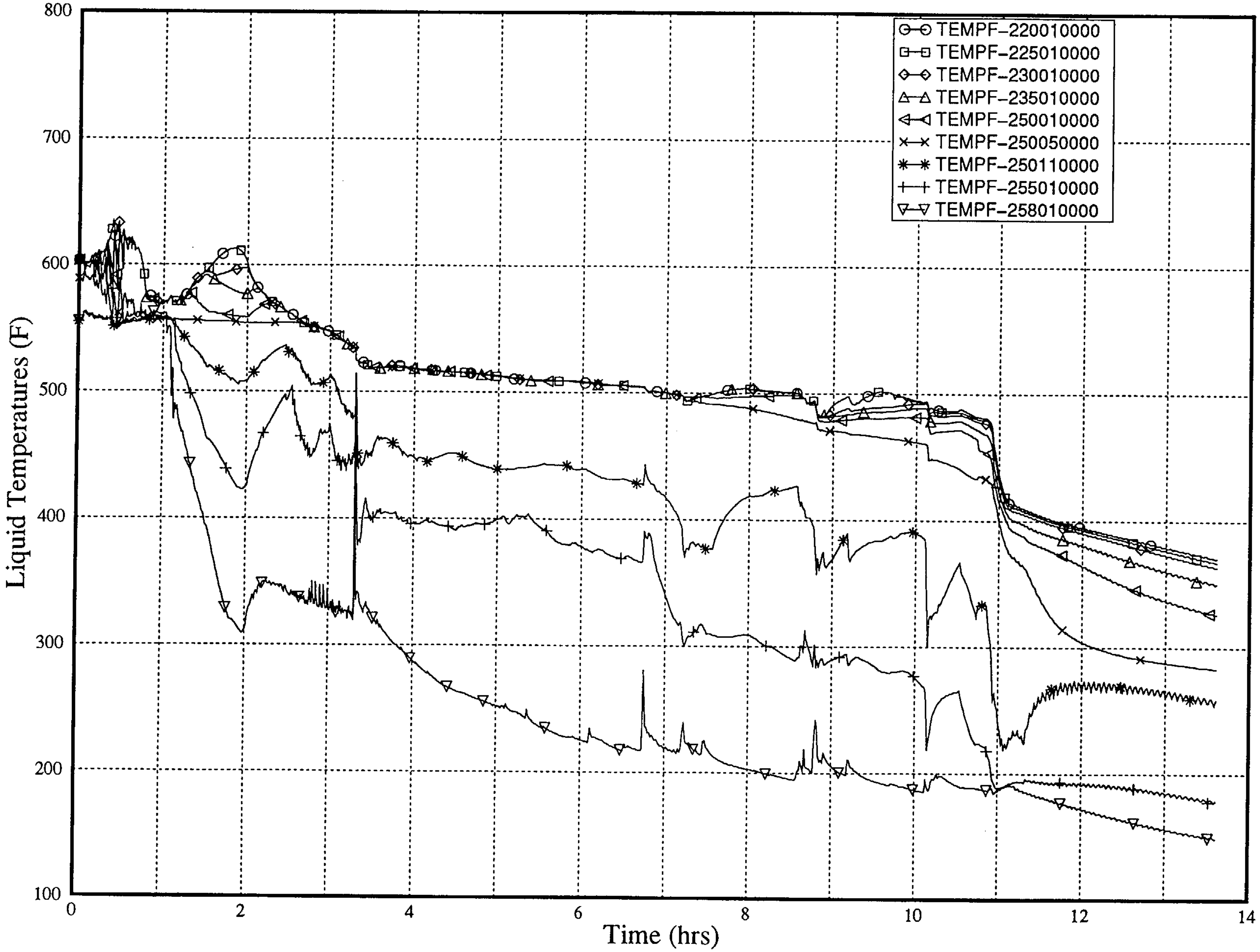


FIGURE A.1.9 : 0.007 ft^2 Hot Leg Break.

Broken Loop SG OP and Pump Suction Liquid Temperatures

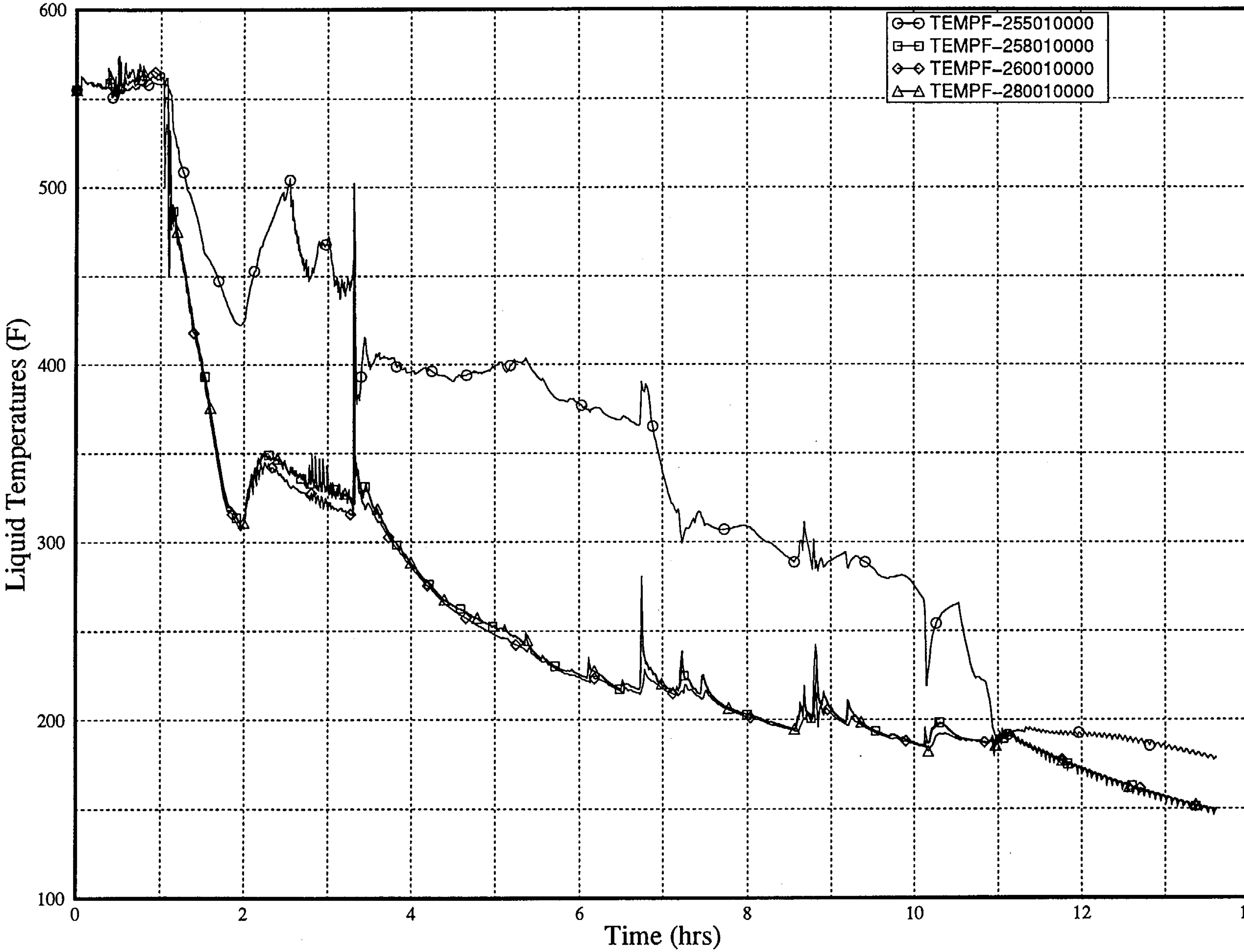


FIGURE A.1.10: 0.007 ft^2 Hot Leg Break.

Broken Loop Hot Leg Temperatures

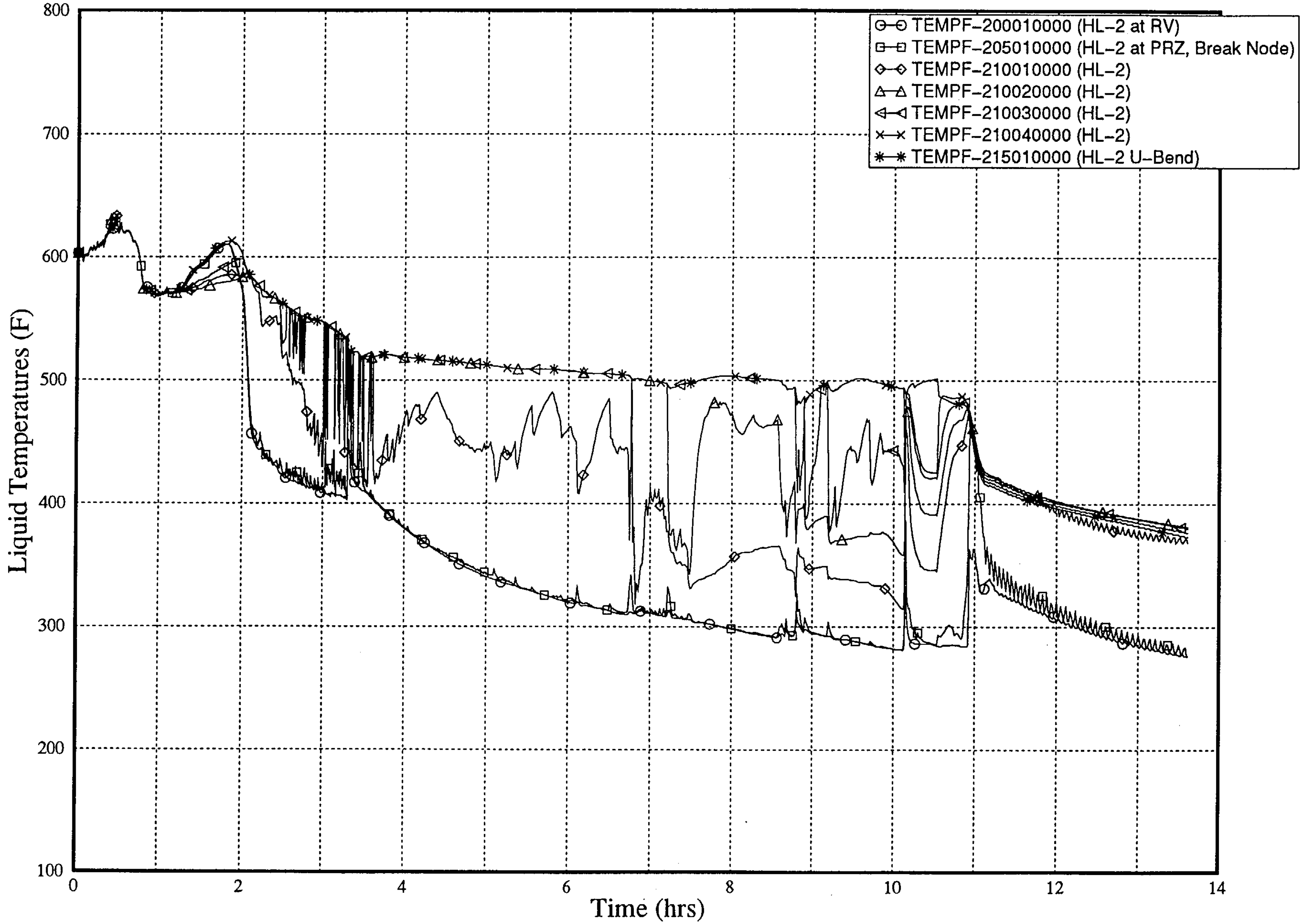


FIGURE A.1.11: 0.007 ft^2 Hot Leg Break.

Downcomer Liquid Temperatures Around Nozzle Belt

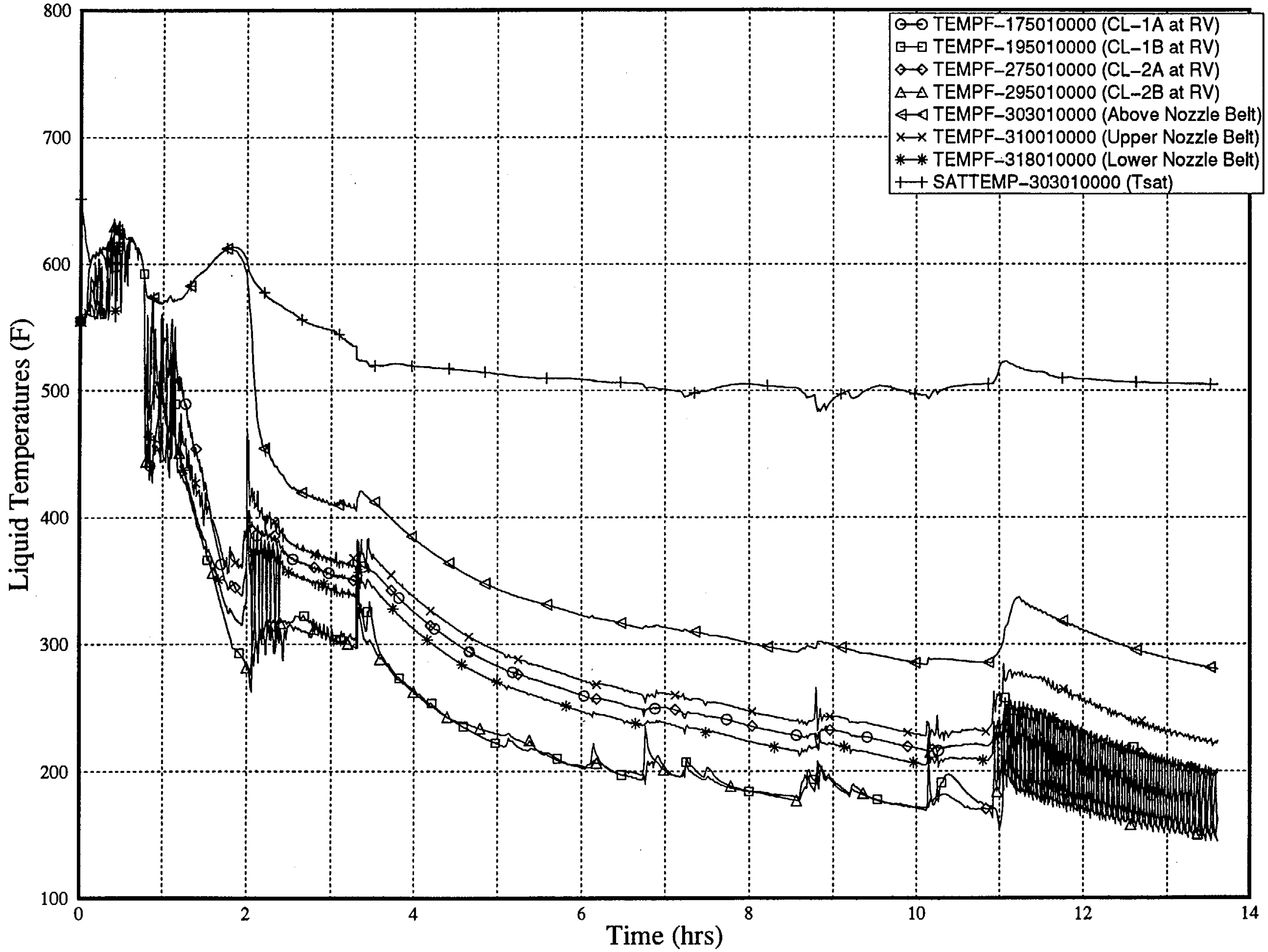


FIGURE A.1.12: 0.007 ft^2 Hot Leg Break.

Upper Plenum Subcooling

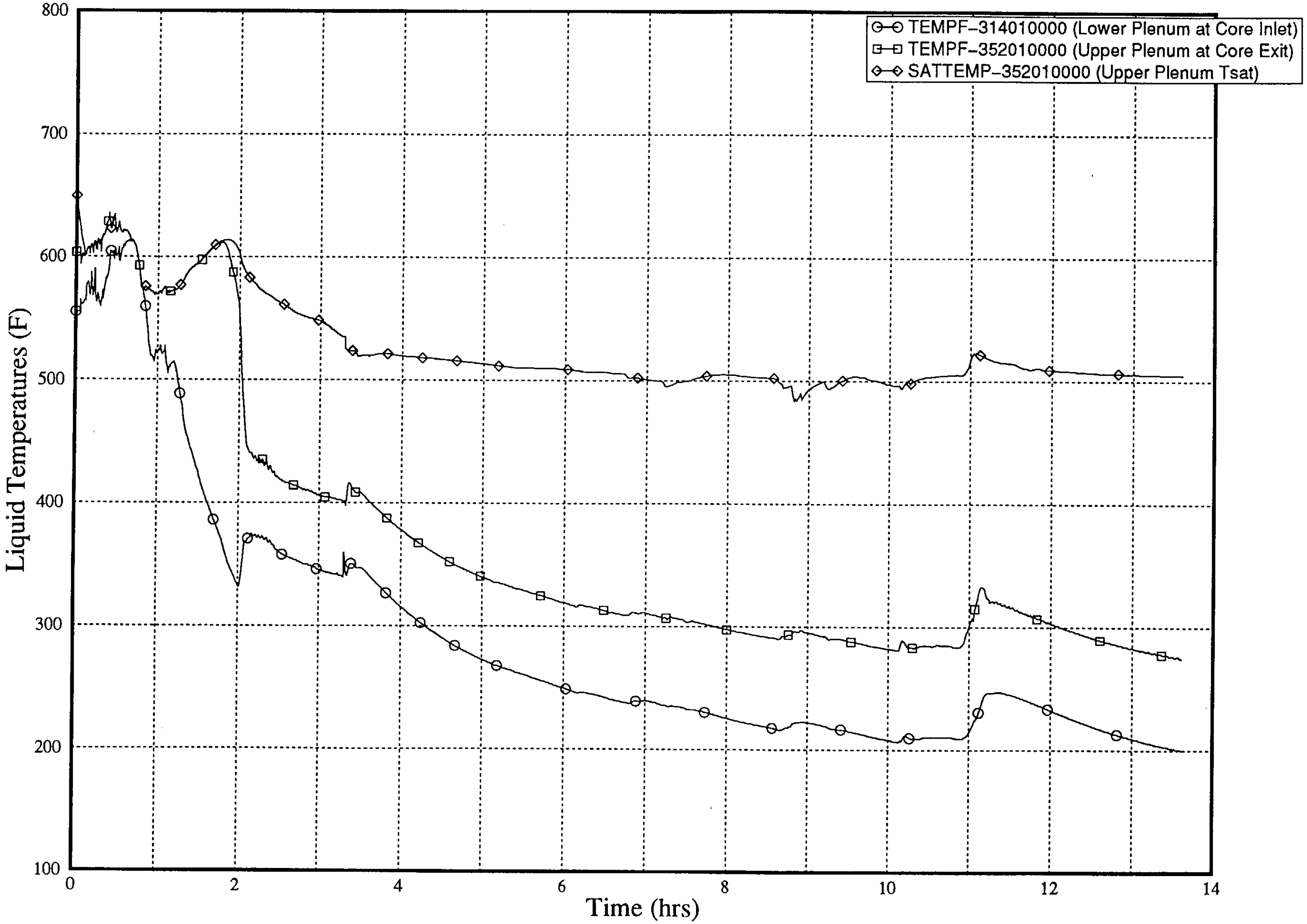


FIGURE A.1.13: 0.007 ft^2 Hot Leg Break.

Total ECCS and Break Flow

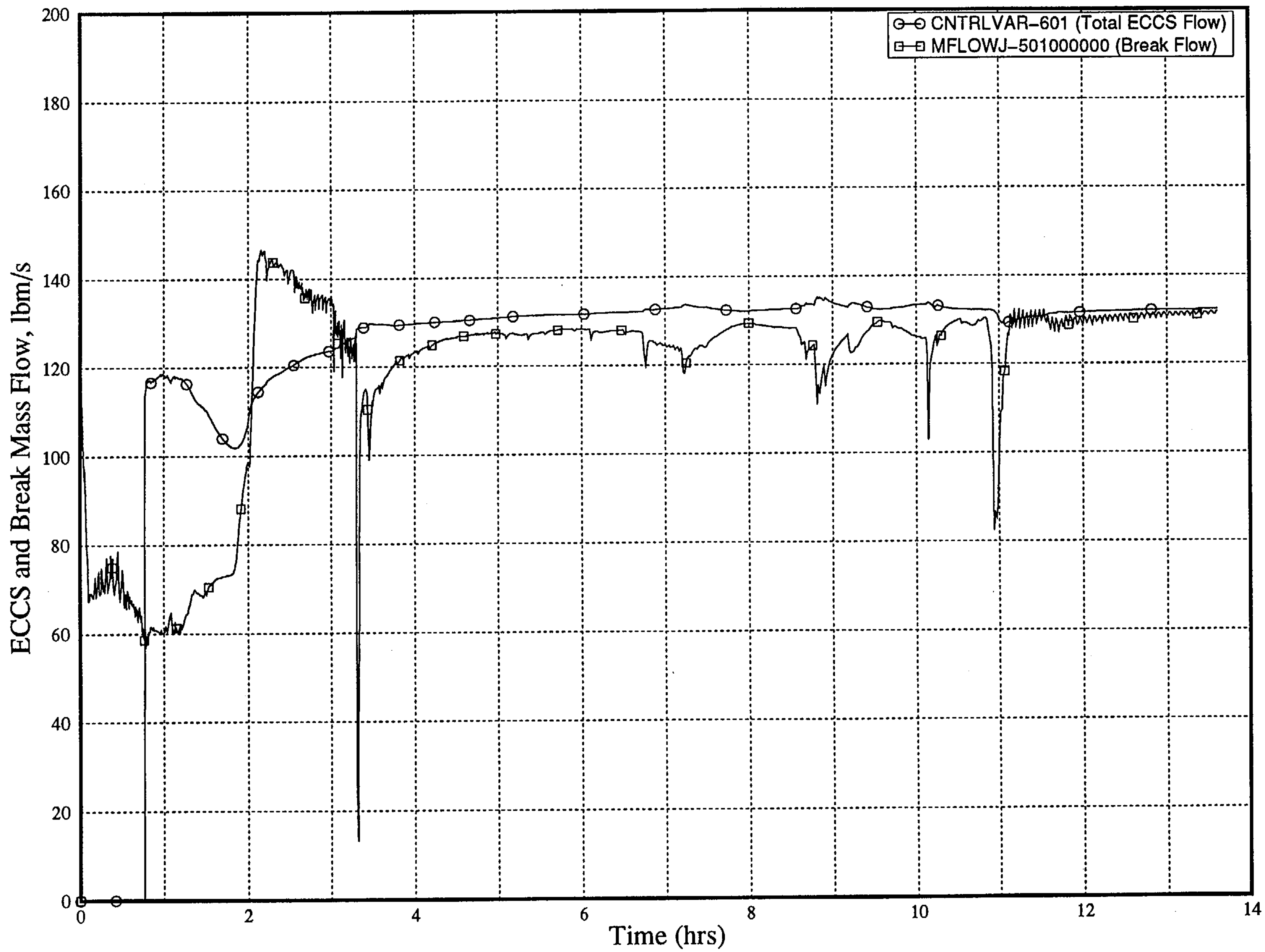


FIGURE A.1.14: 0.007 ft^2 Hot Leg Break.

Break Flow Temperature

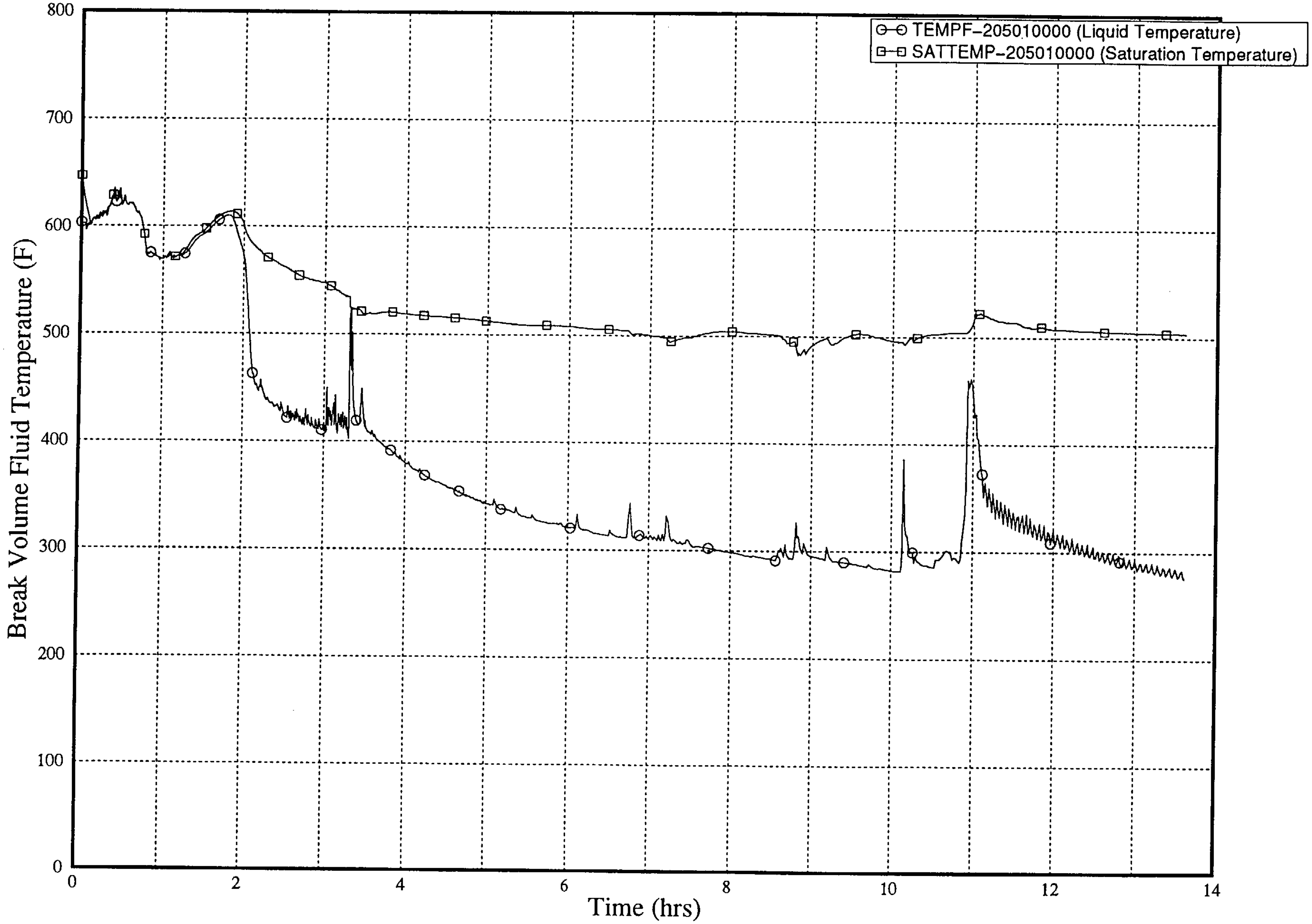


FIGURE A.1.15: 0.007 ft^2 Hot Leg Break.

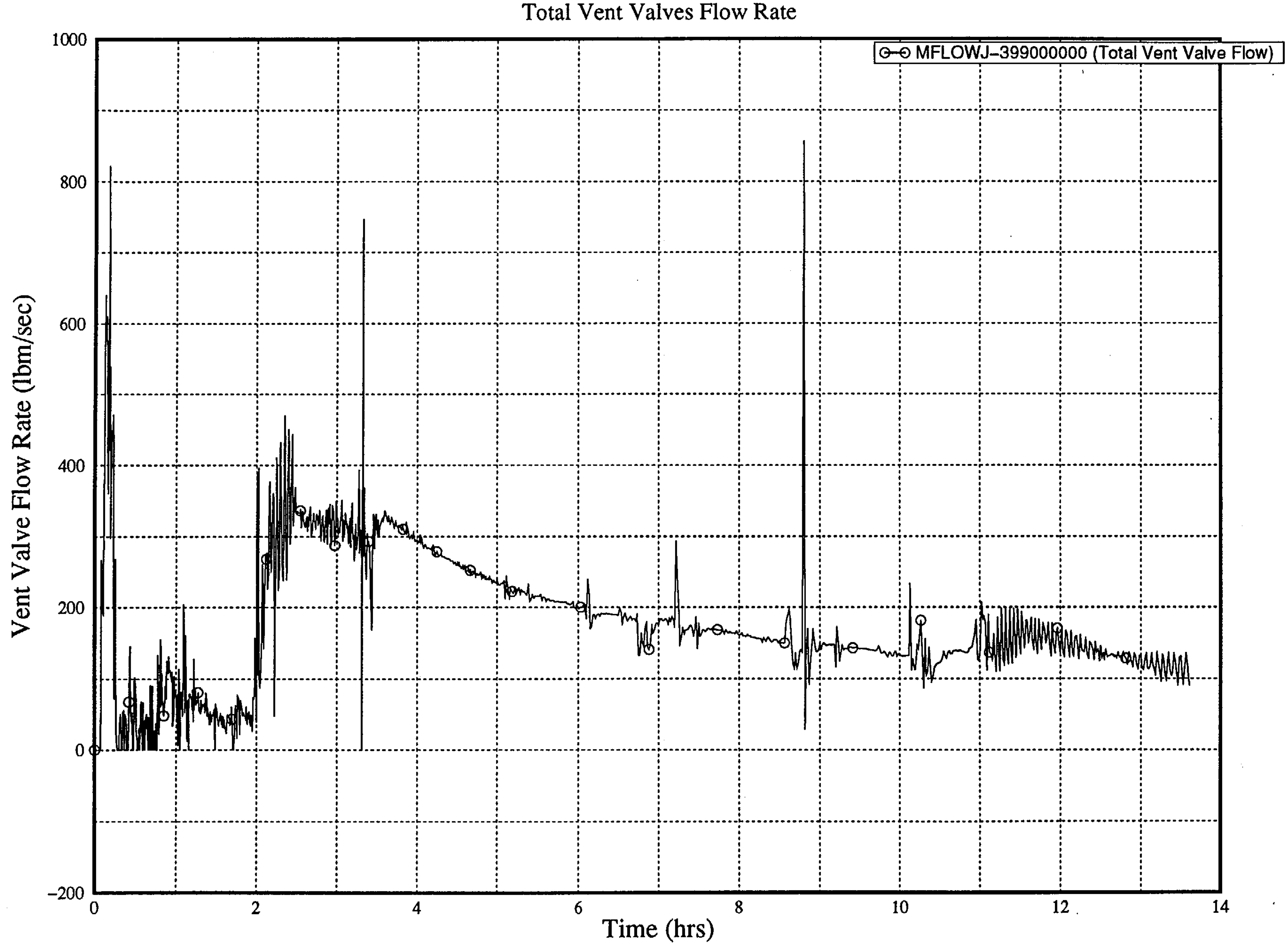


FIGURE A.1.16: 0.007 ft^2 Hot Leg Break.

Vent Valves Flow Quality

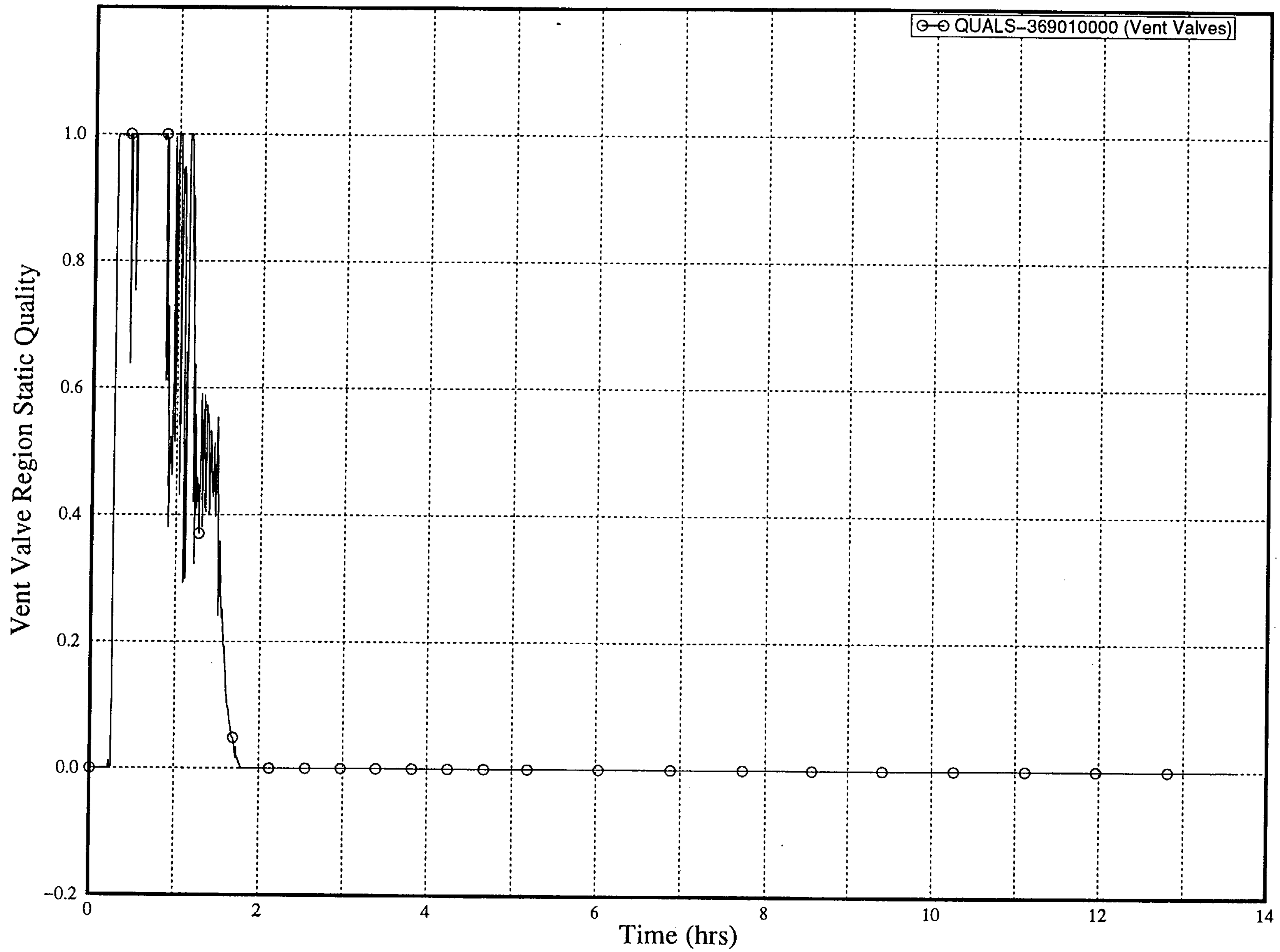


FIGURE A.1.17: 0.007 ft² Hot Leg Break.

Vent Valves Flow Temperature

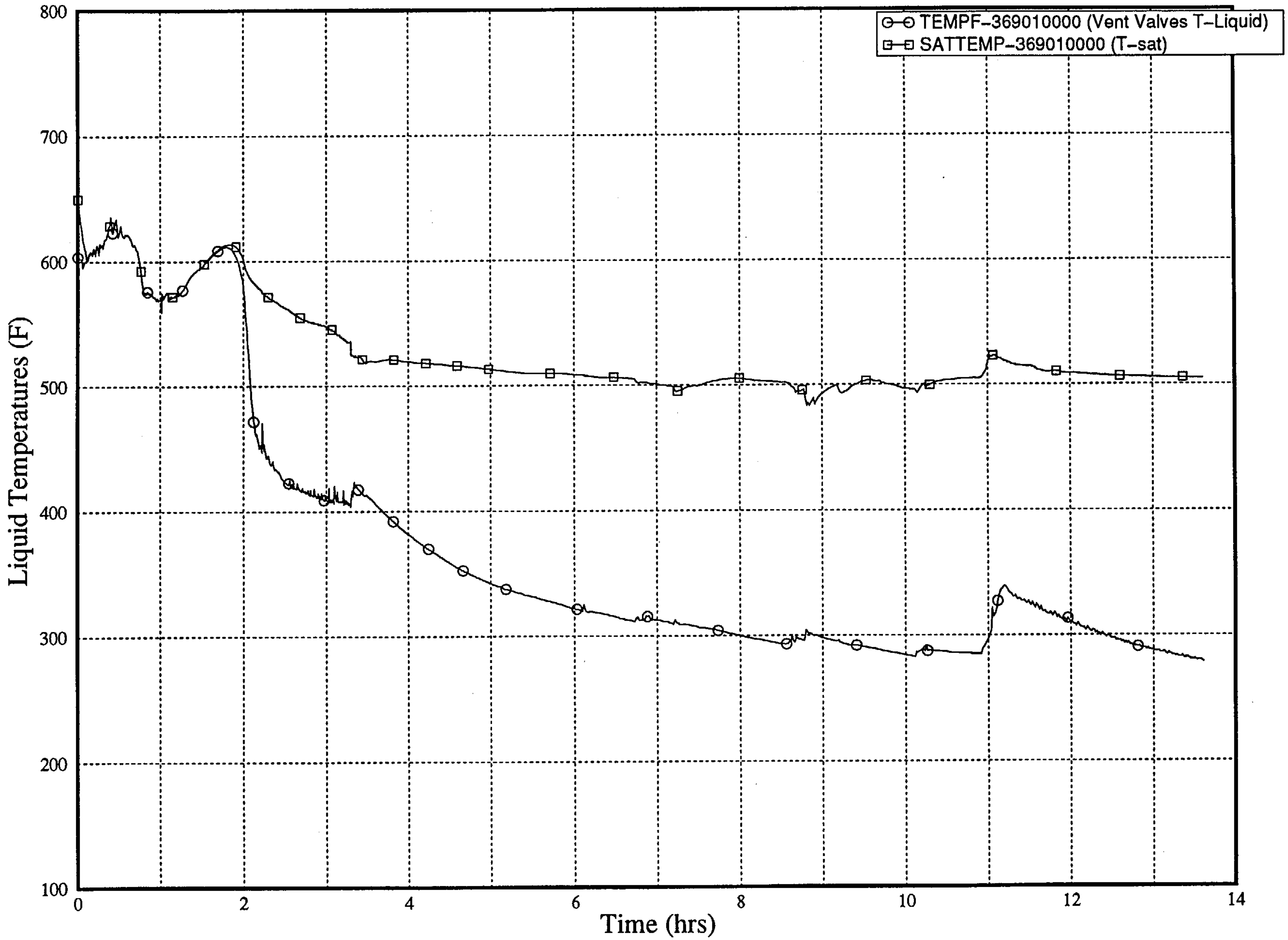


FIGURE A.1.18: 0.007 ft^2 Hot Leg Break.

Intact Loop SG Outlet and Cold Leg Flow Rates

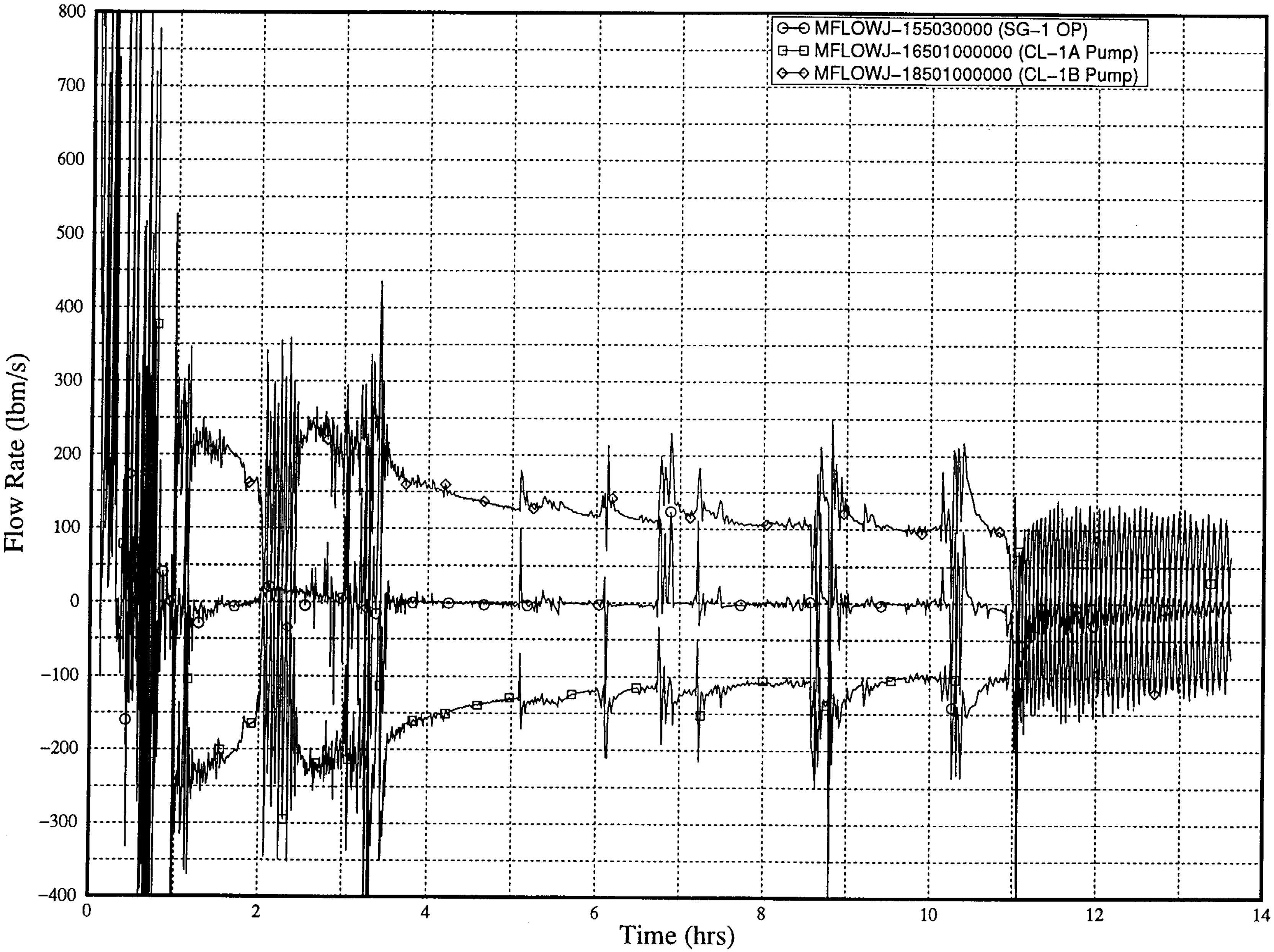


FIGURE A.1.19: 0.007 ft^2 Hot Leg Break.

Broken Loop SG Outlet and Cold Leg Flow Rates

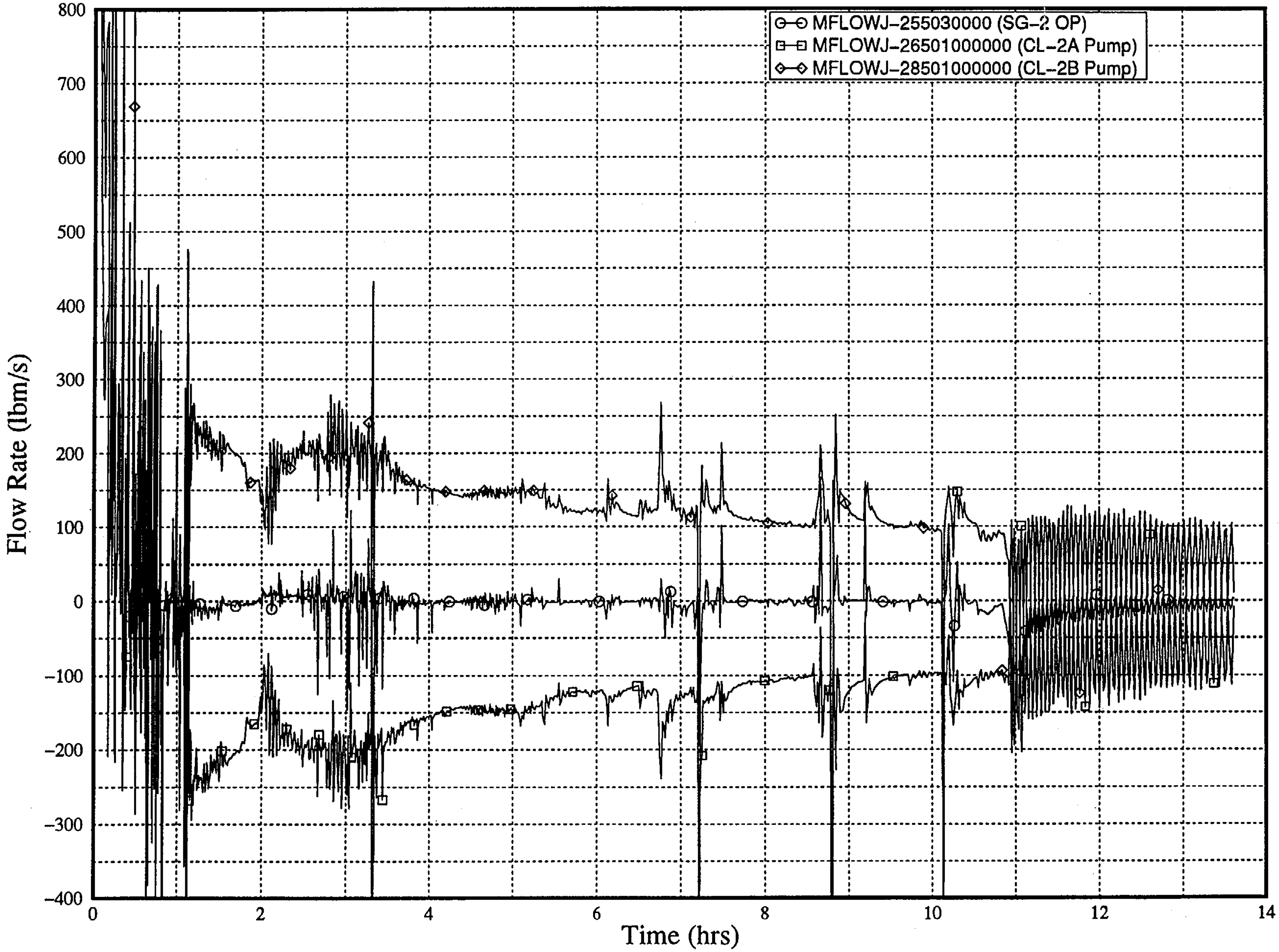


FIGURE A.1.20: 0.007 ft^2 Hot Leg Break.

Intact Loop Hot Leg Flow at U–Bend

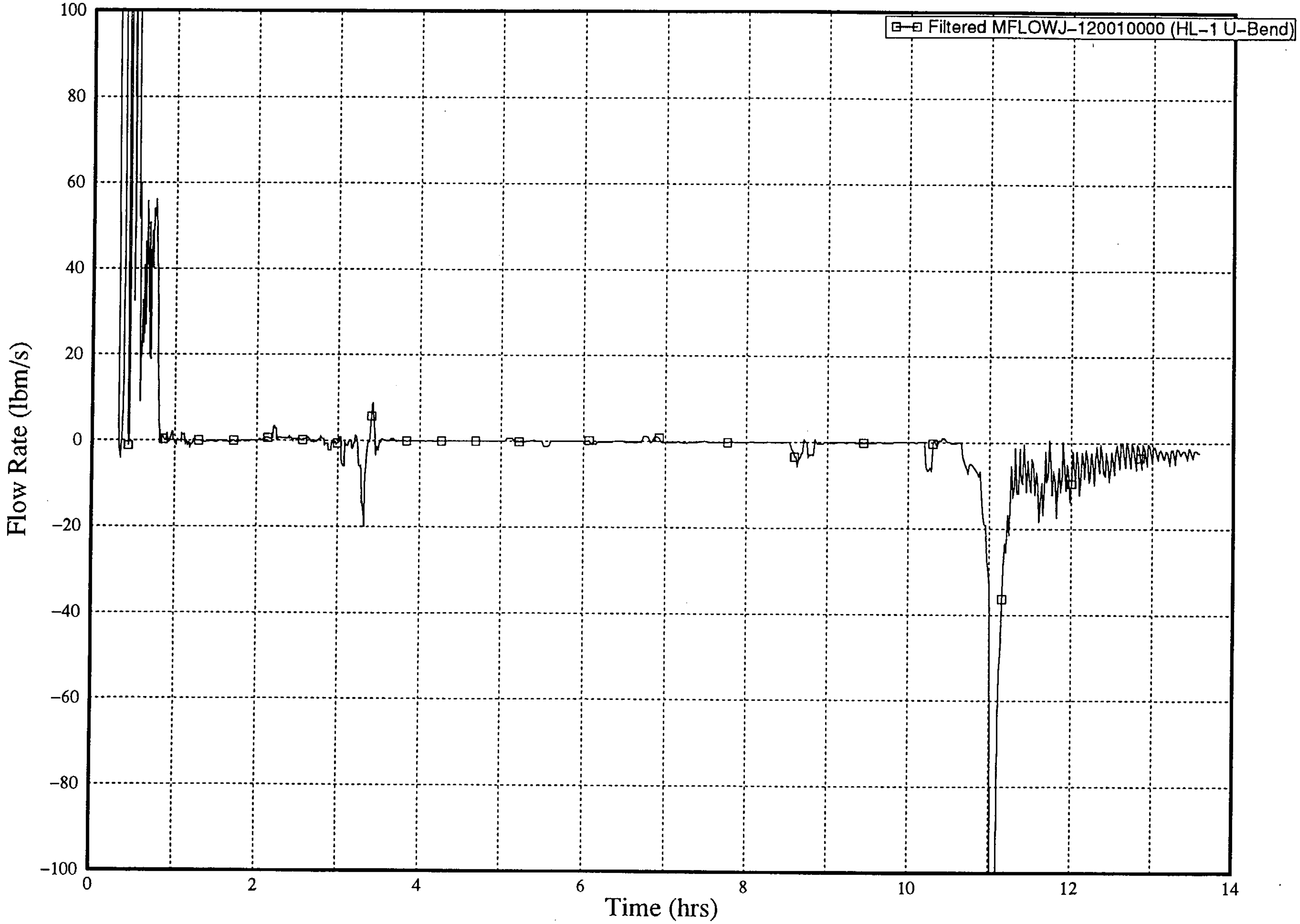


FIGURE A.1.21: 0.007 ft^2 Hot Leg Break.

Broken Loop Hot Leg Flow at U–Bend

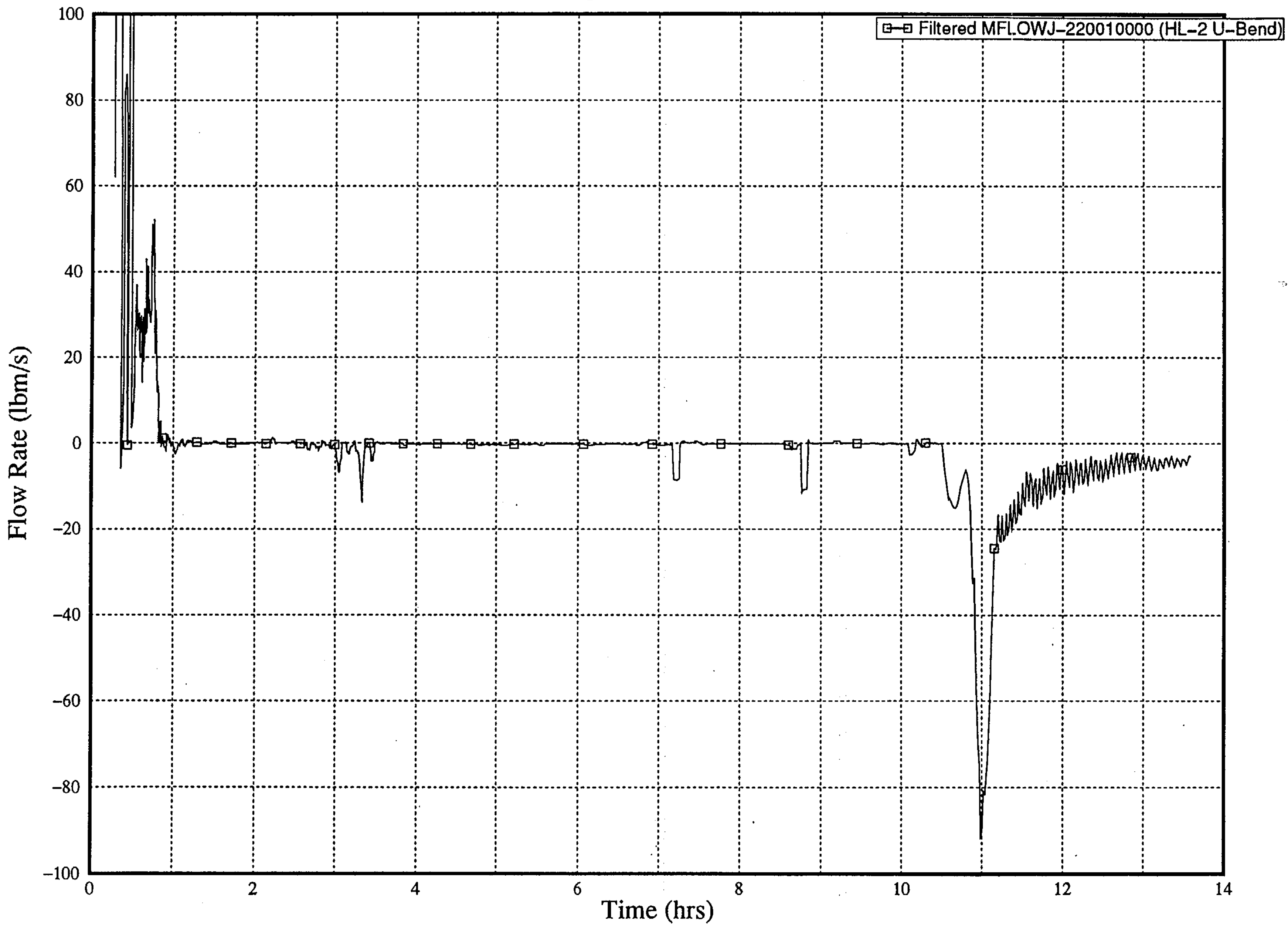


FIGURE A.1.22: 0.007 ft² Hot Leg Break.

Deborate Accumulation Due to Steam Condensation in SG

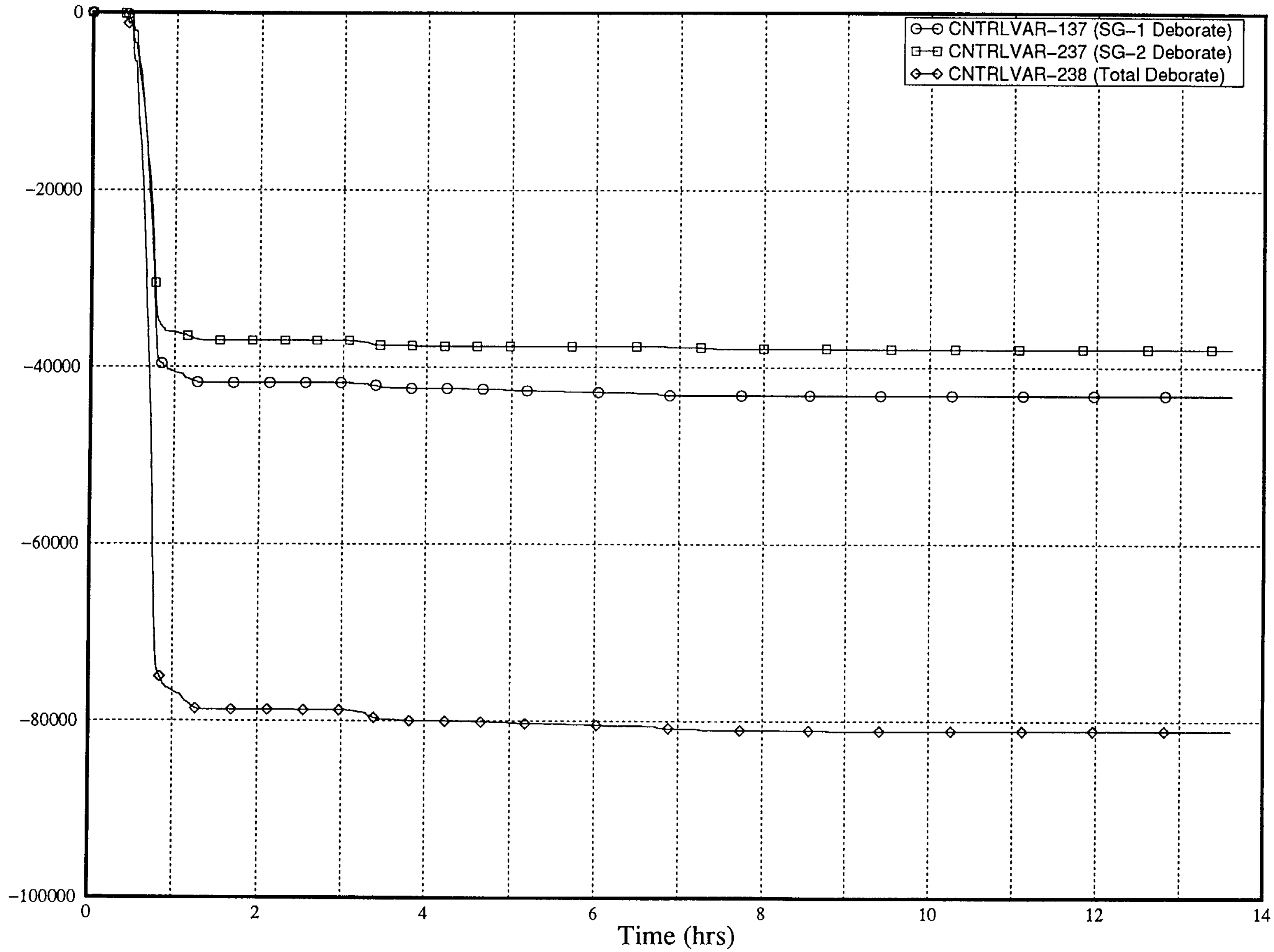


FIGURE A.1.23: 0.007 ft^2 Hot Leg Break.

Lower Plenum and Hot Legs at RV Flow Rates

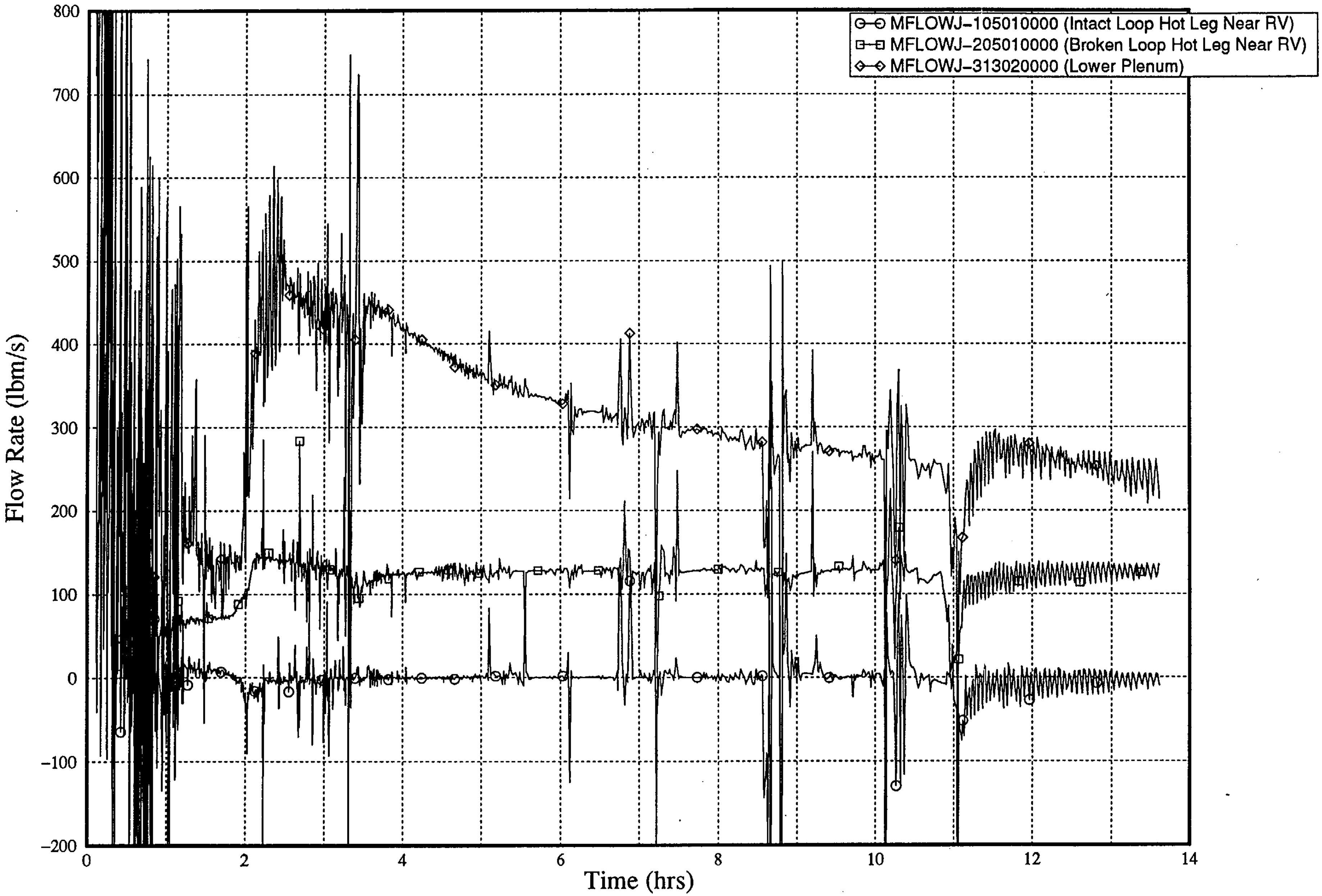


FIGURE A.1.24: 0.007 ft^2 Hot Leg Break.

Normalized Core Power Generation

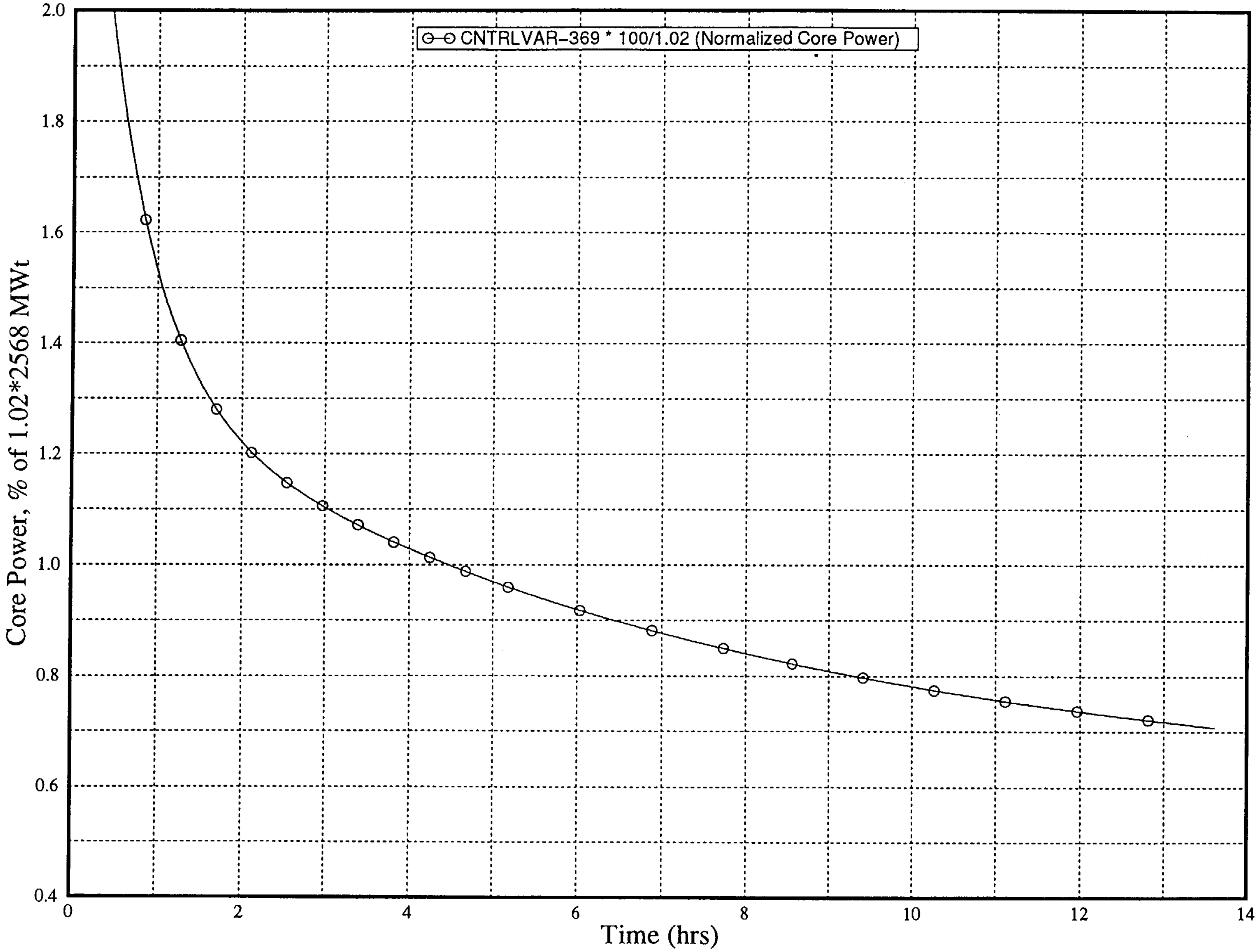


FIGURE A.2.1 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

System Pressures

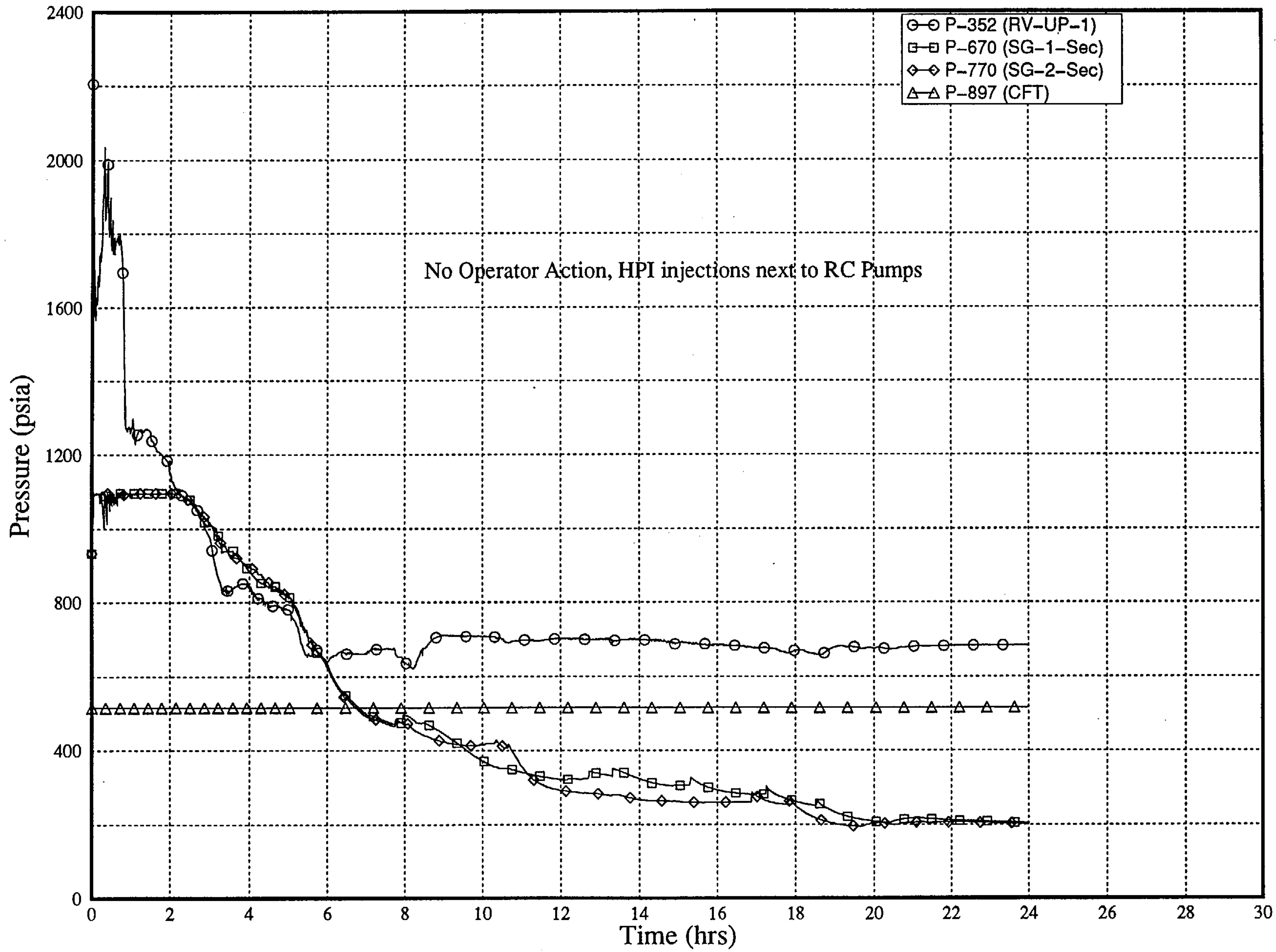


FIGURE A.2.2 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Intact Loop Collapsed Liquid Elevations

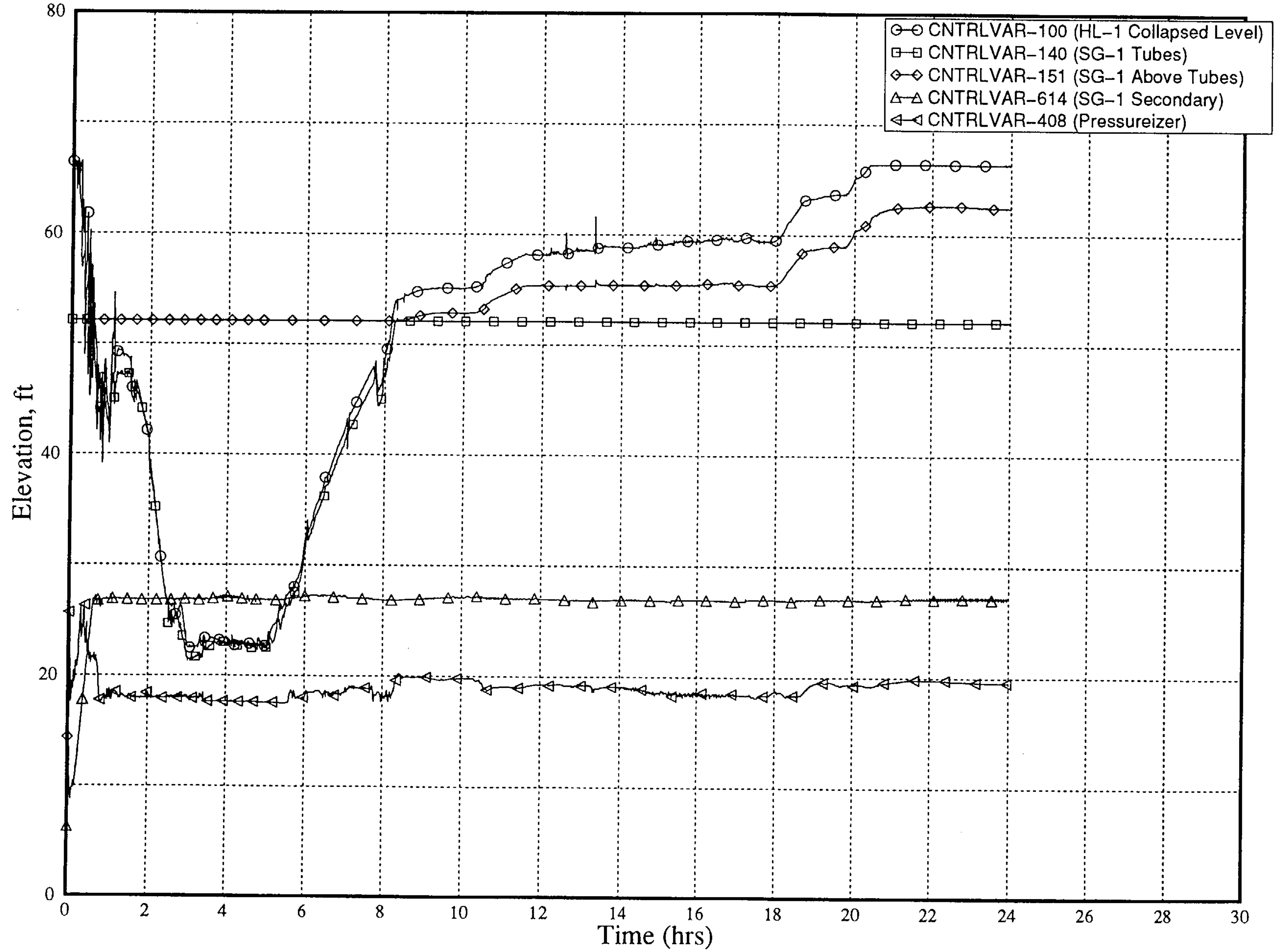


FIGURE A.2.3 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Broken Loop Collapsed Liquid Elevations

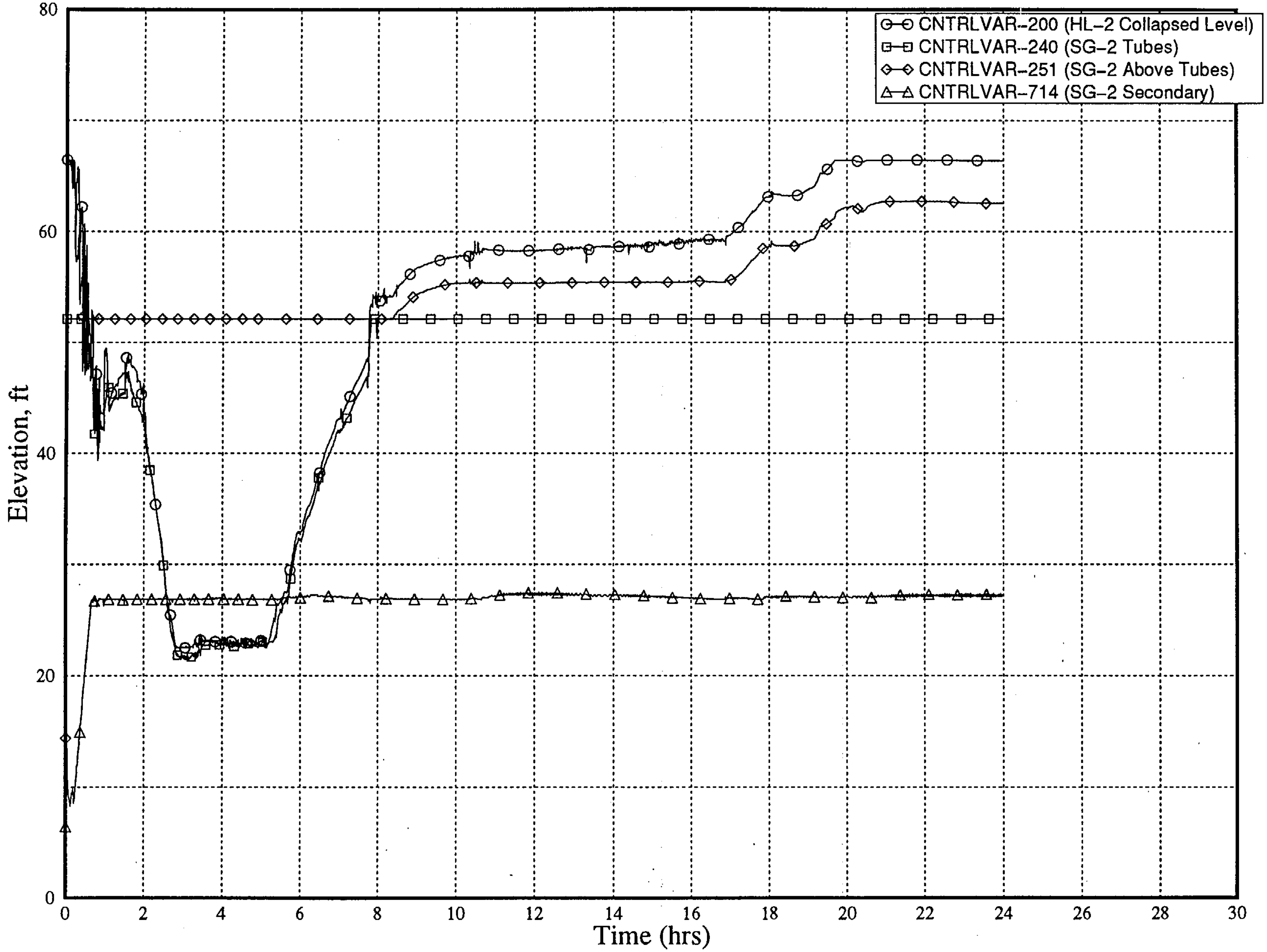


FIGURE A.2.4 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Total Vent–Valves Flow Rate

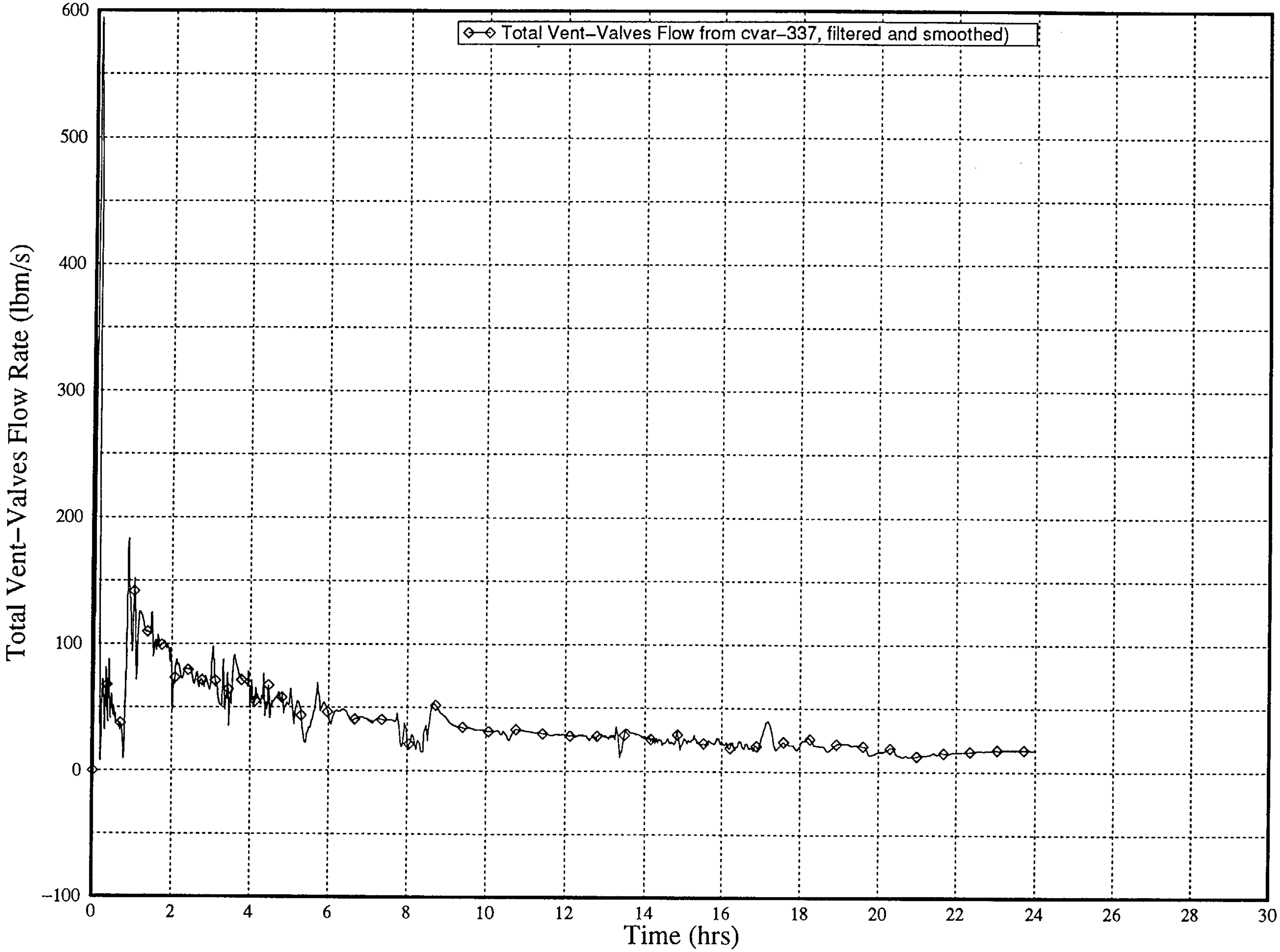


FIGURE A.2.5 : 0.007 ft² Cold Leg Break at RV, DC stratification at CL bottom

Vent Valve, Upper Plenum, Upper Head Voiding

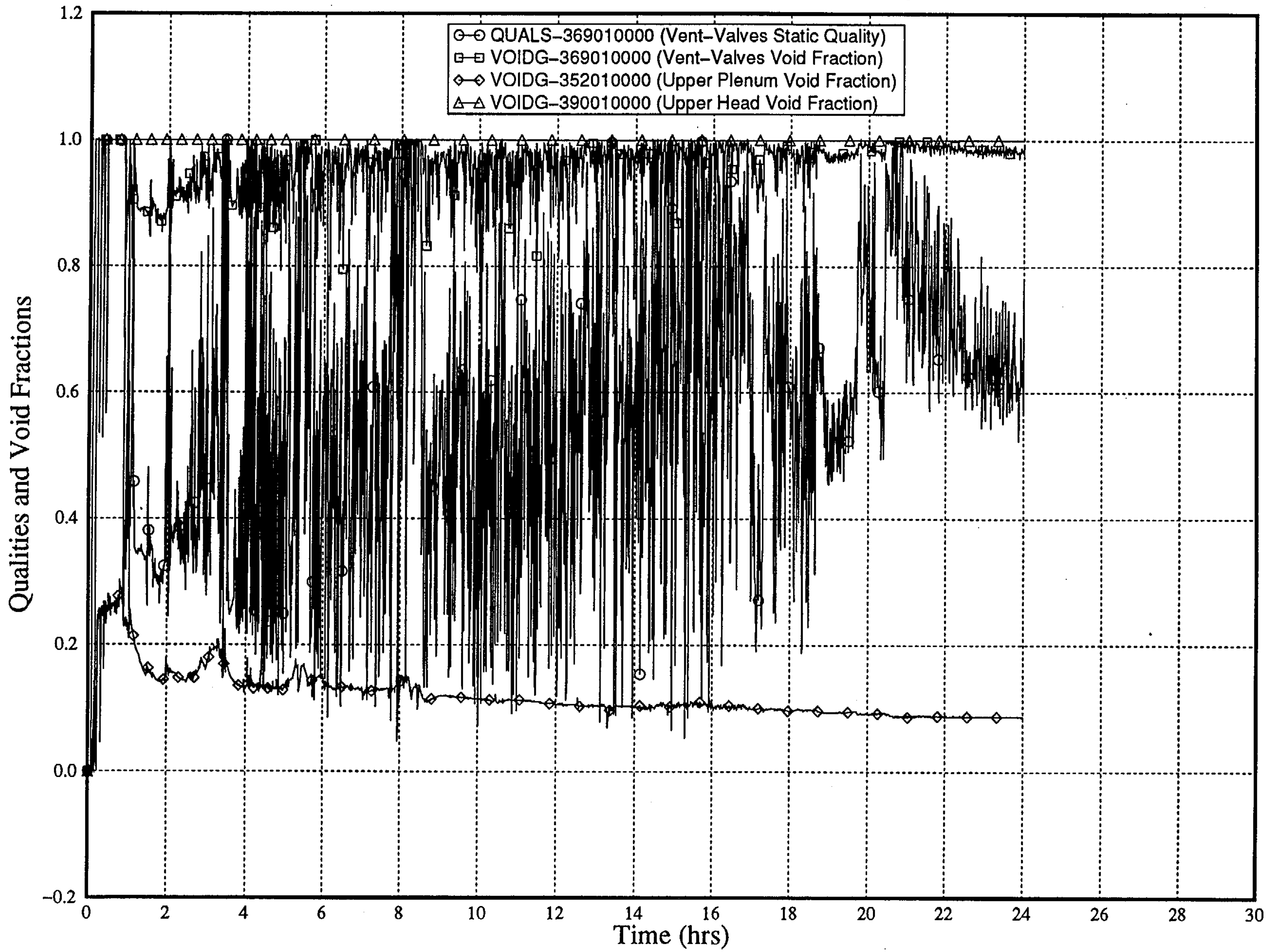


FIGURE A.2.6 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Total ECCS and Break Flow

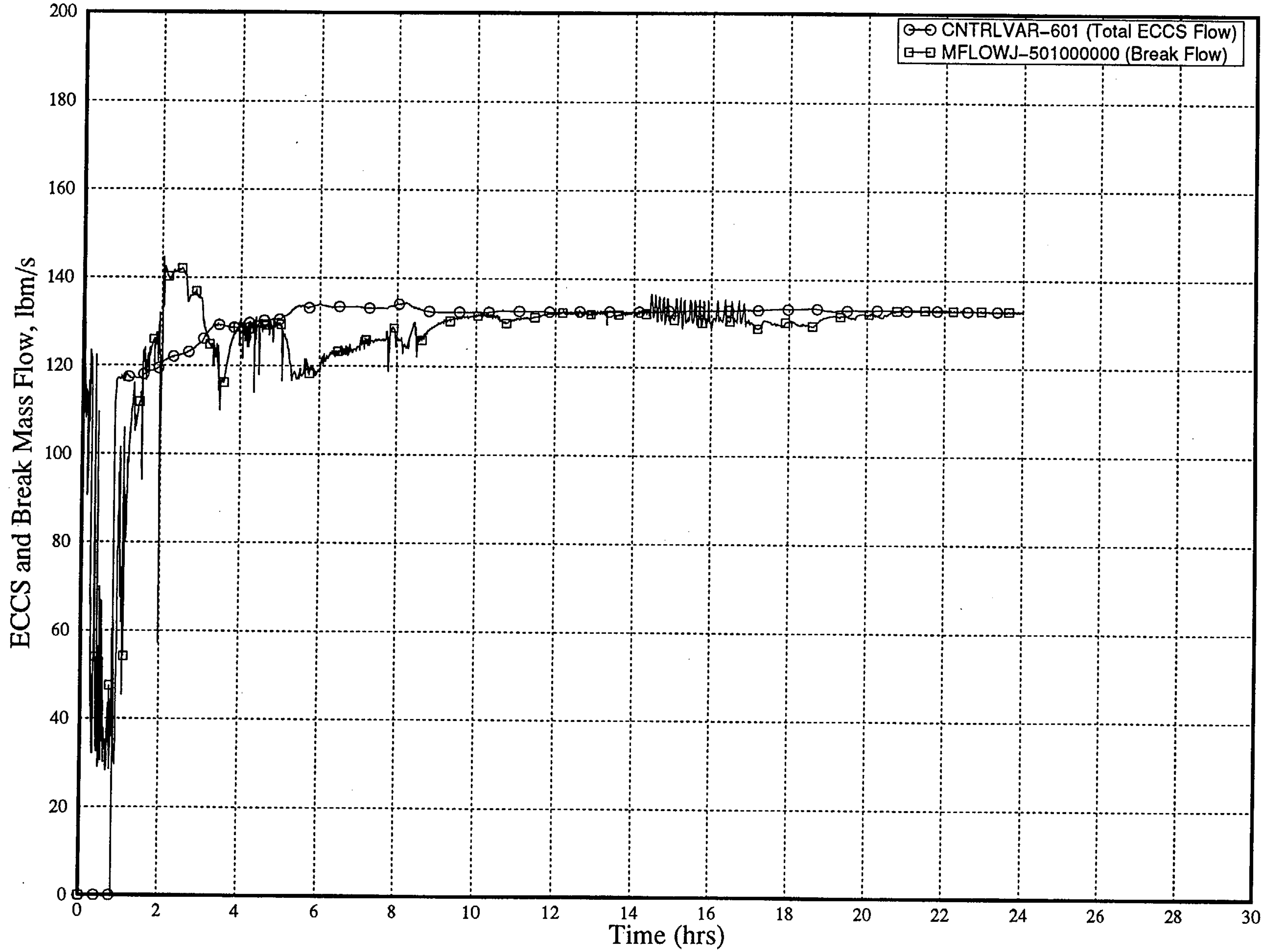


FIGURE A.2.7 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

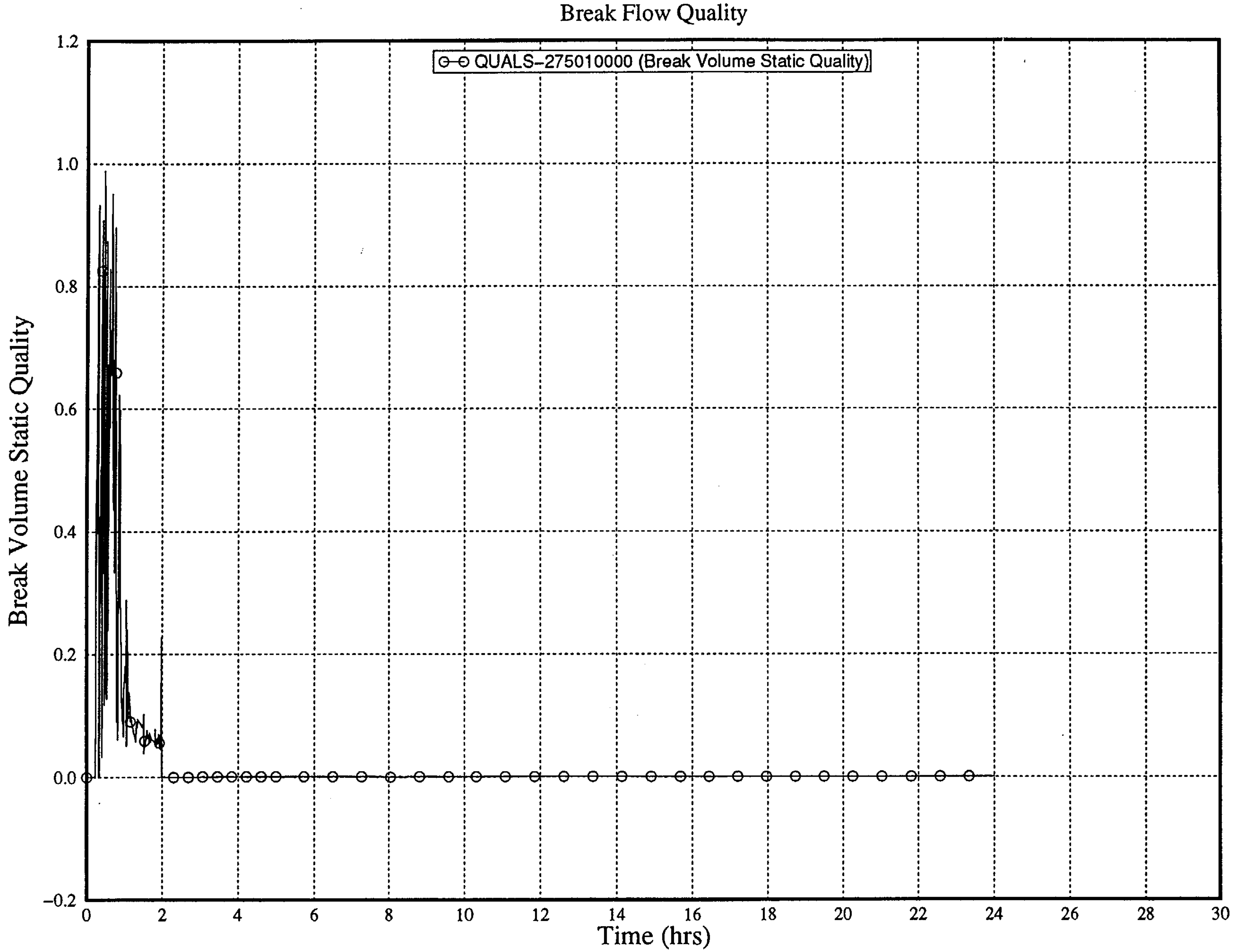


FIGURE A.2.8 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Break Flow Temperature

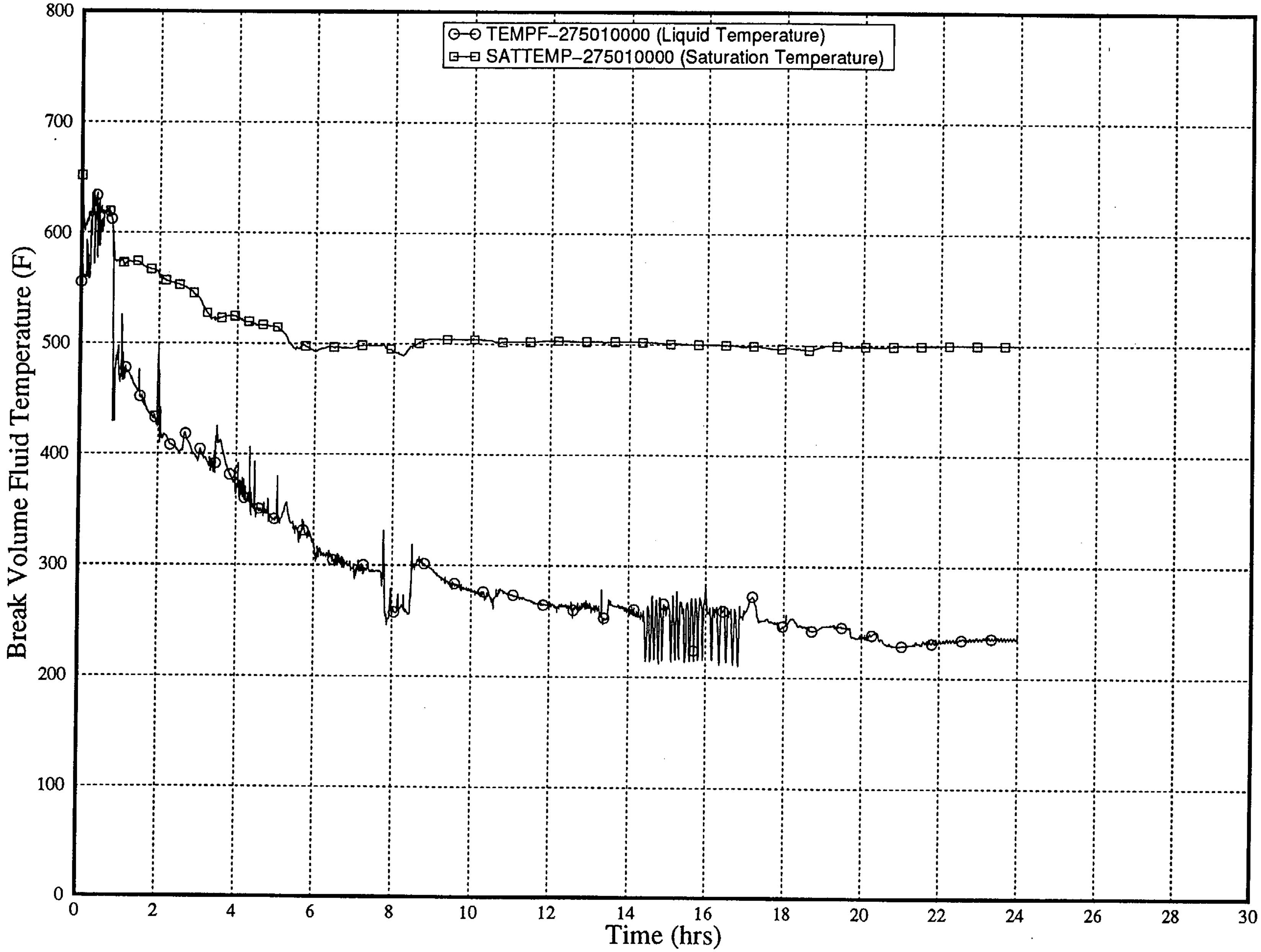


FIGURE A.2.9 : 0.007 ft² Cold Leg Break at RV, DC stratification at CL bottom

Intact Loop Cold Leg Flow Rates

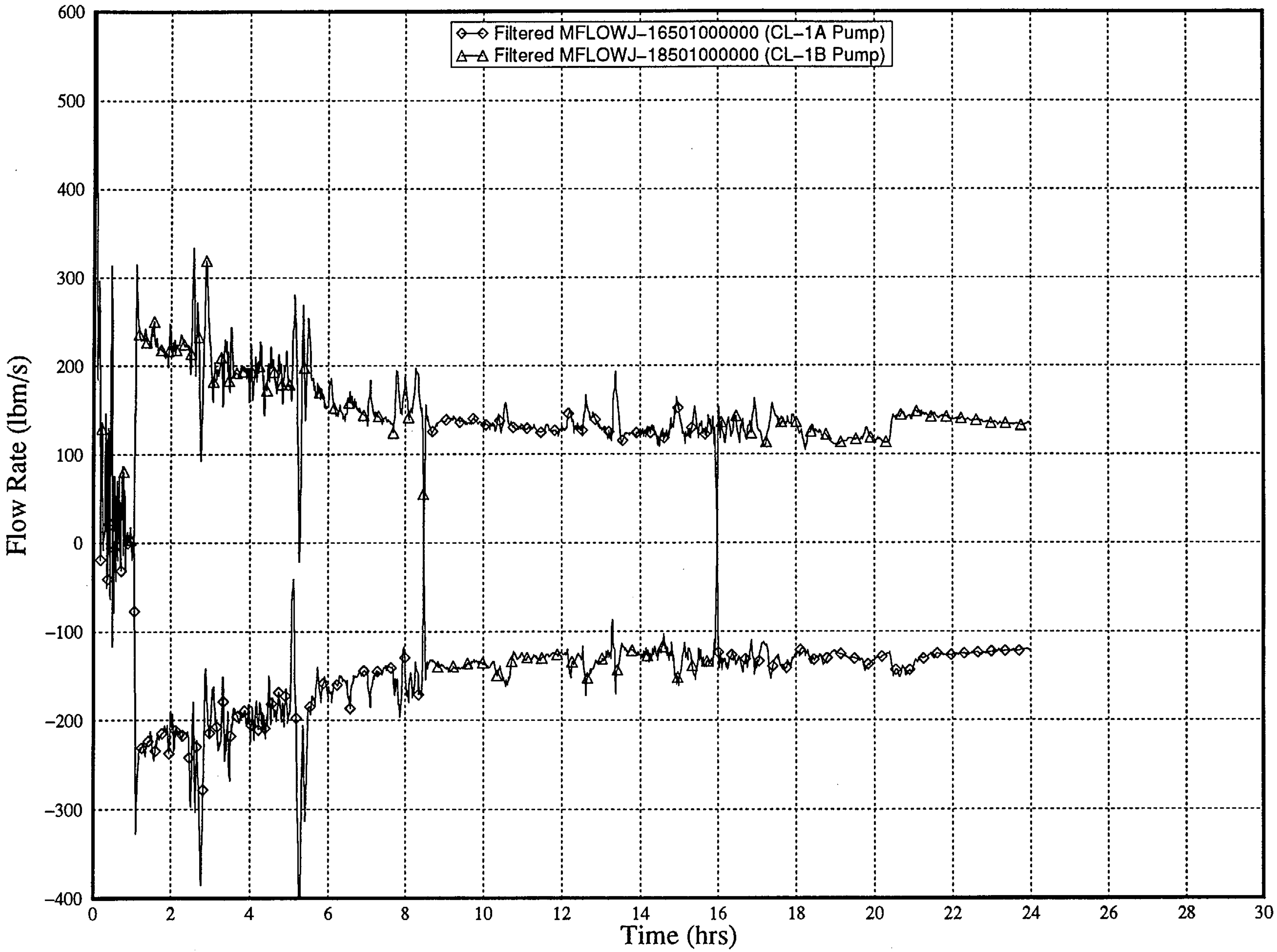


FIGURE A.2.10: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Broken Loop Cold Leg Flow Rates

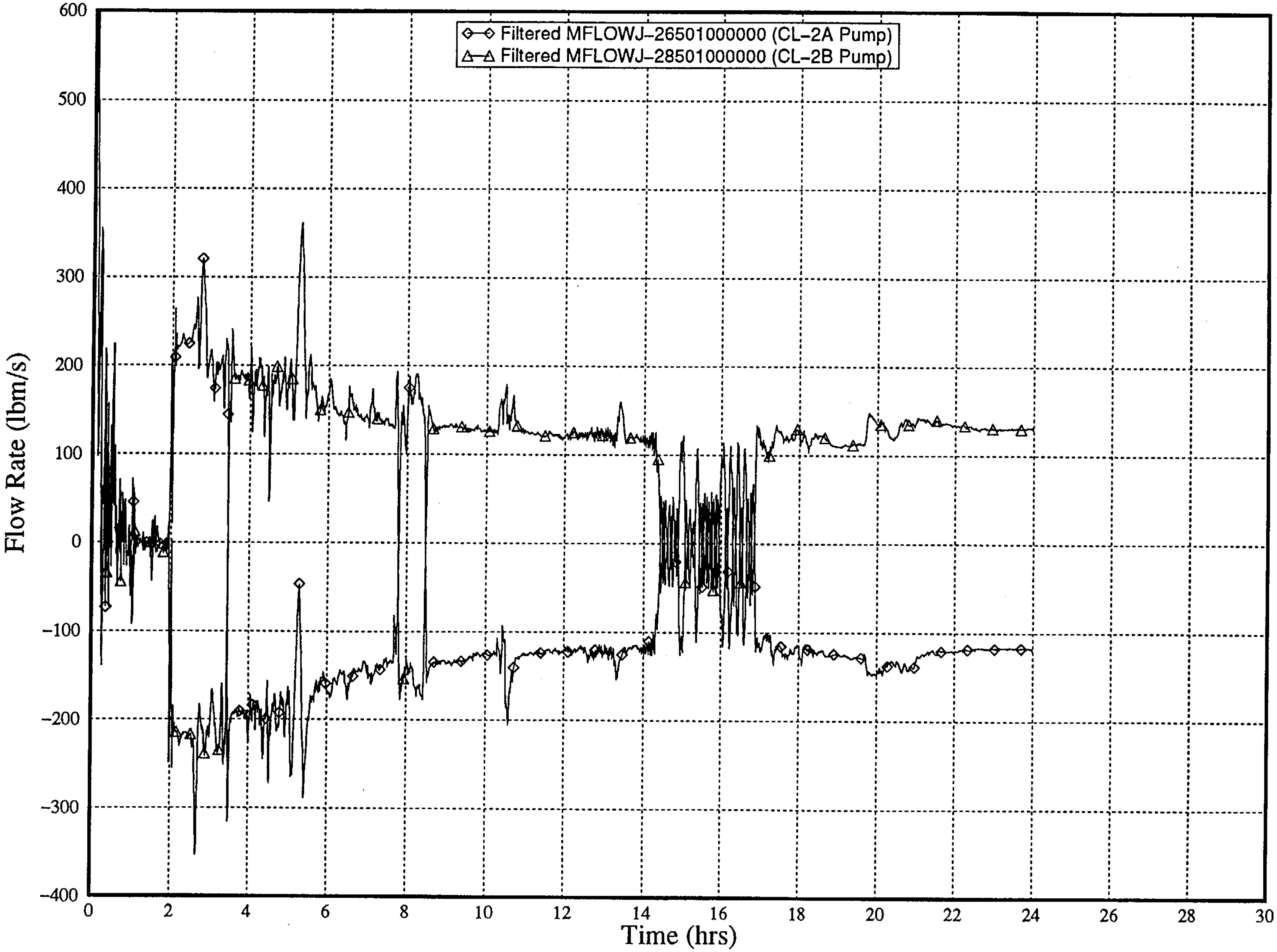


FIGURE A.2.11: 0.007 ft² Cold Leg Break at RV, DC stratification at CL bottom

Loop Circulation Flow Rates at Hot Leg U–Bends

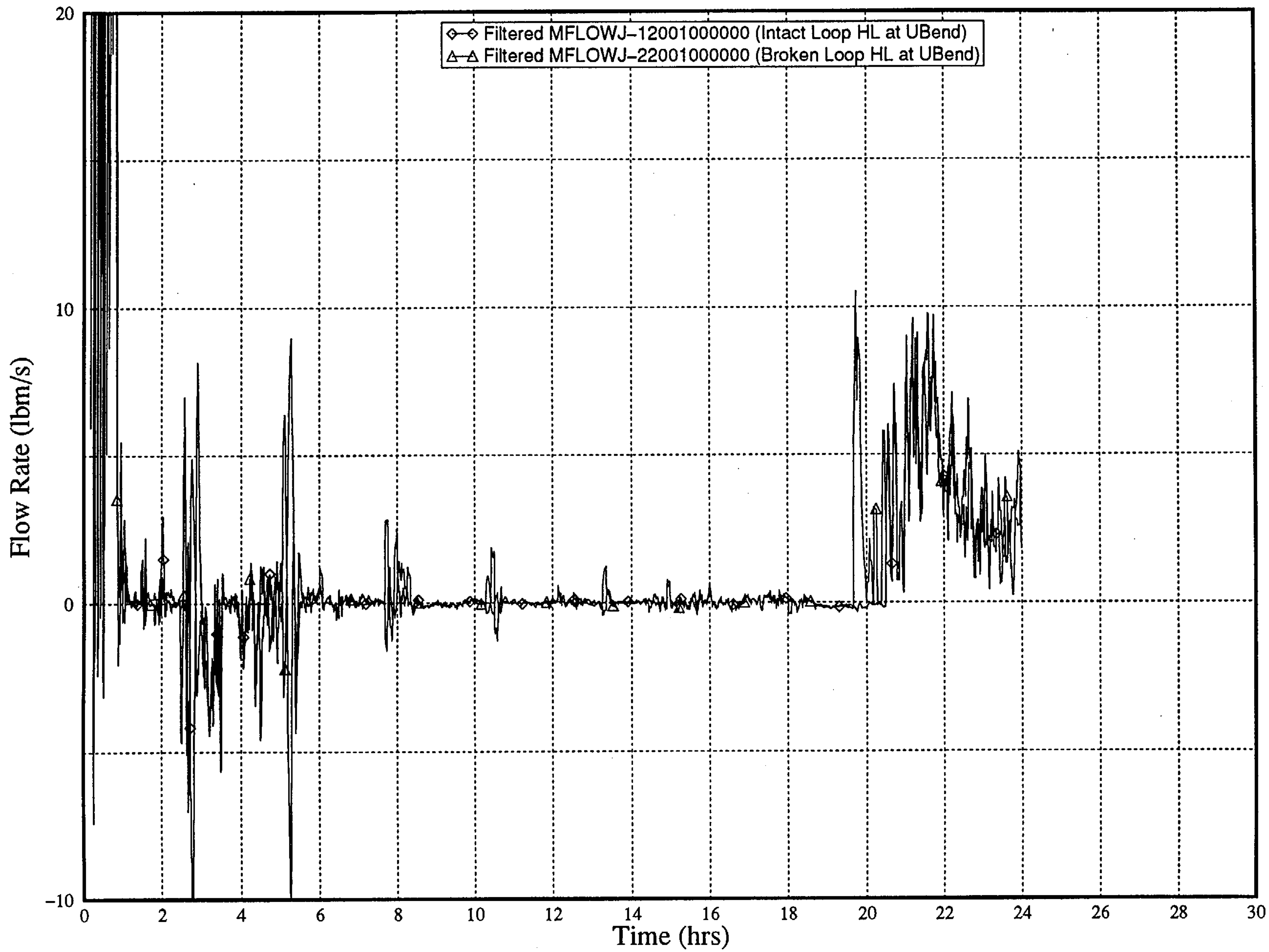


FIGURE A.2.12: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Core Inlet Flow

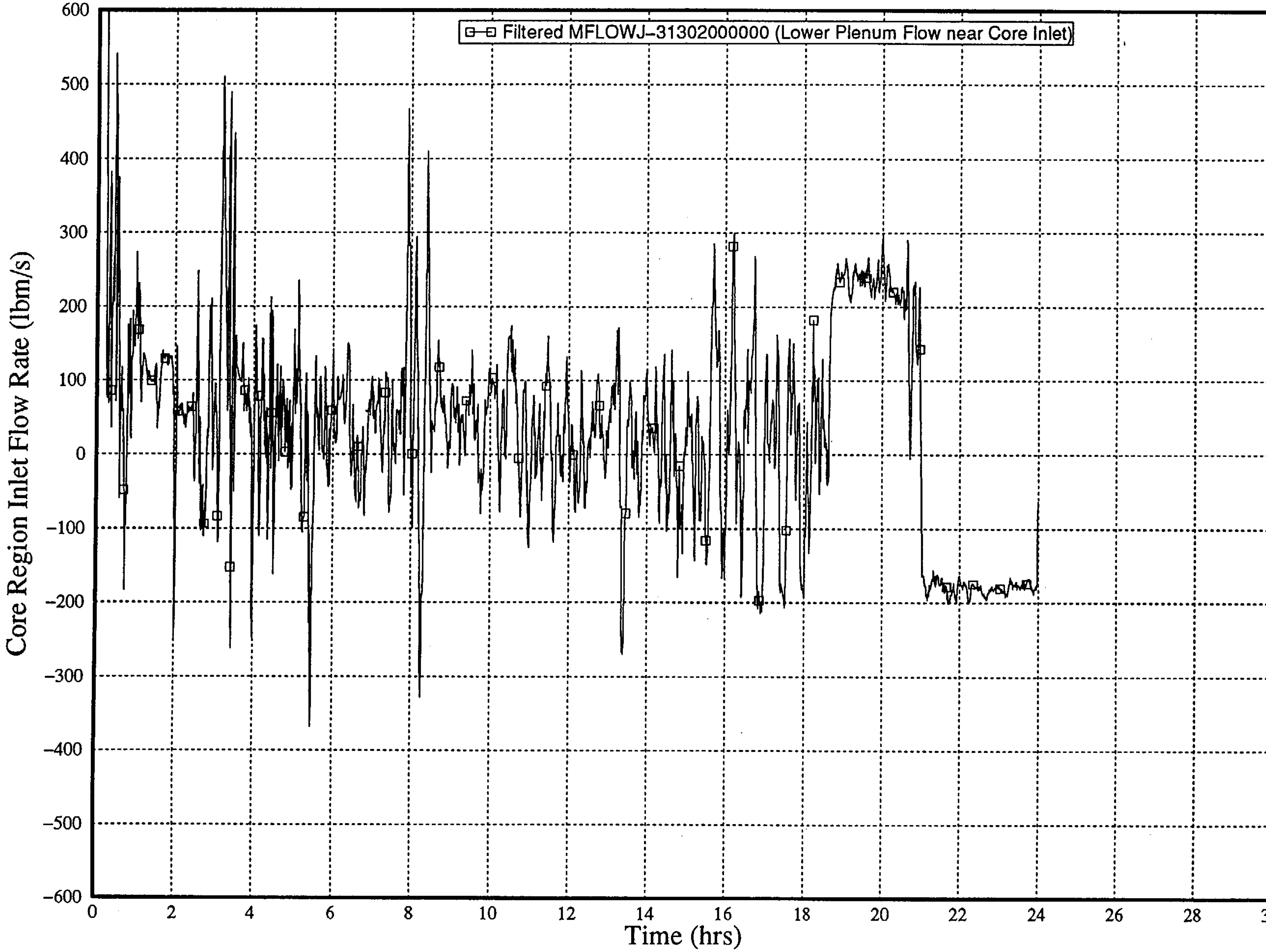


FIGURE A.2.13: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom

Reactor Vessel Temperature Distribution

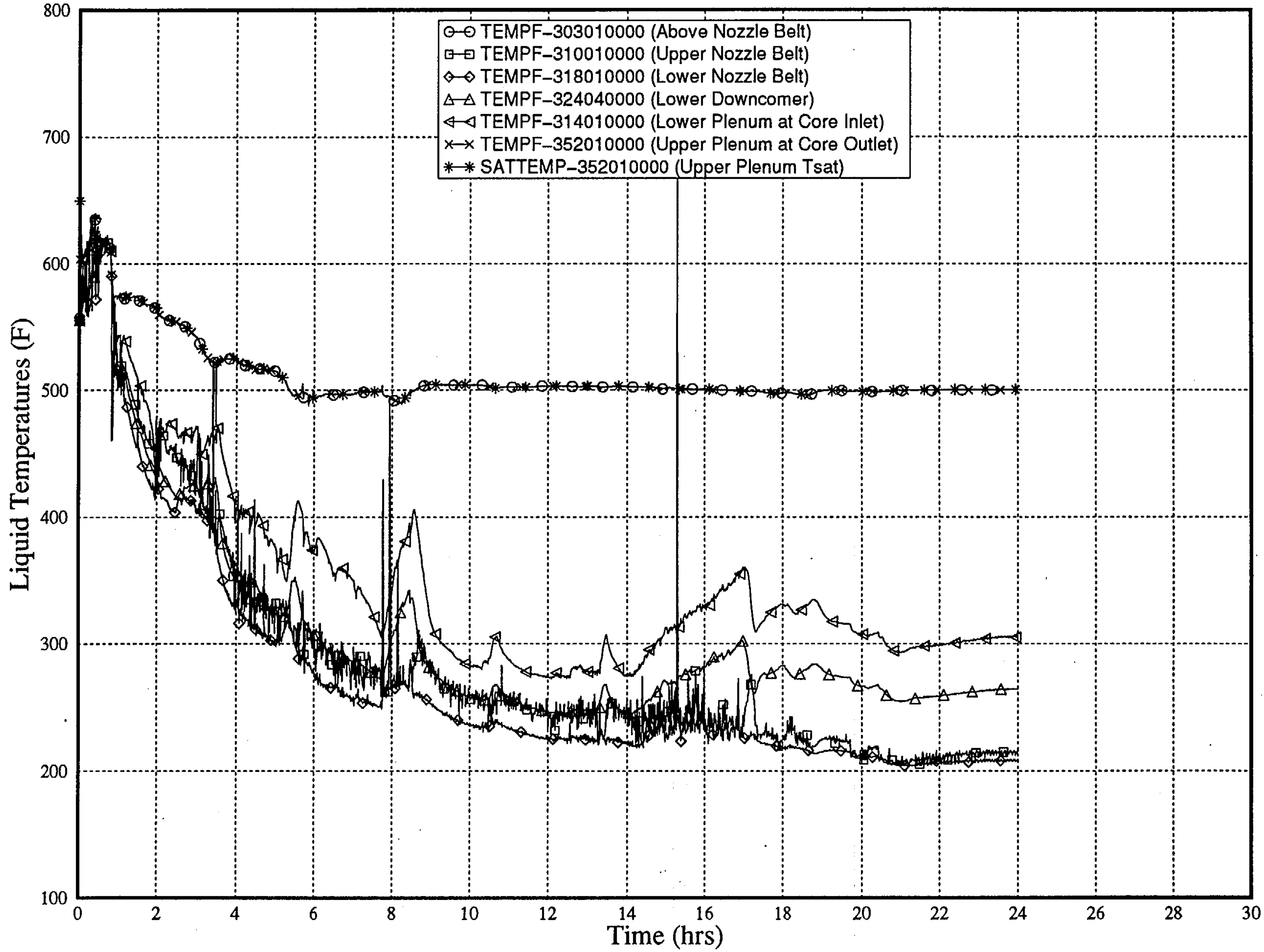
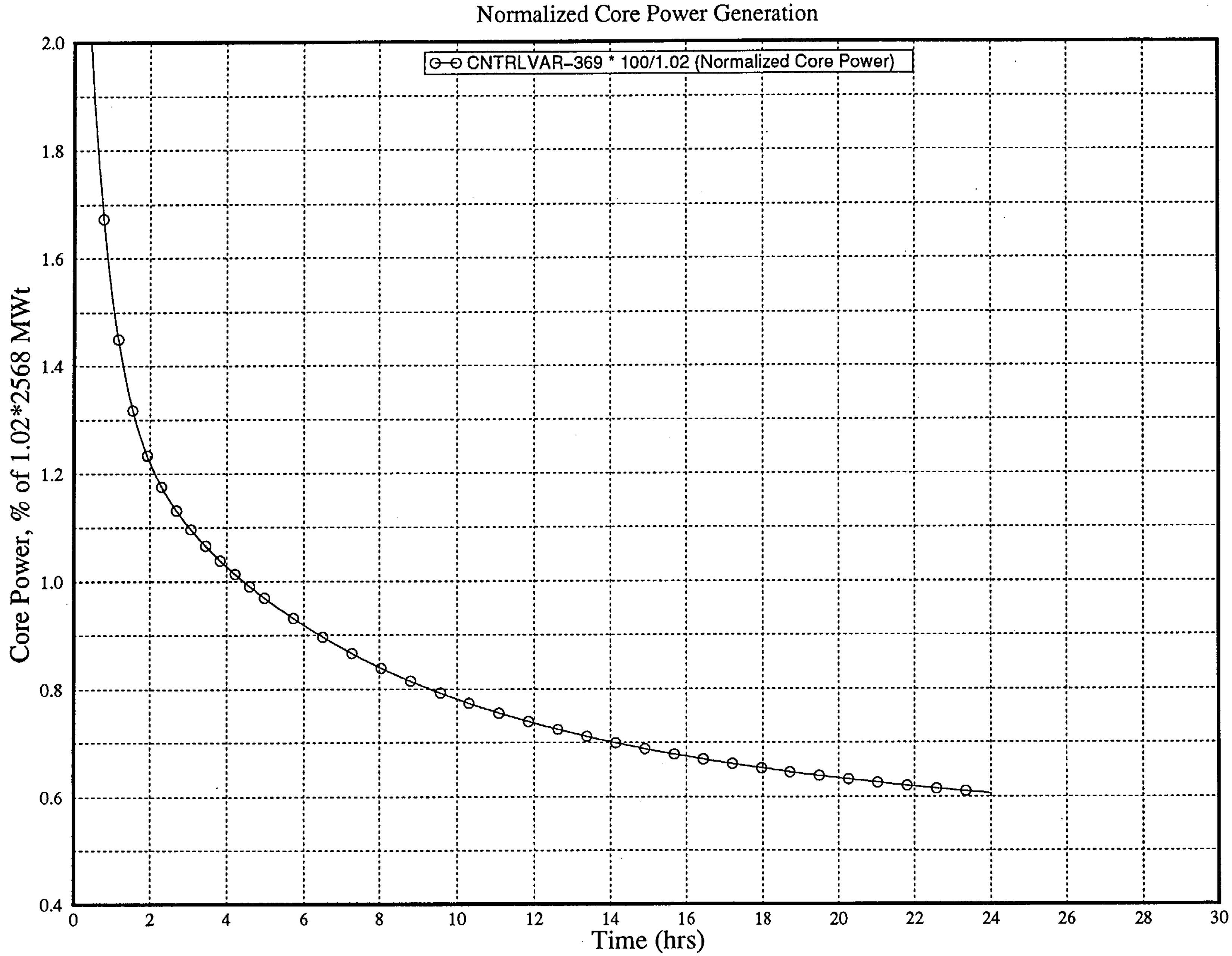


FIGURE A.2.14: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL bottom



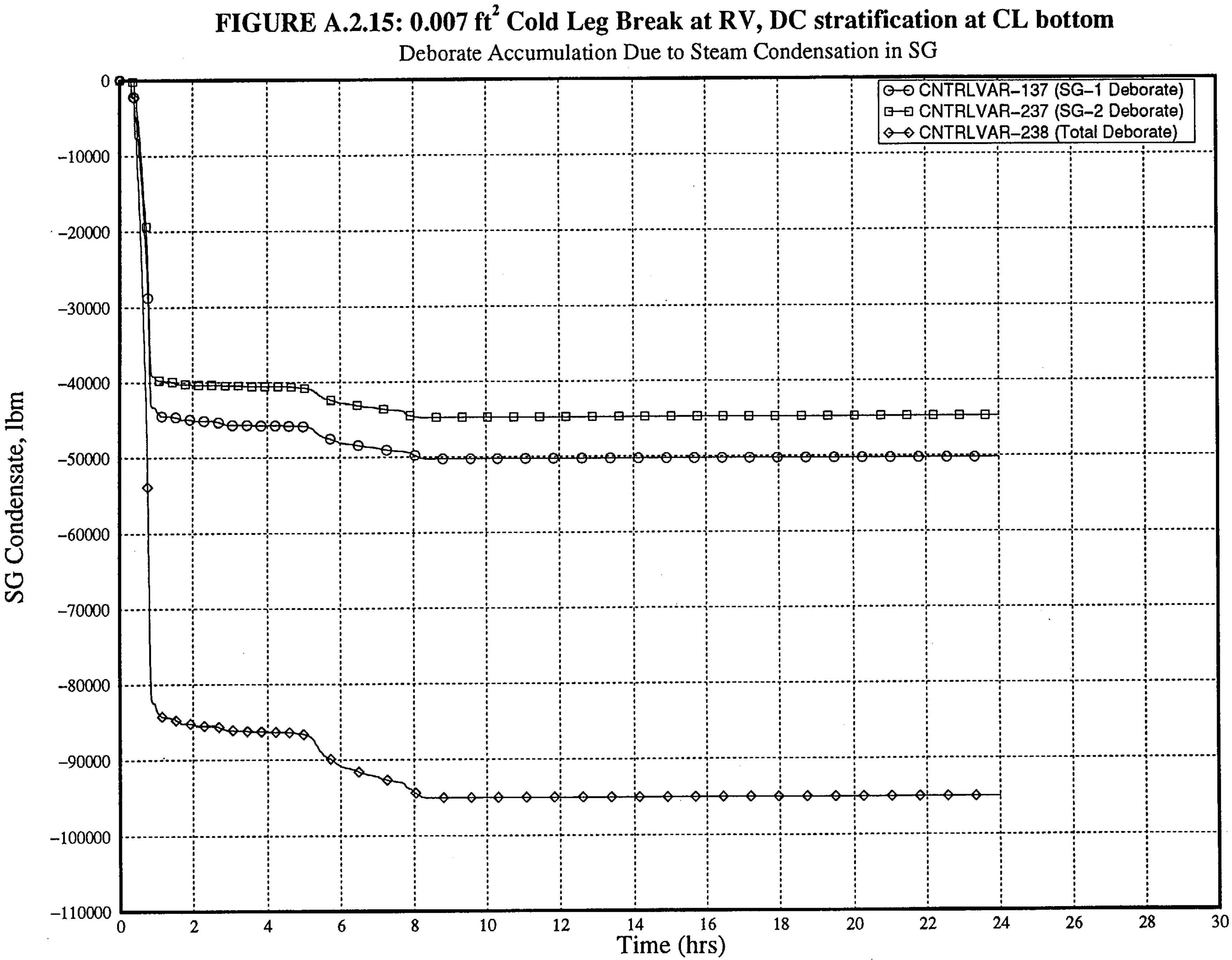


FIGURE A.2.15: 0.007 ft² Cold Leg Break at RV, DC stratification at CL bottom
Deborate Accumulation Due to Steam Condensation in SG
CNTRLVAR–137 (SG–1 Deborate)
CNTRLVAR–237 (SG–2 Deborate)
CNTRLVAR–238 (Total Deborate)
SG Condensate, lbm
Time (hrs)
0
–10000
–20000
–30000
–40000
–50000
–60000
–70000
–80000
–90000
–100000
–110000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

FIGURE A.3.1 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

System Pressures

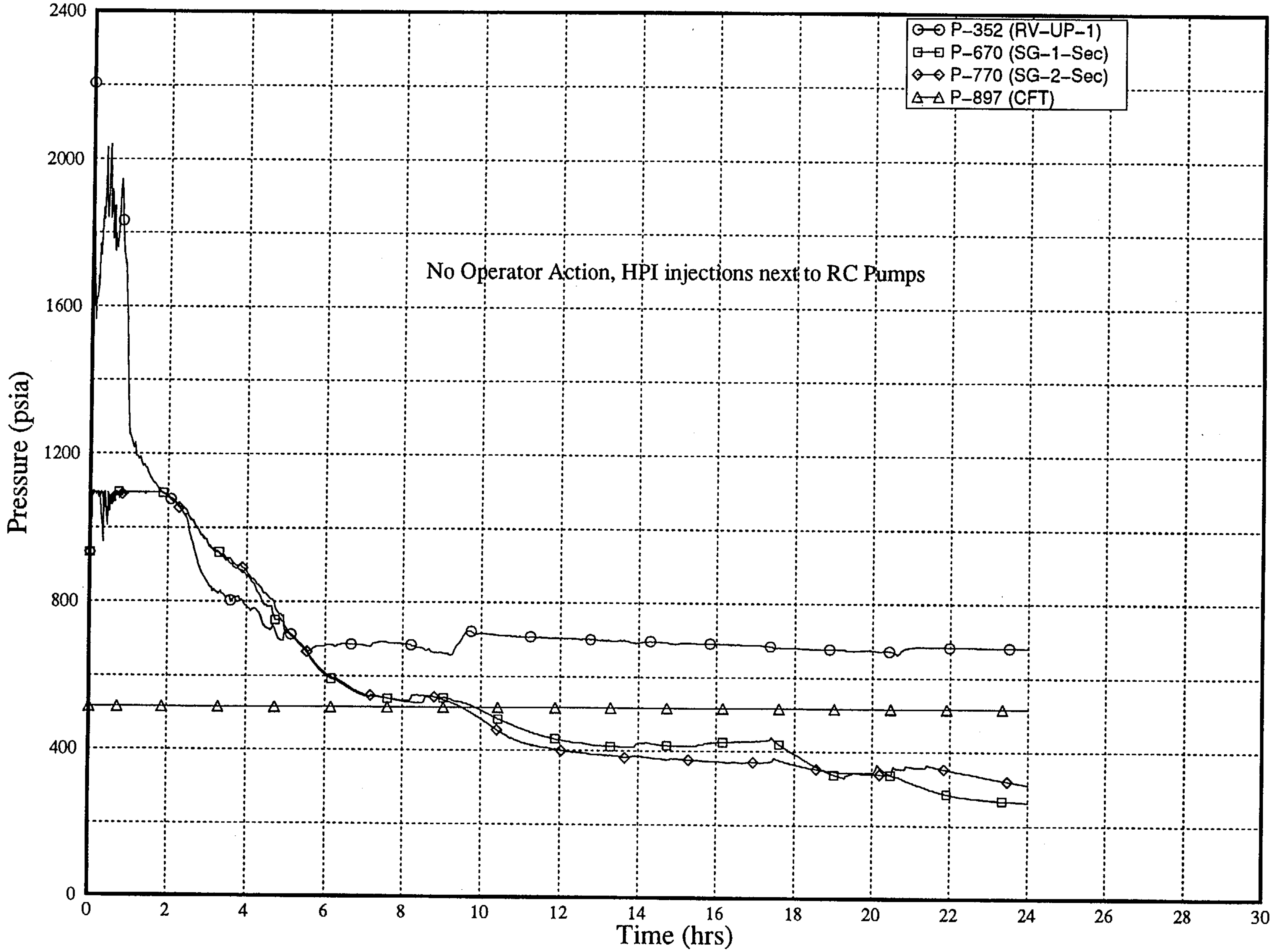


FIGURE A.3.2 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Intact Loop Collapsed Liquid Elevations

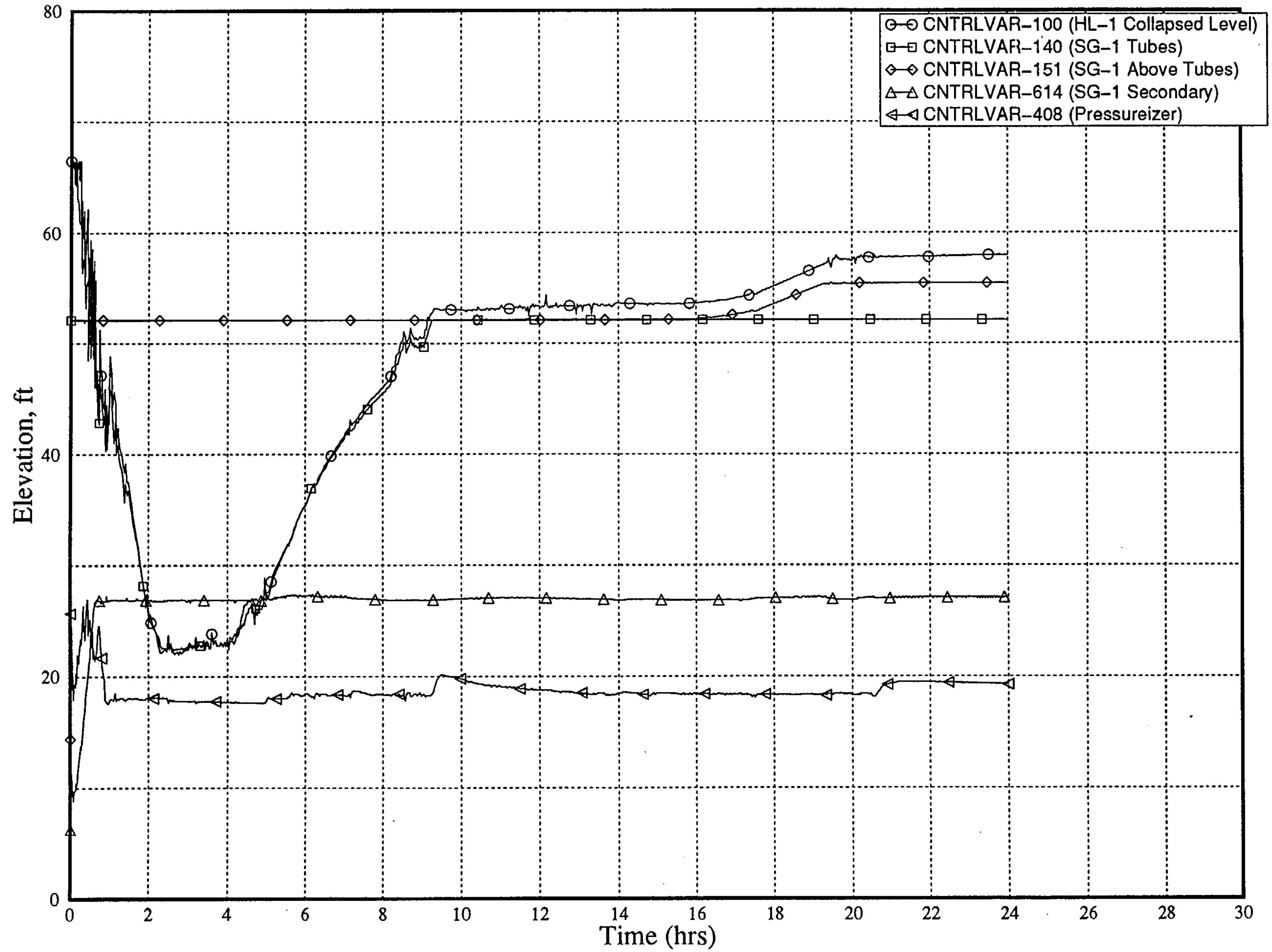


FIGURE A.3.3 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Broken Loop Collapsed Liquid Elevations

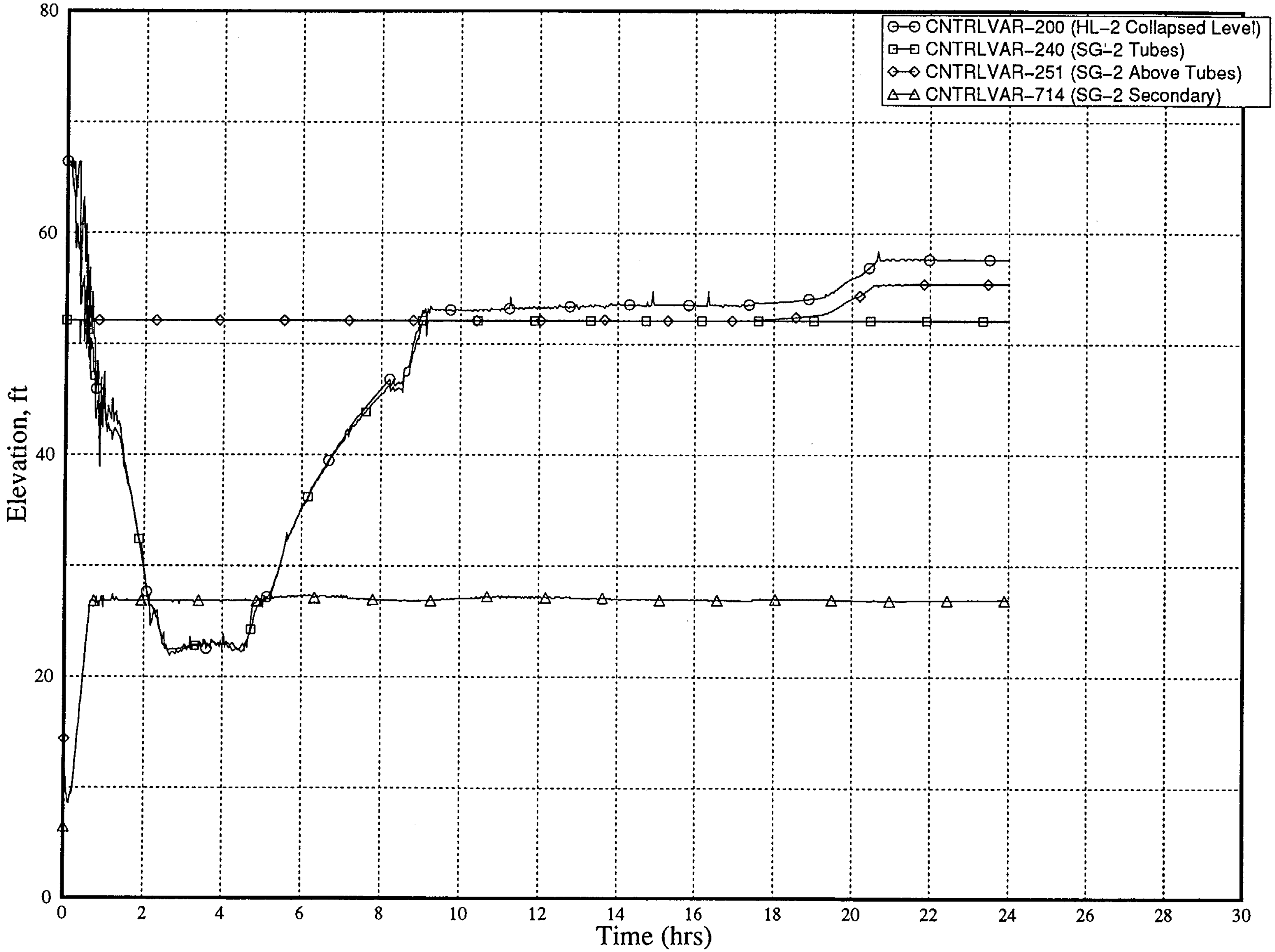


FIGURE A.3.4 : 0.007 ft² Cold Leg Break at RV, DC stratification at CL Centerline

Total Vent–Valves Flow Rate

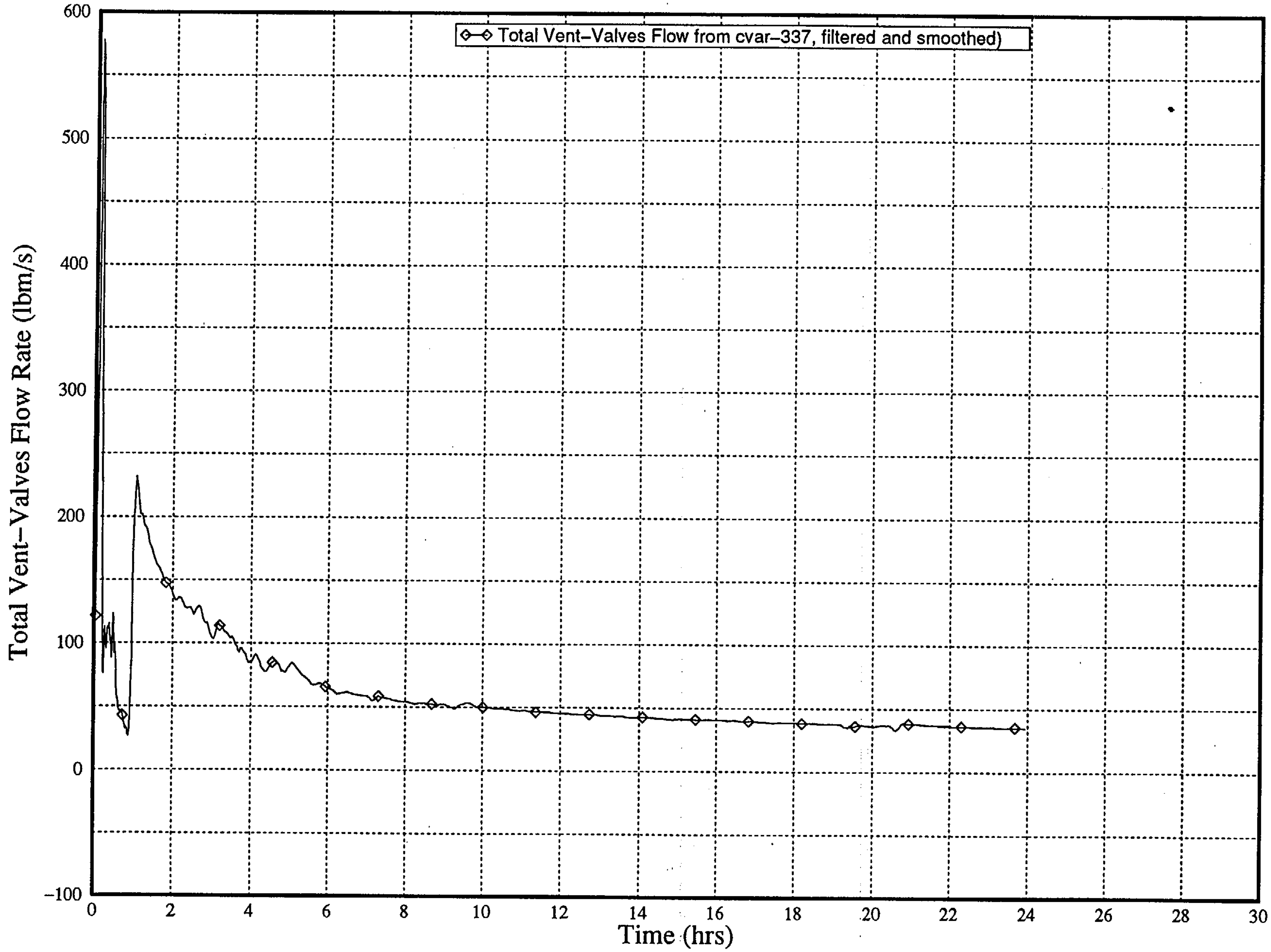


FIGURE A.3.5 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Vent Valve, Upper Plenum, Upper Head Voiding

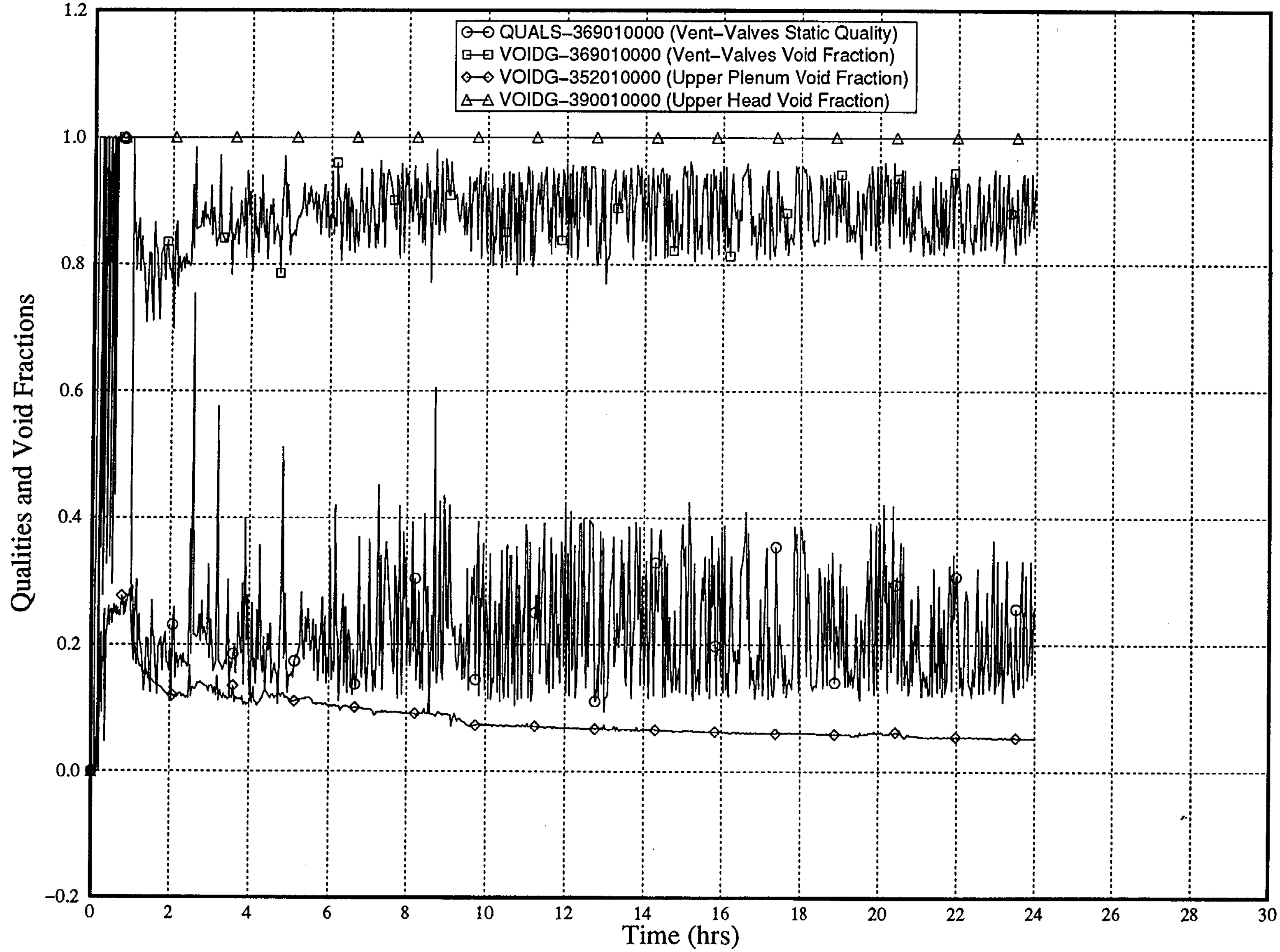


FIGURE A.3.6 : 0.007 ft² Cold Leg Break at RV, DC stratification at CL Centerline

Total ECCS and Break Flow

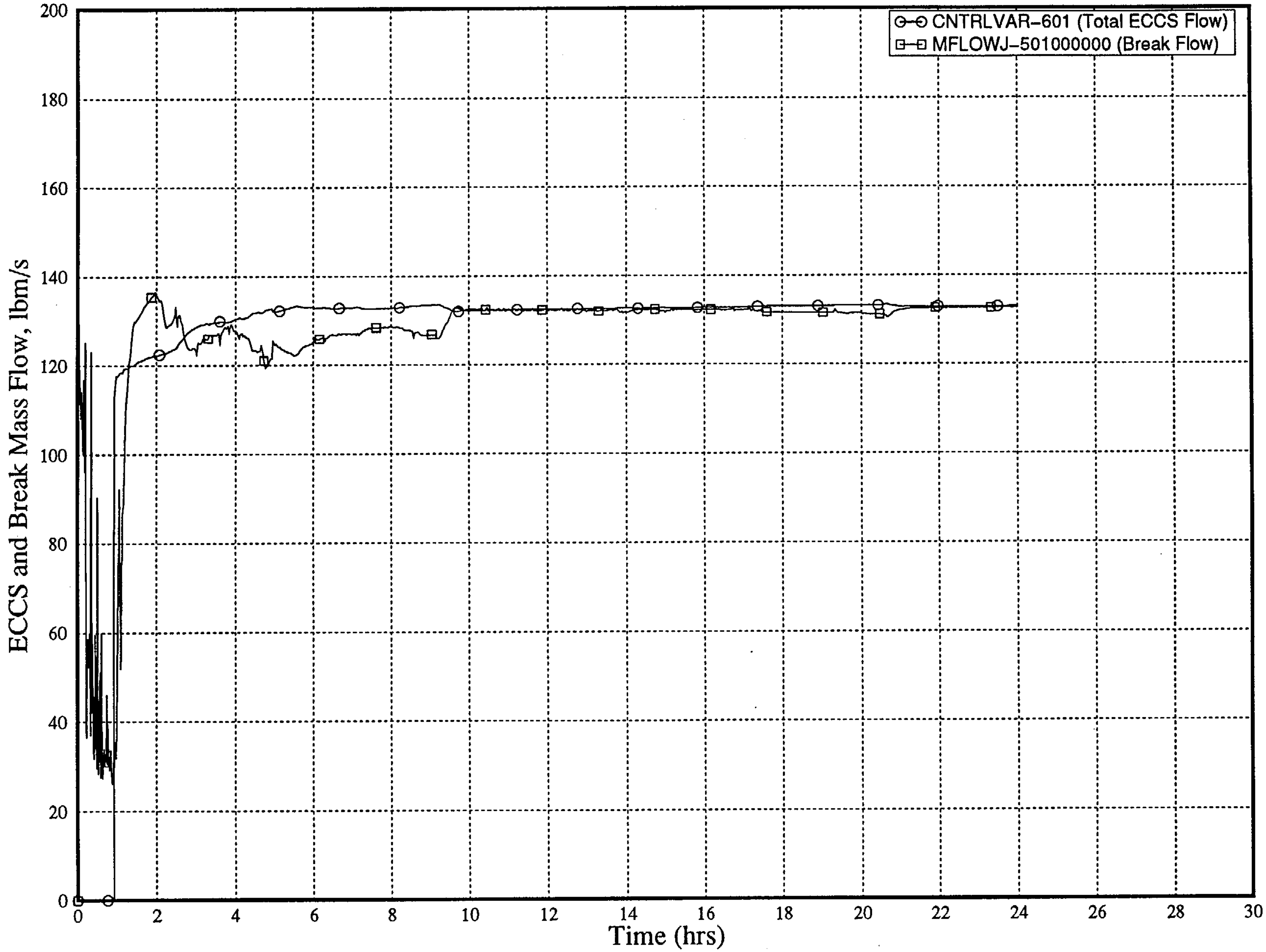


FIGURE A.3.7 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

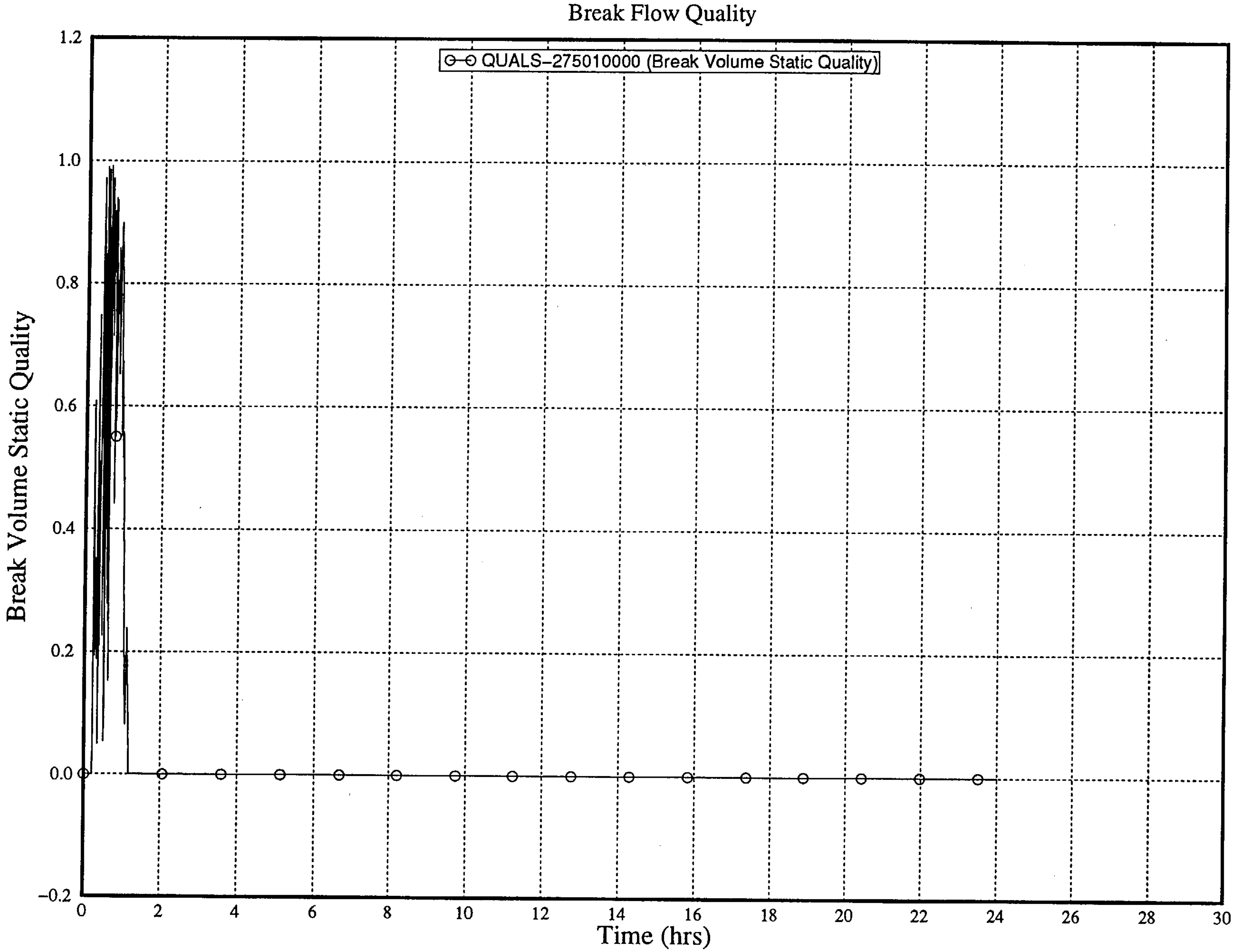


FIGURE A.3.8 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Break Flow Temperature

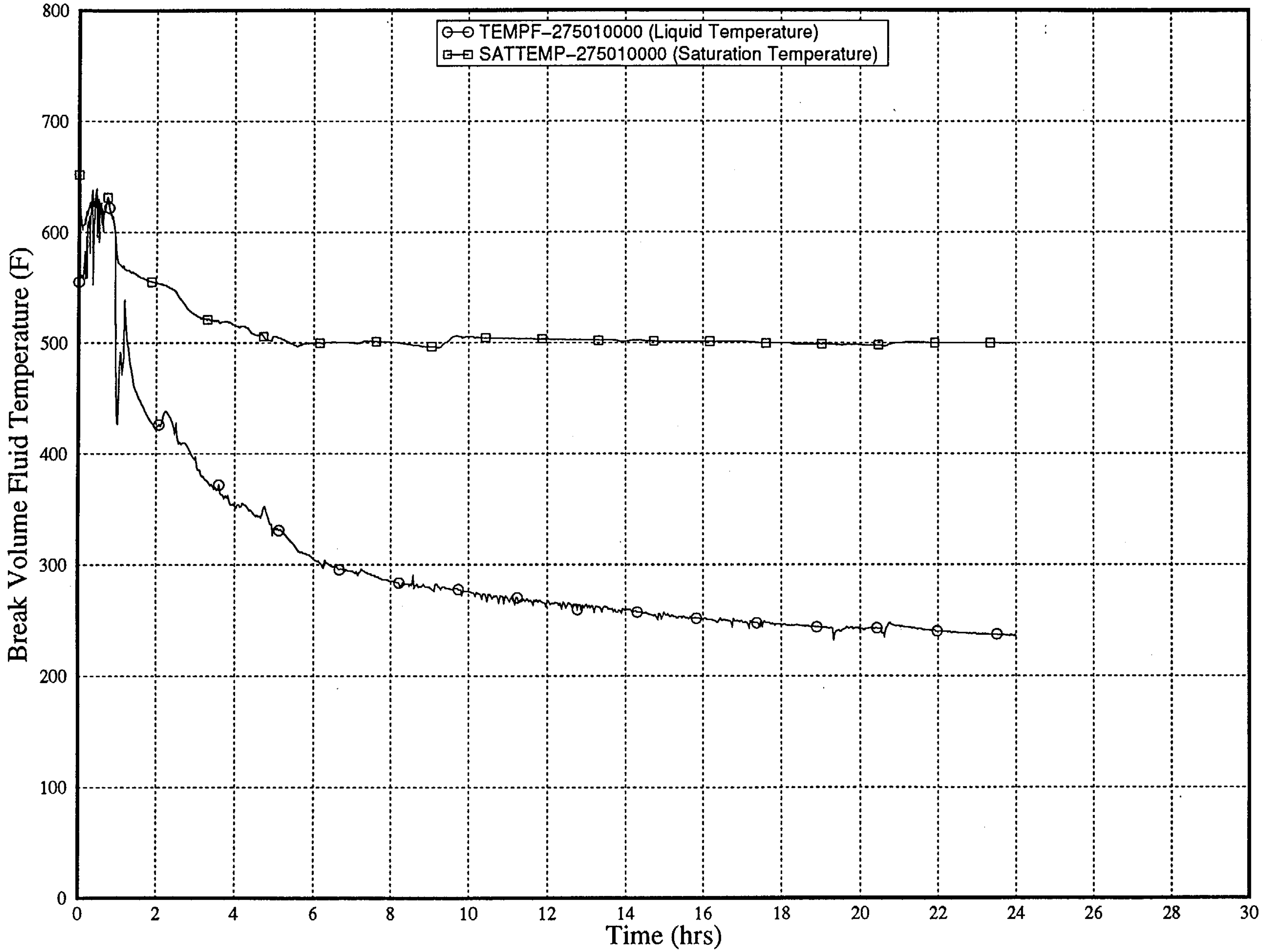


FIGURE A.3.9 : 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Intact Loop Cold Leg Flow Rates

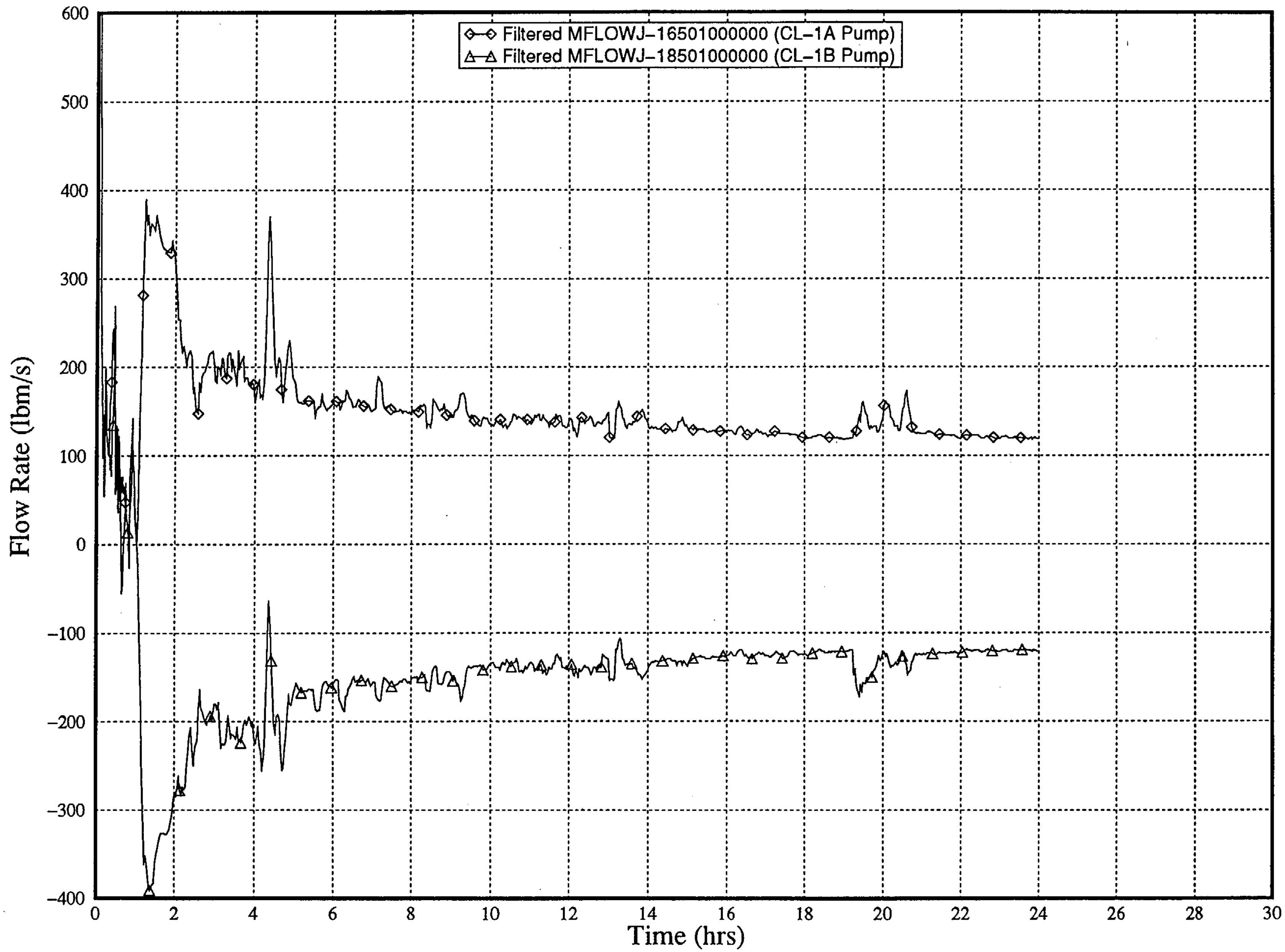


FIGURE A.3.10: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Broken Loop Cold Leg Flow Rates

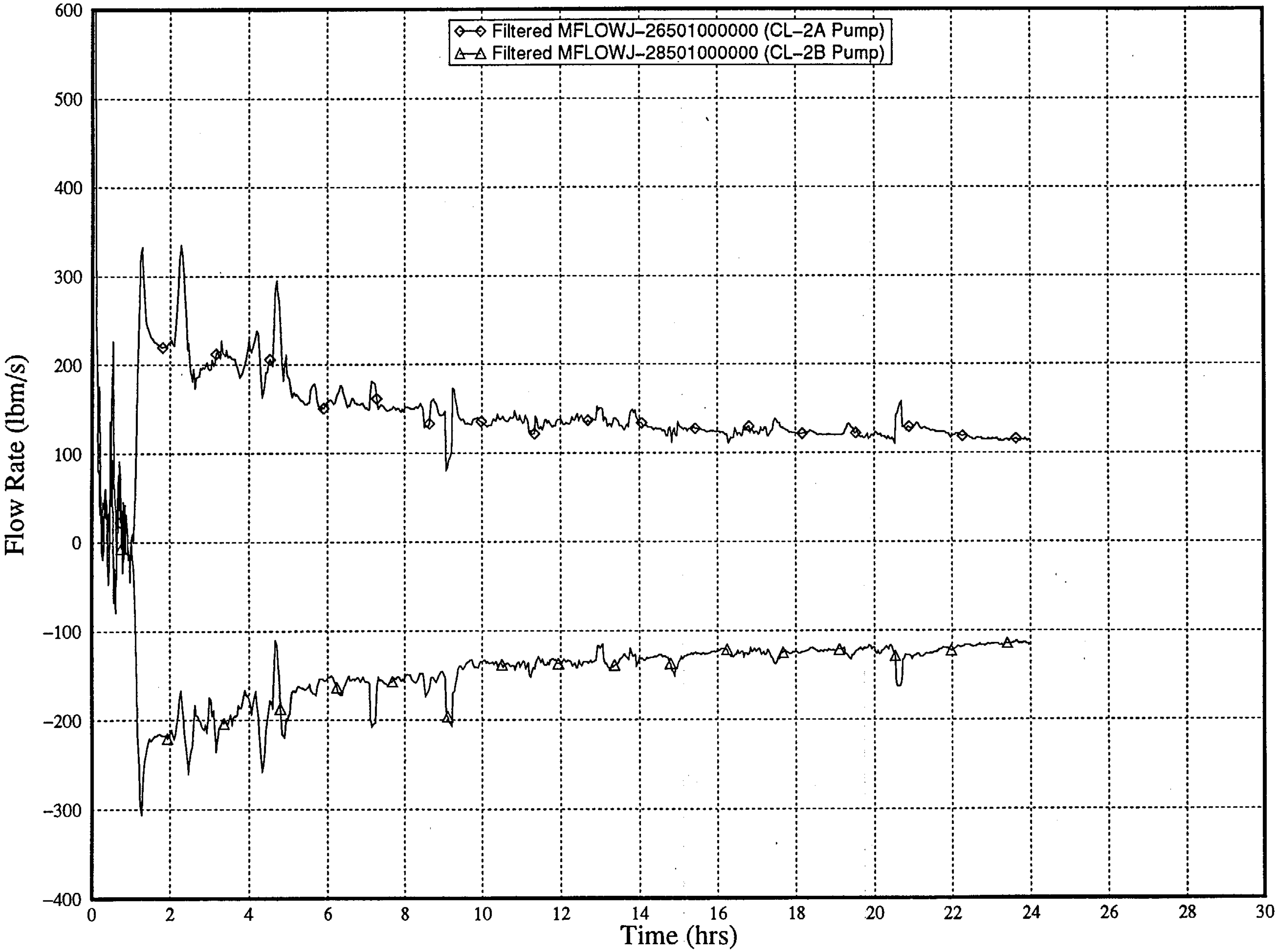


FIGURE A.3.11: 0.007 ft² Cold Leg Break at RV, DC stratification at CL Centerline

Loop Circulation Flow Rates

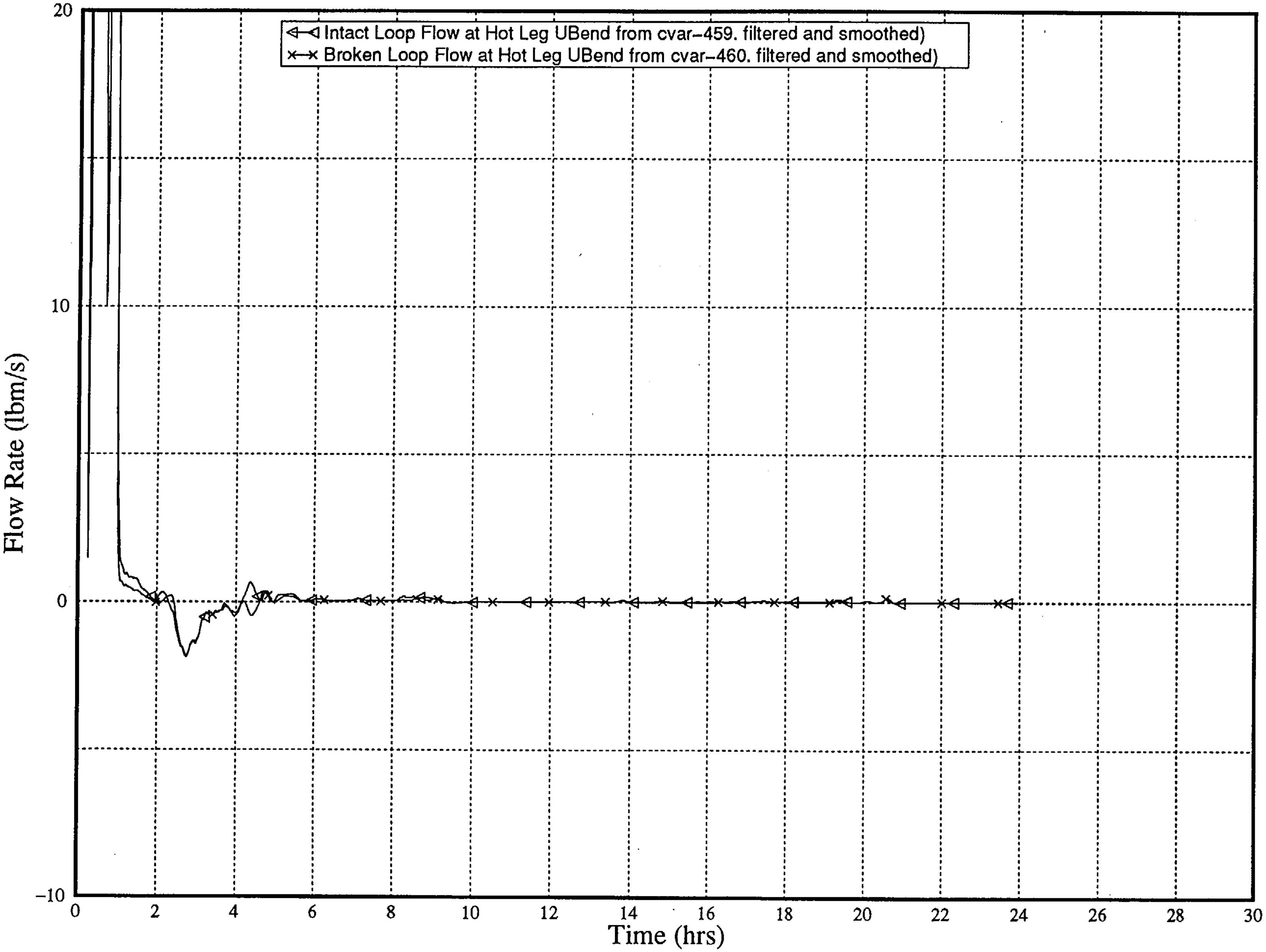


FIGURE A.3.12: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Core Inlet Flow

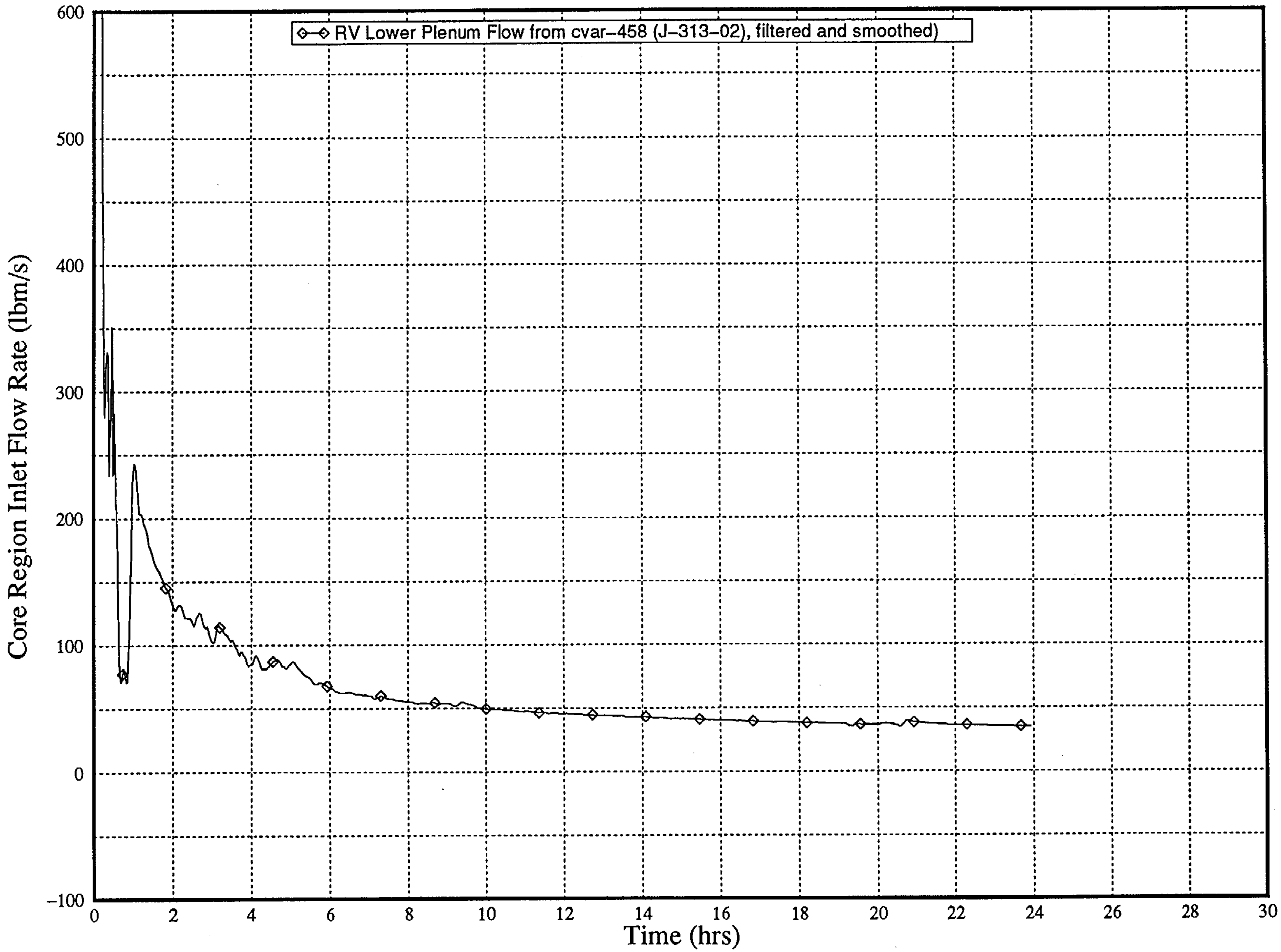


FIGURE A.3.13: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Reactor Vessel Temperature Distribution

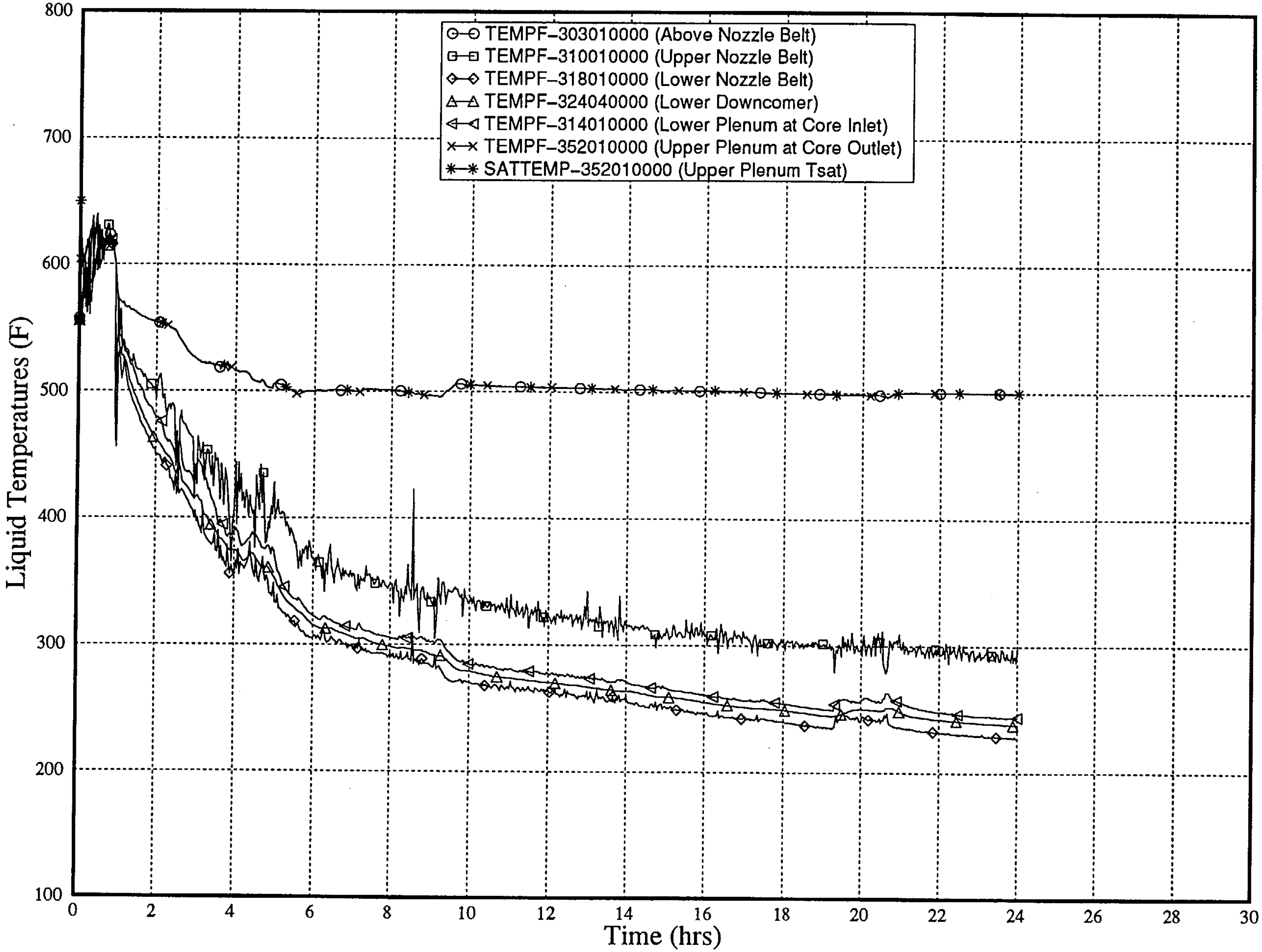


FIGURE A.3.14: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Normalized Core Power Generation

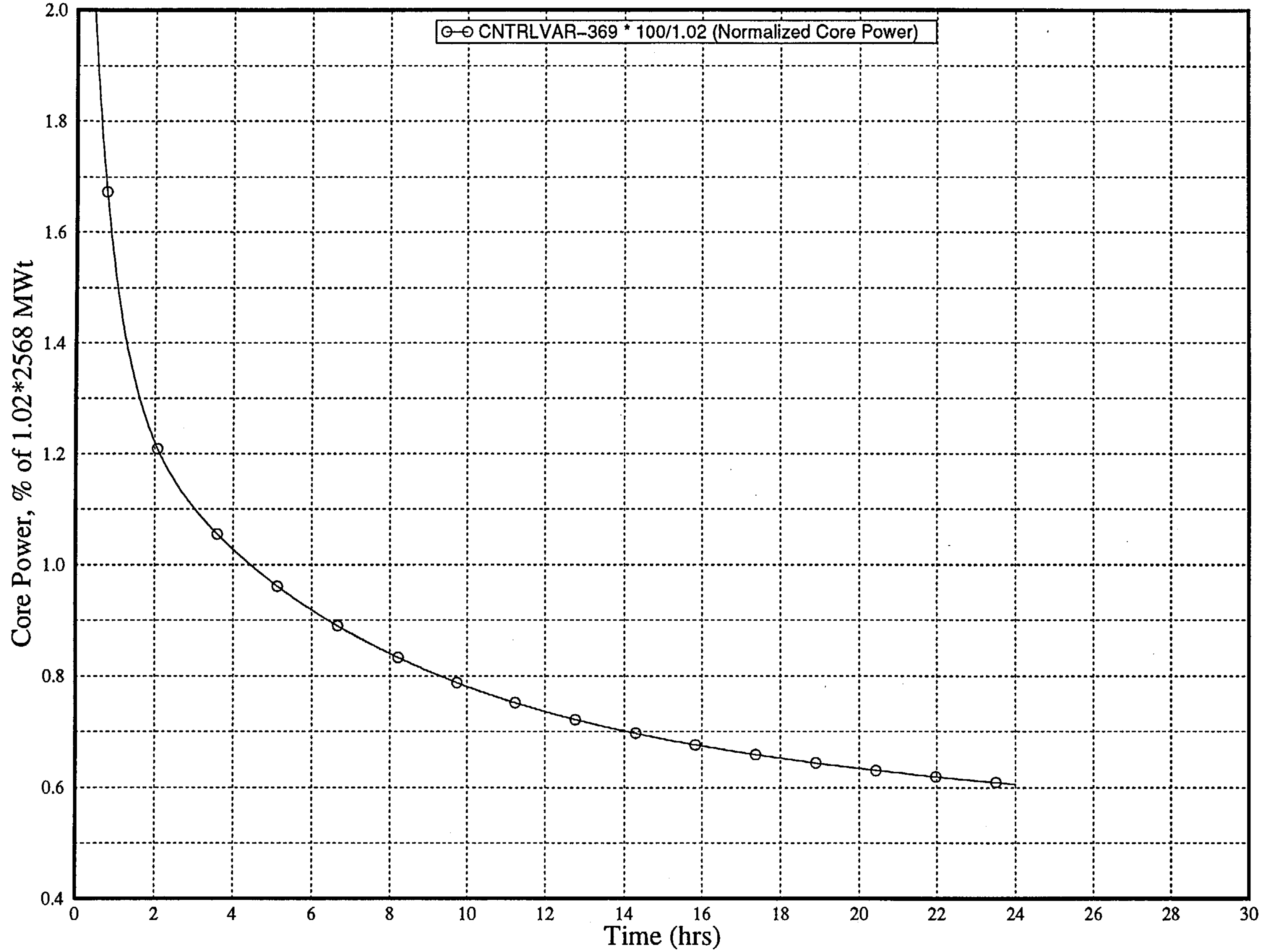


FIGURE A.3.15: 0.007 ft^2 Cold Leg Break at RV, DC stratification at CL Centerline

Deborate Accumulation Due to Steam Condensation in SG

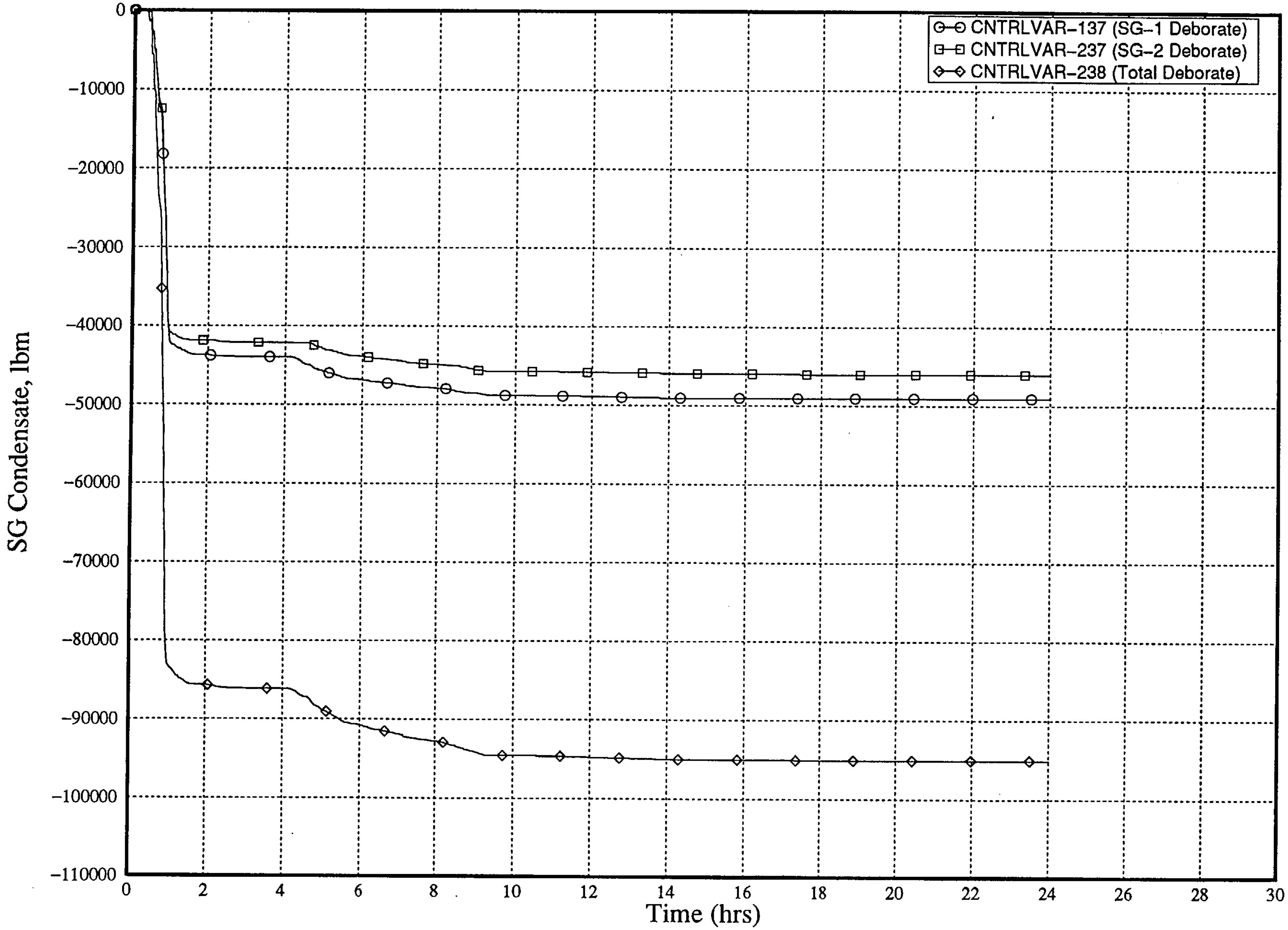


FIGURE A.4.1 : 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

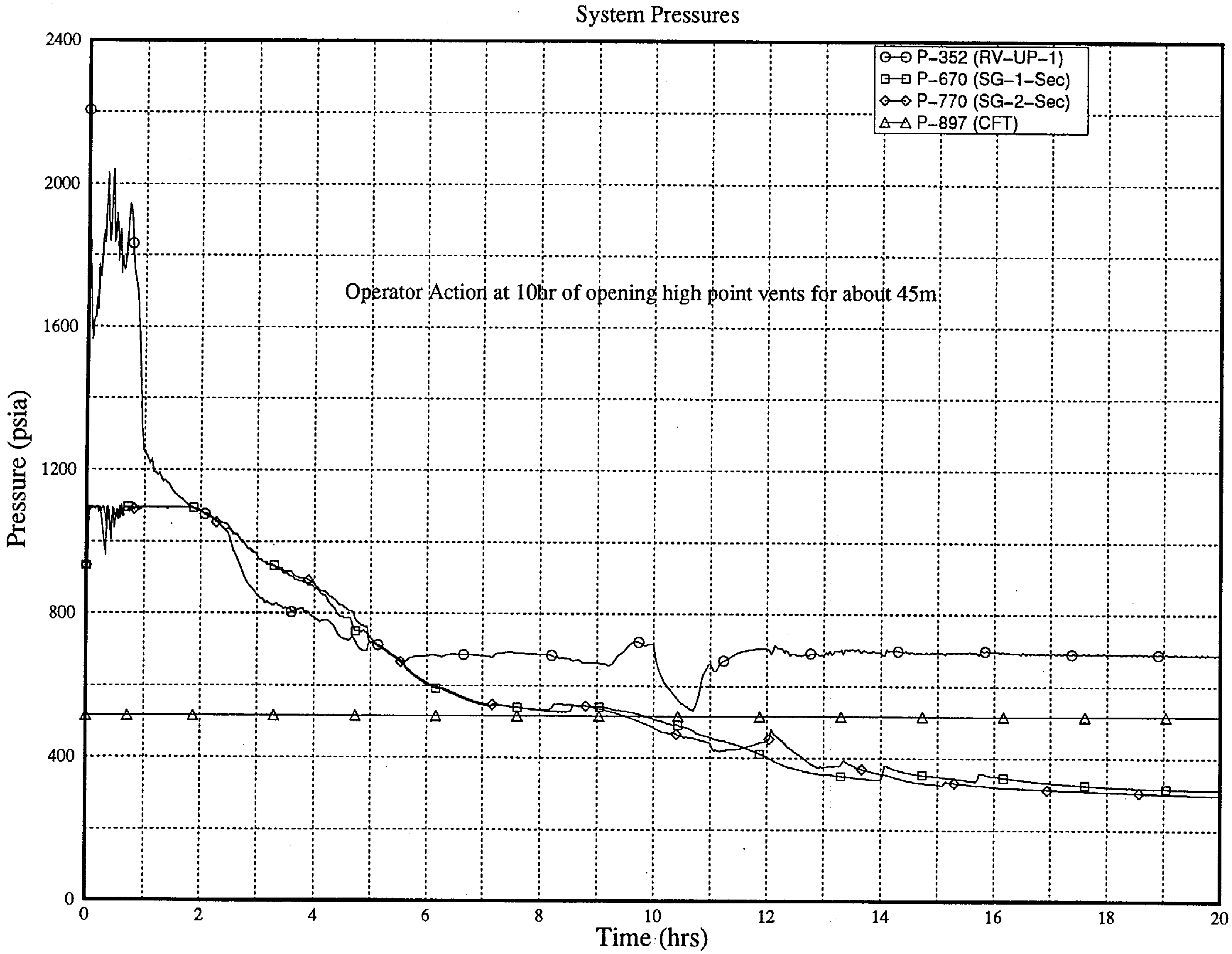


FIGURE A.4.2 : 0.007 ft² Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Intact Loop Collapsed Liquid Elevations

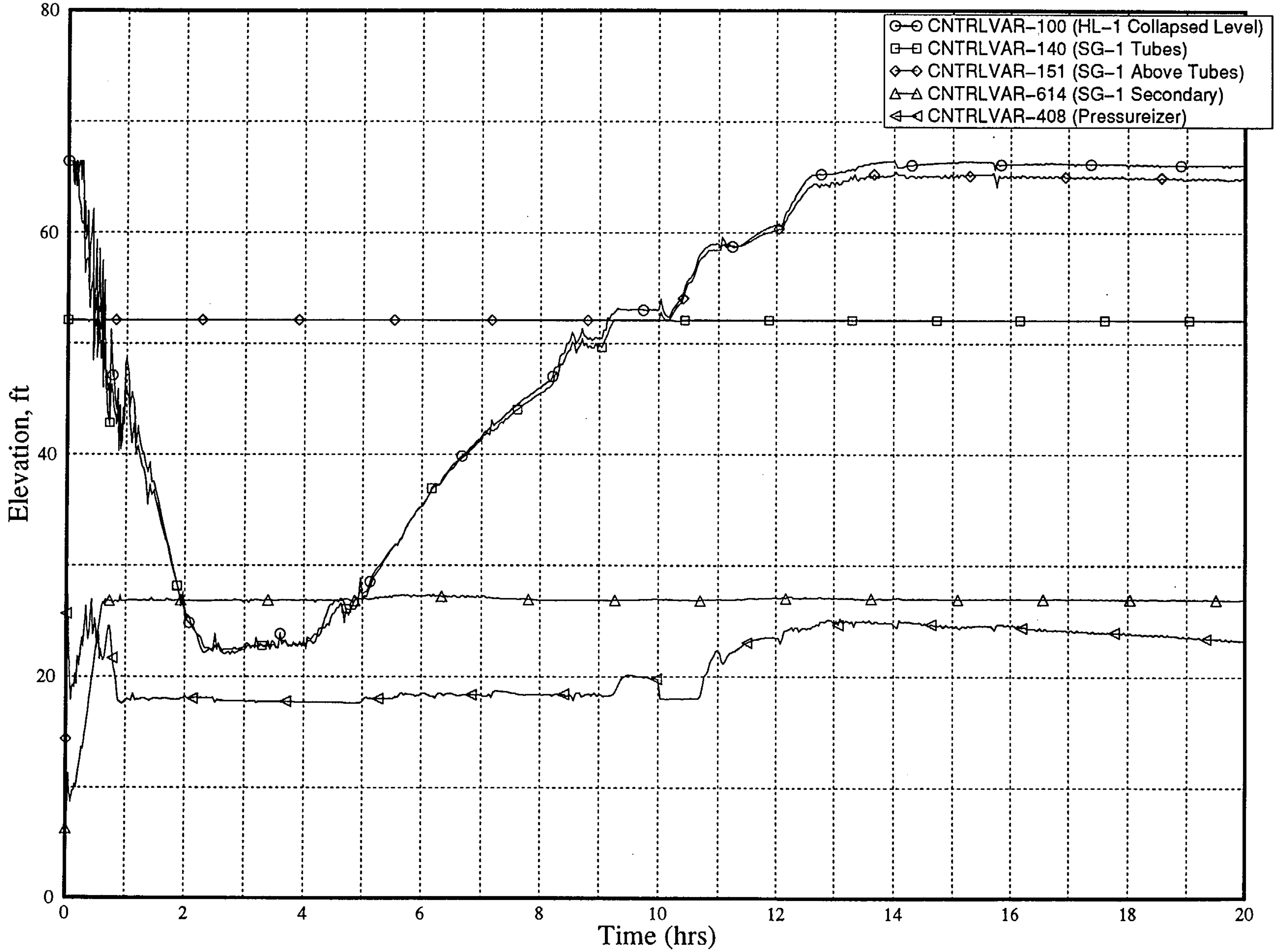


FIGURE A.4.3 : 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Broken Loop Collapsed Liquid Elevations

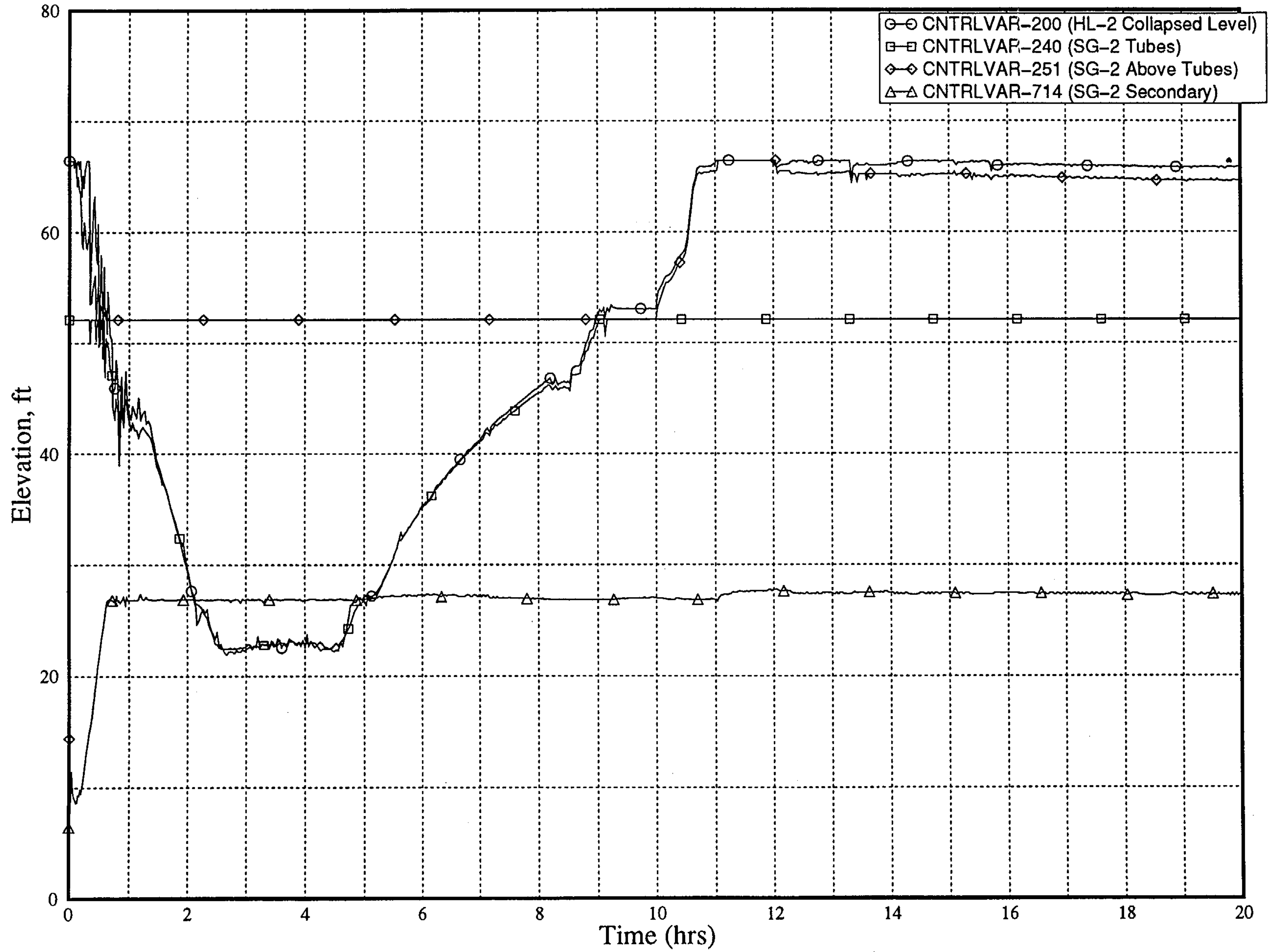


FIGURE A.4.4 : 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

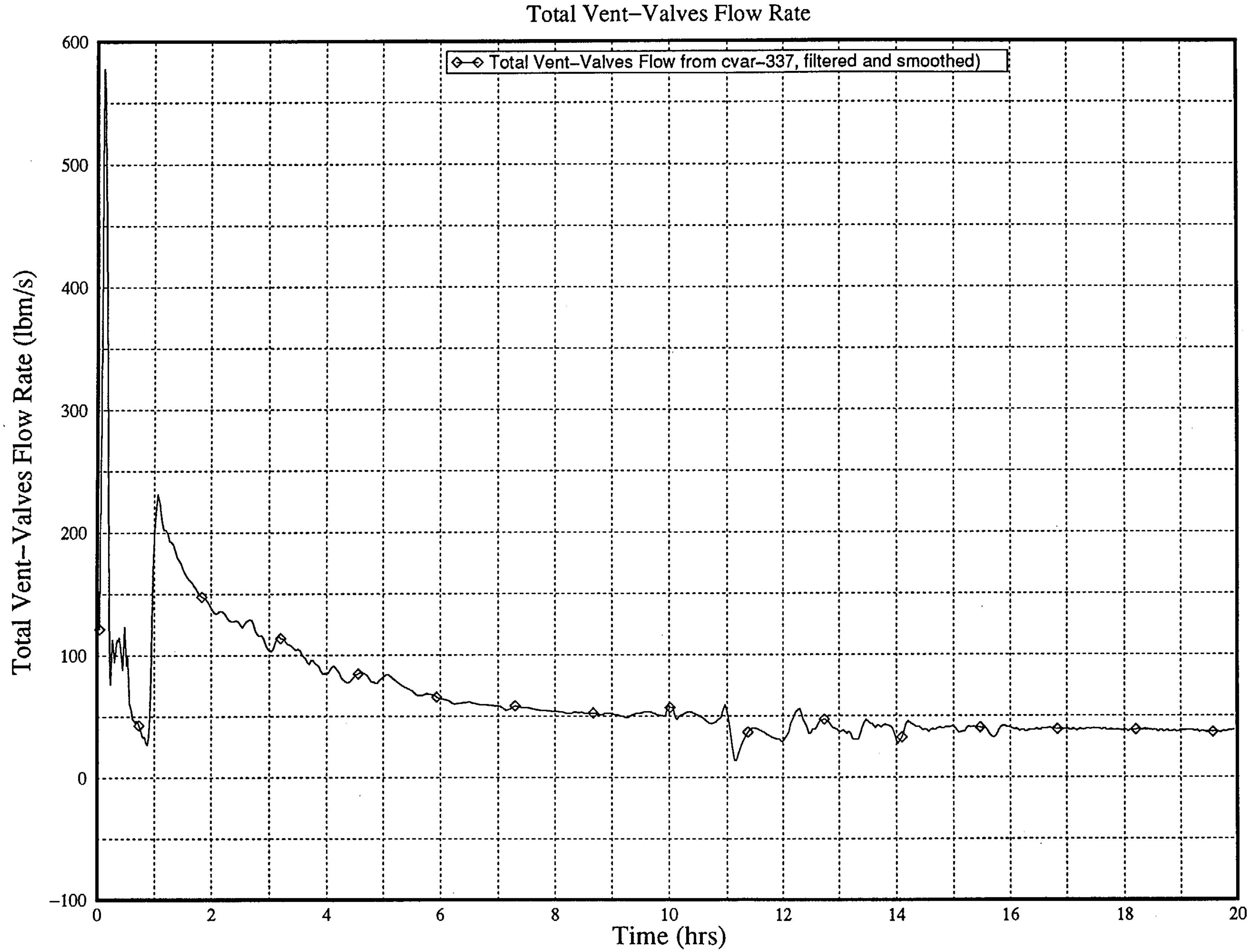


FIGURE A.4.5 : 0.007 ft² Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Vent Valve, Upper Plenum, Upper Head Voiding

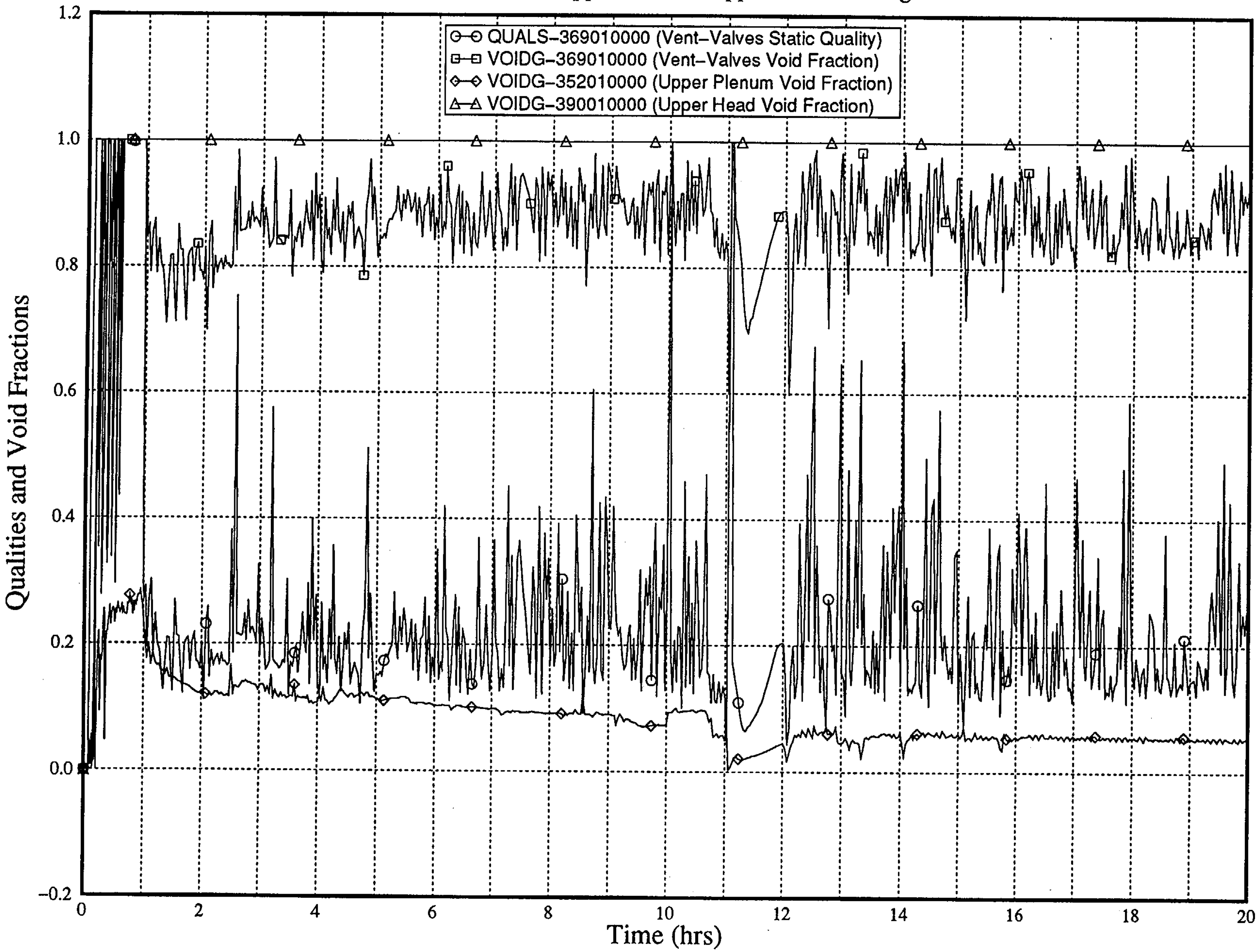


FIGURE A.4.6 : 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Total ECCS and Break Flow

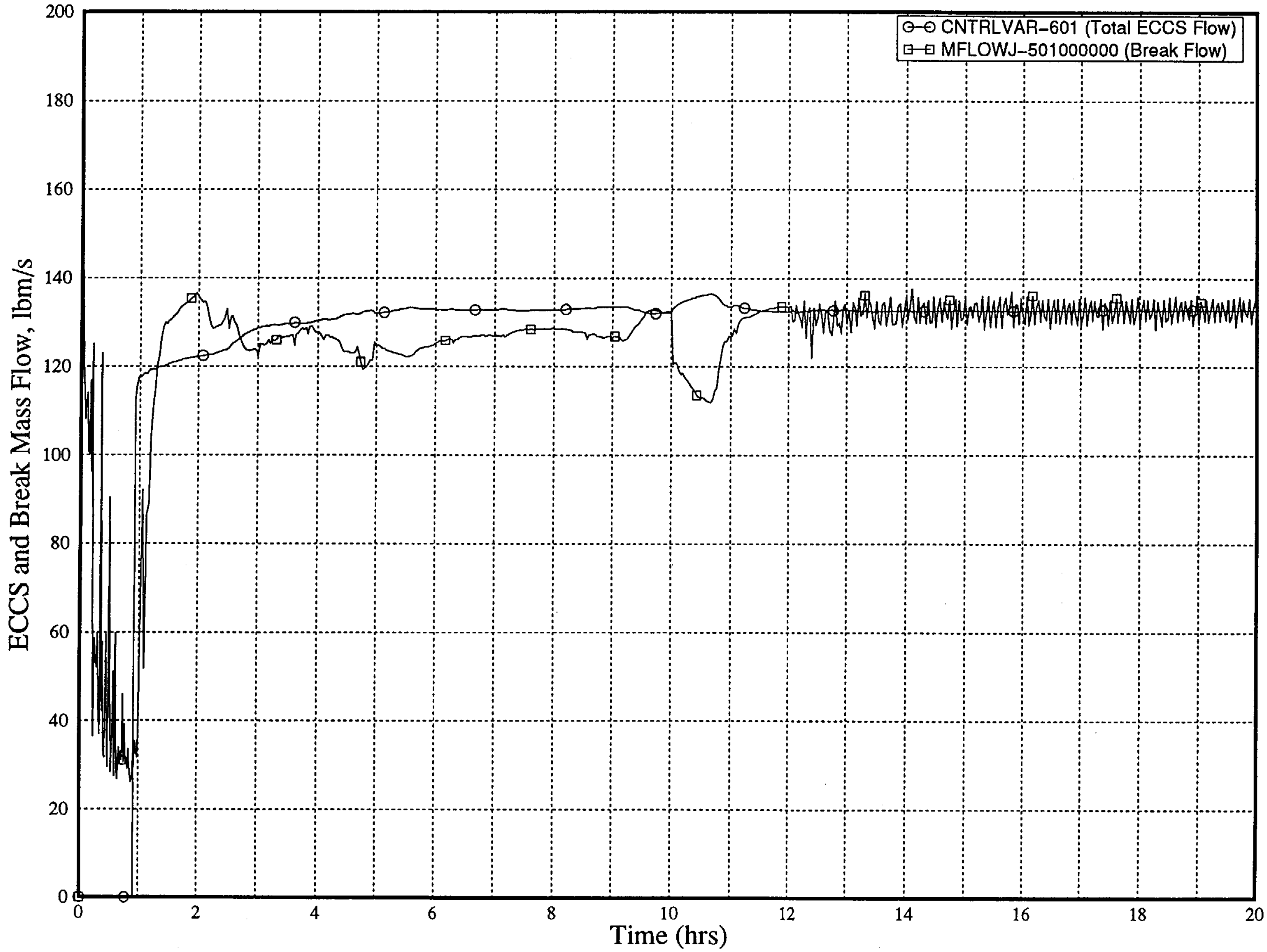


FIGURE A.4.7 : 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Break Flow Quality

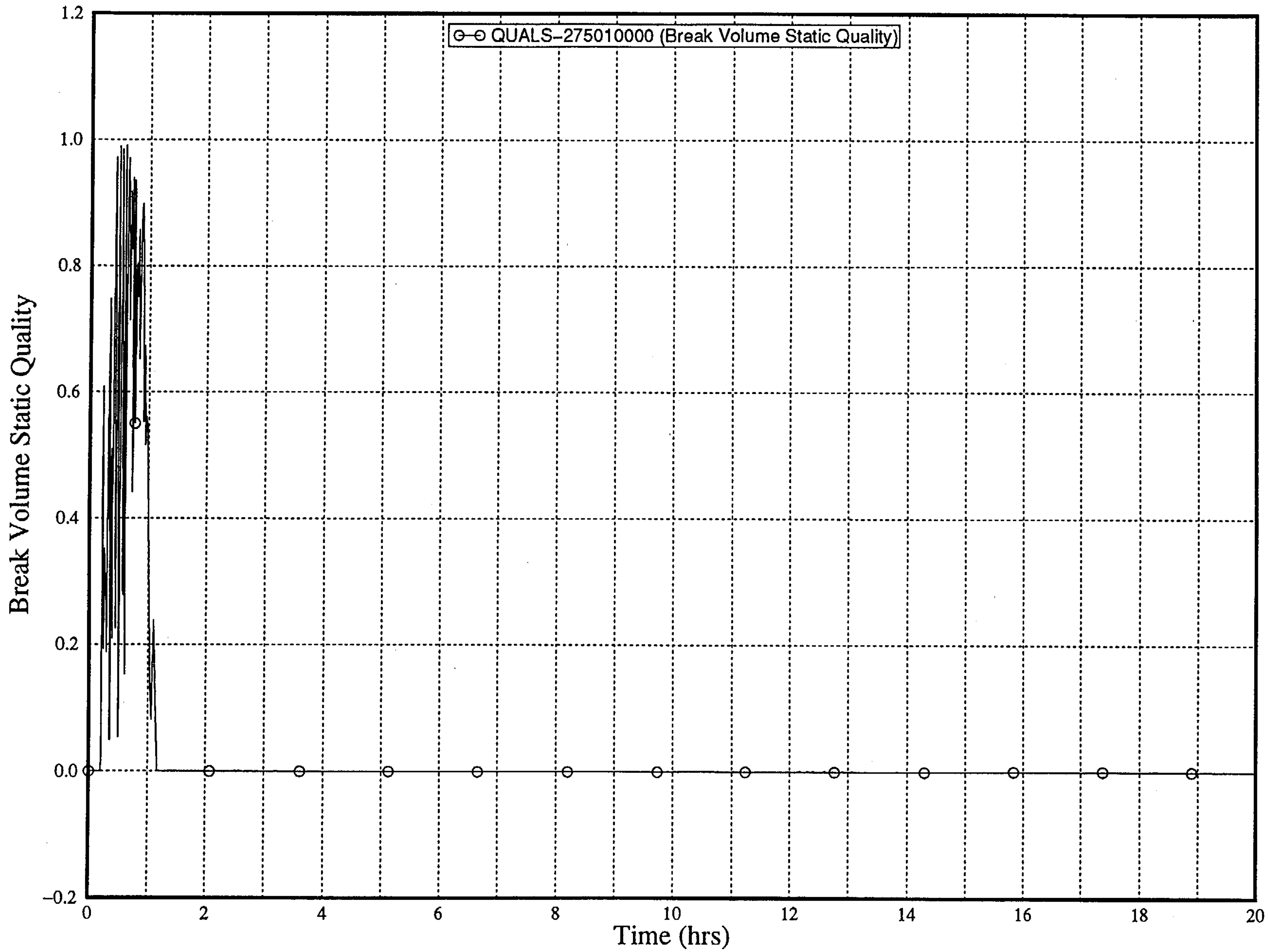


FIGURE A.4.8 : 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Break Flow Temperature

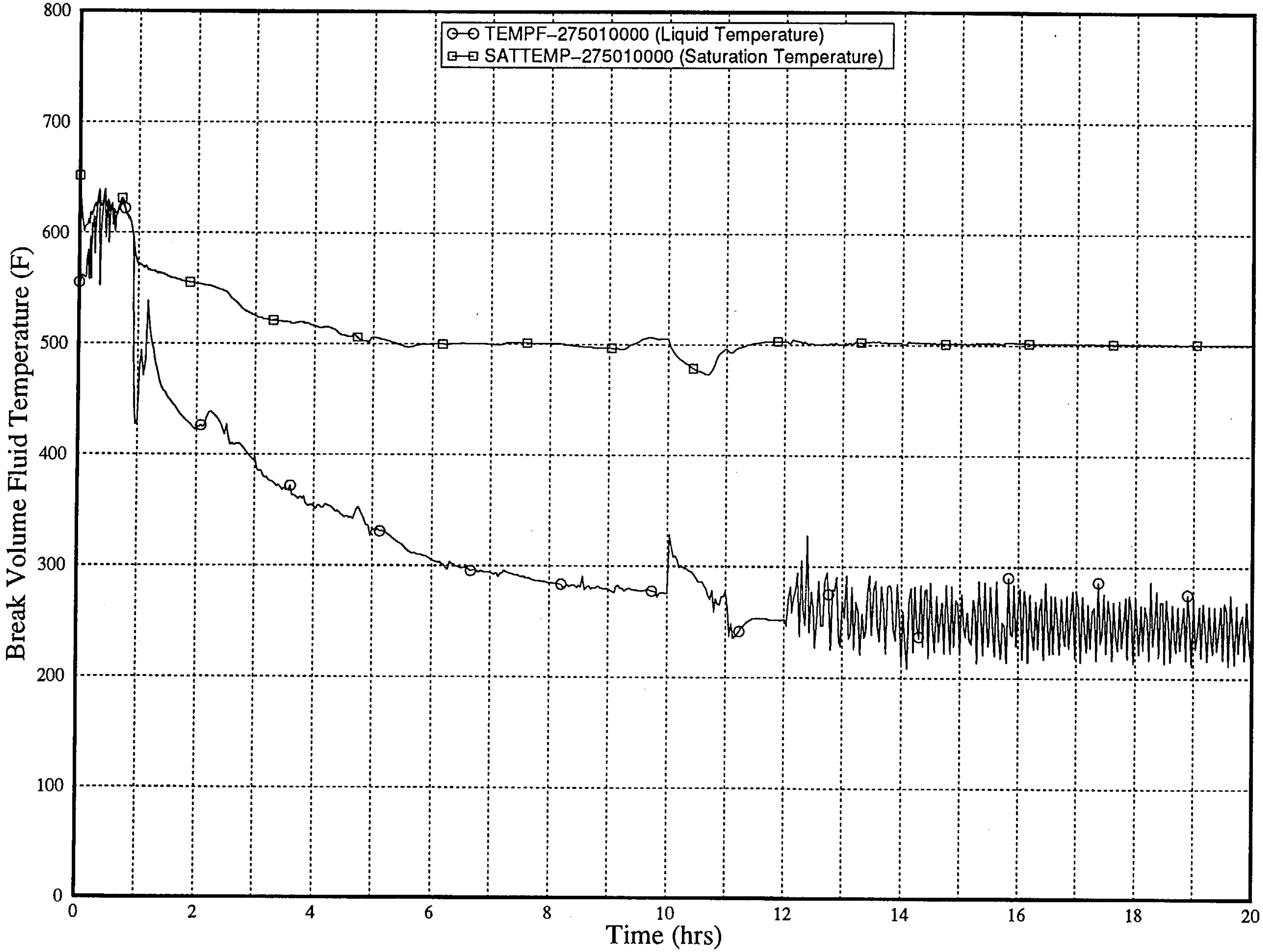


FIGURE A.4.9 : 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Intact Loop Cold Leg Flow Rates

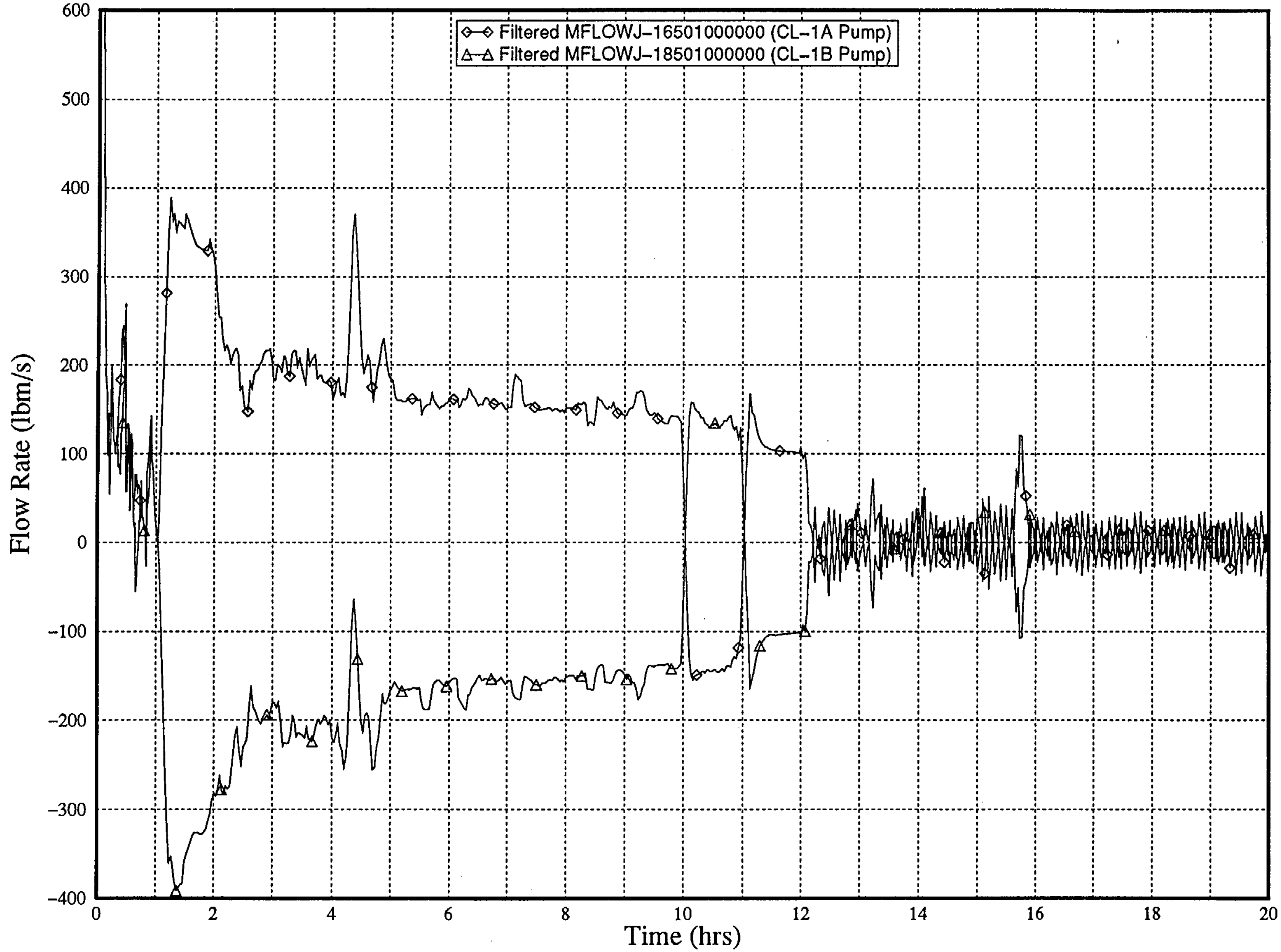


FIGURE A.4.10: 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

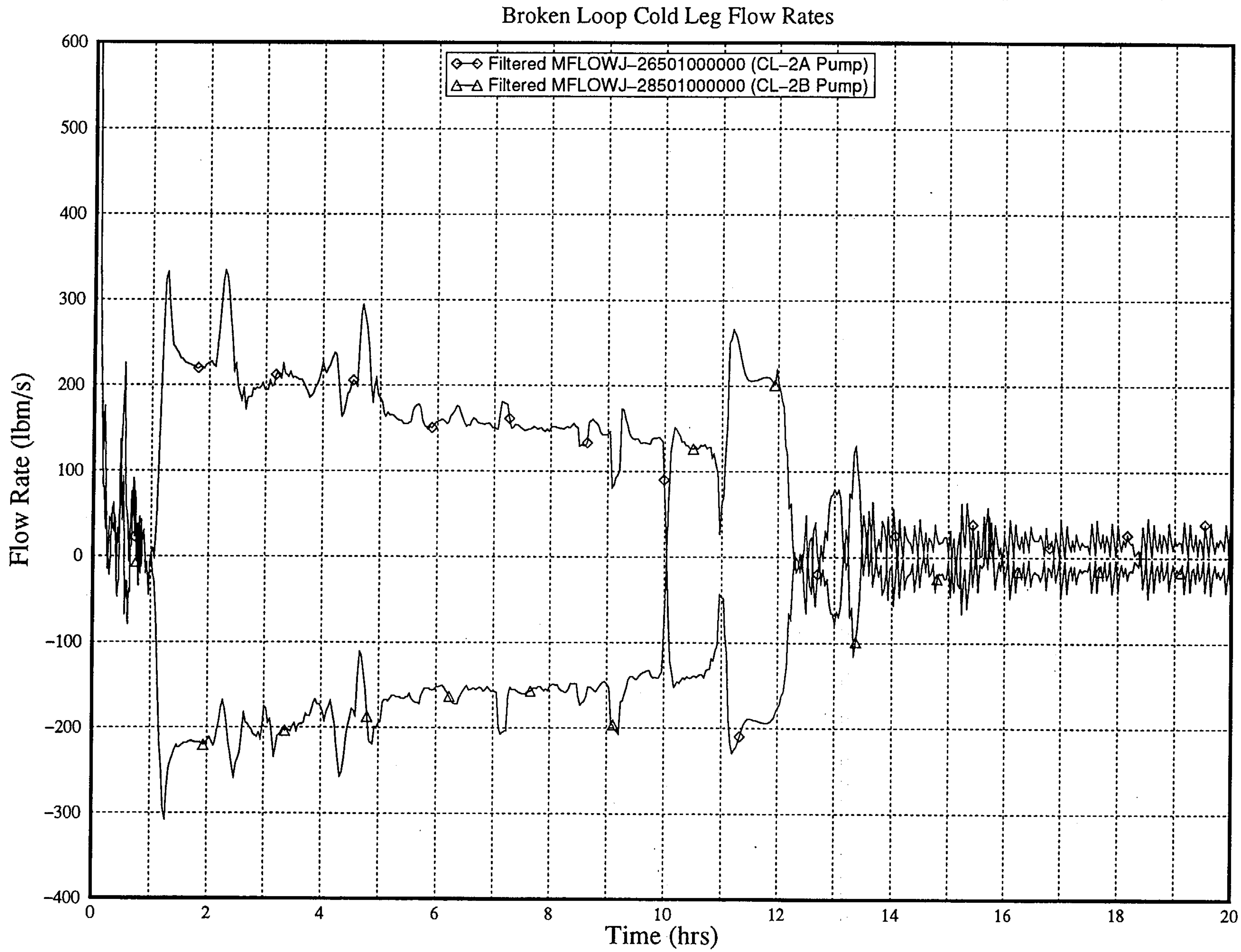


FIGURE A.4.11: 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Loop Circulation Flow Rates

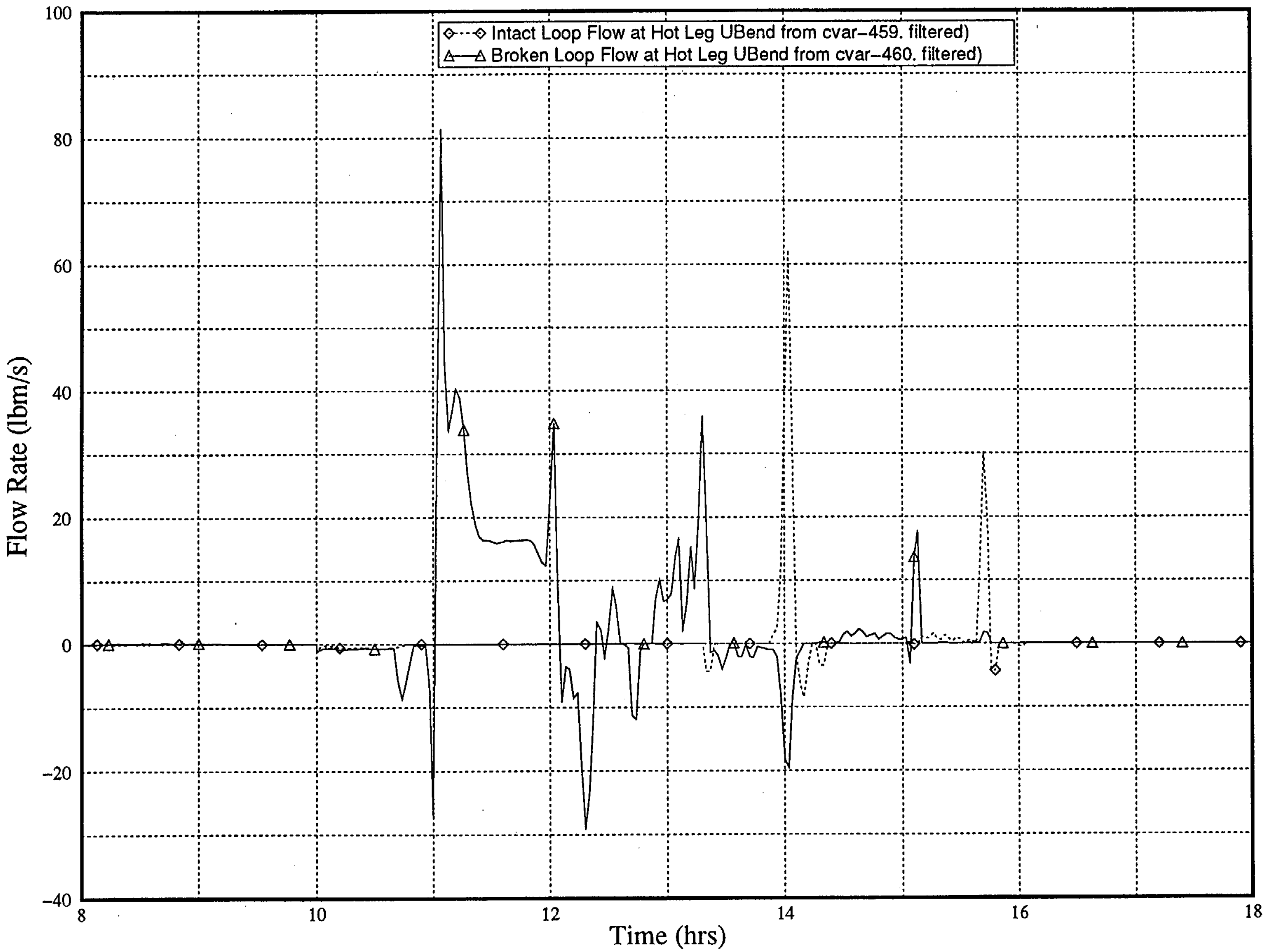


FIGURE A.4.12: 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

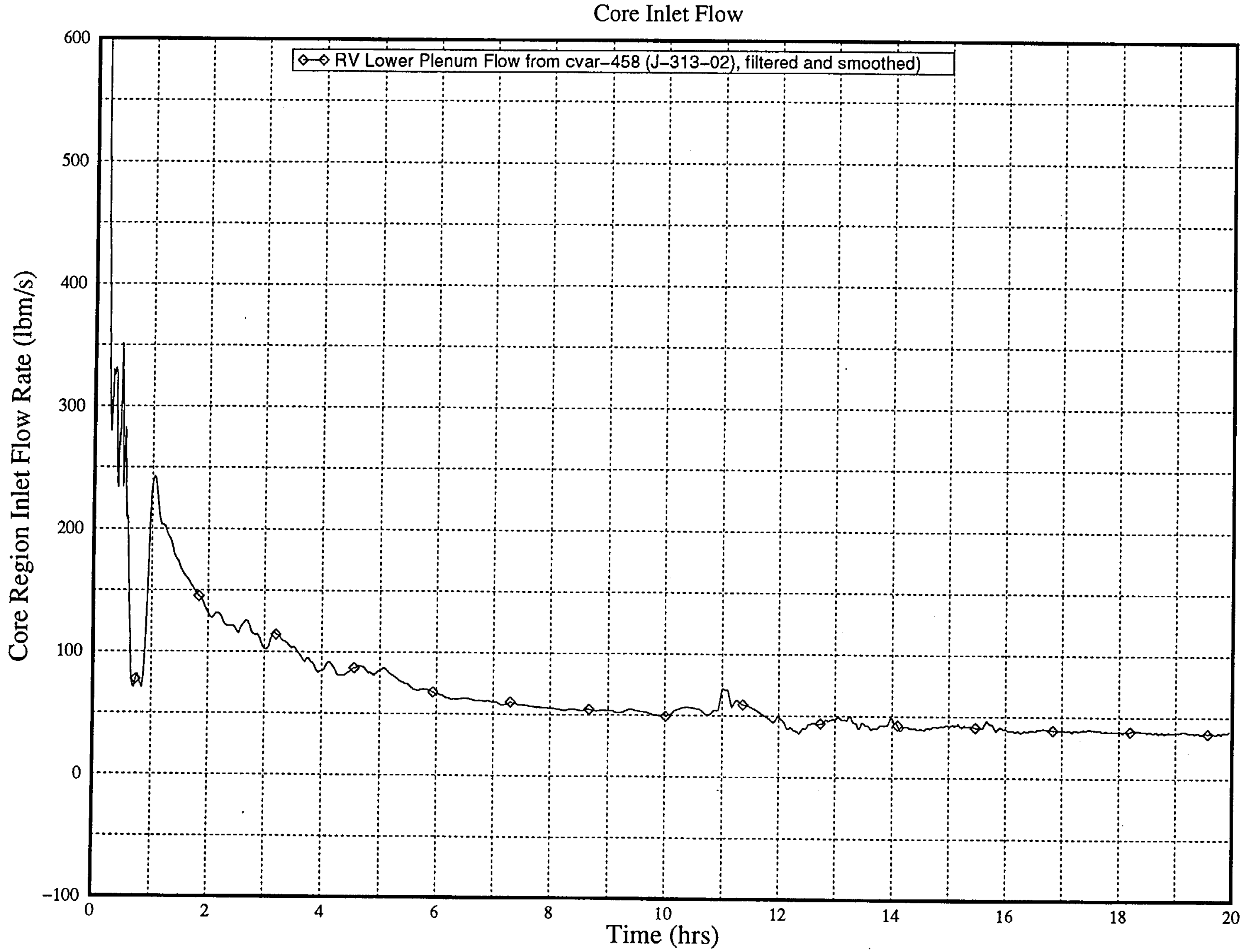


FIGURE A.4.13: 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Reactor Vessel Temperature Distribution

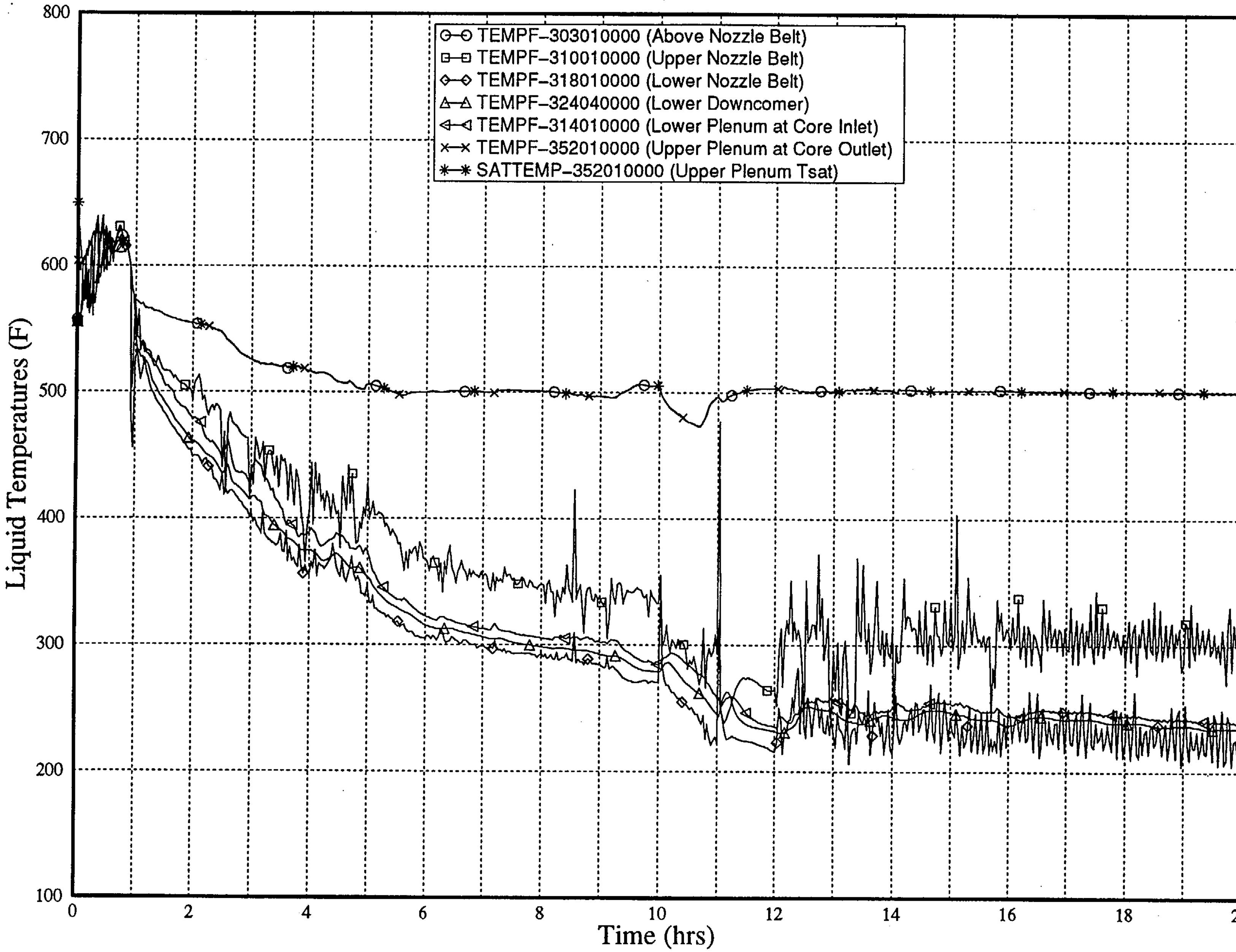


FIGURE A.4.14: 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Normalized Core Power Generation

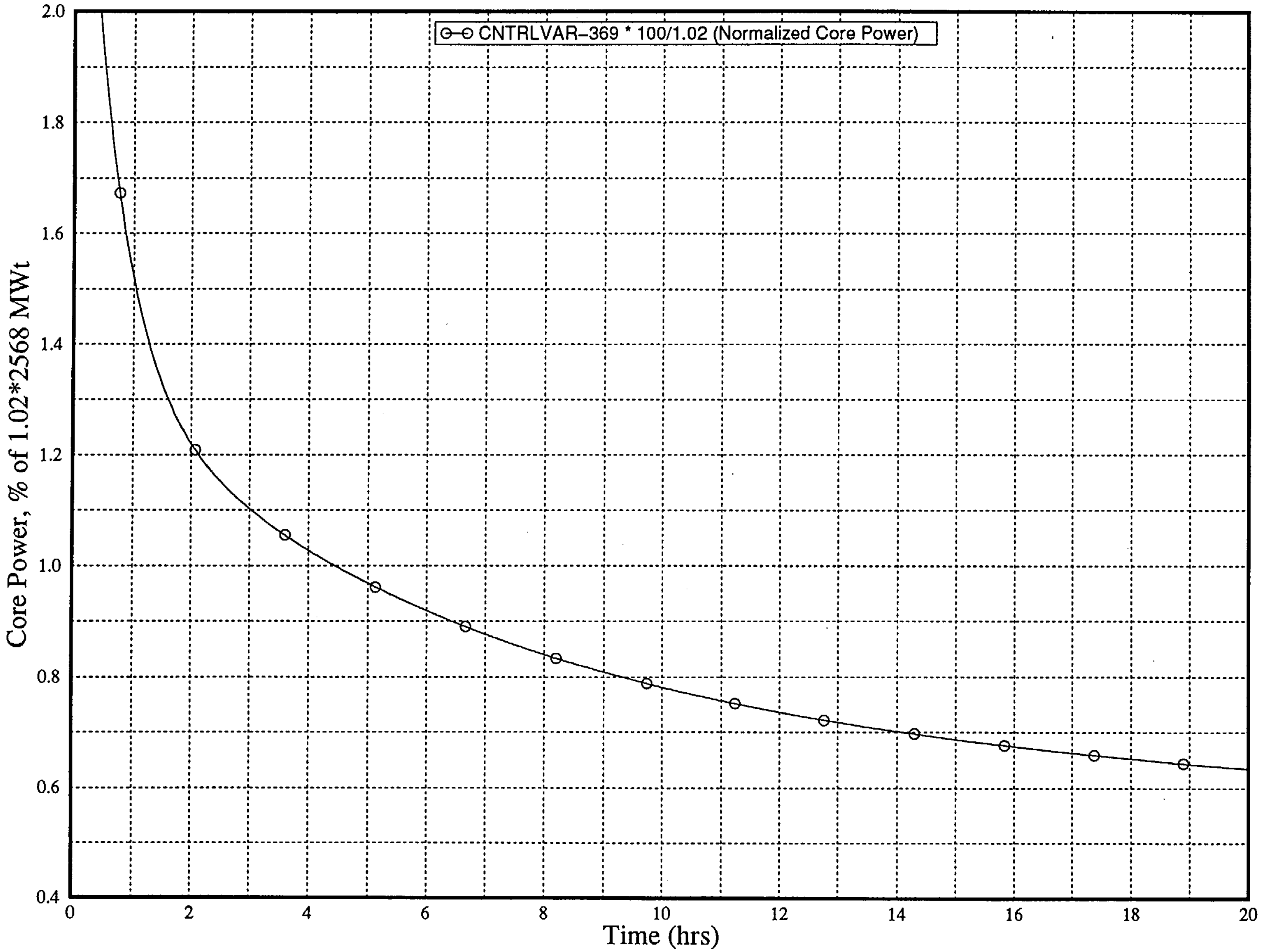


FIGURE A.4.15: 0.007 ft^2 Cold Leg Break, Mid Operator Action (HPVs opened at 10hr).

Deborate Accumulation Due to Steam Condensation in SG

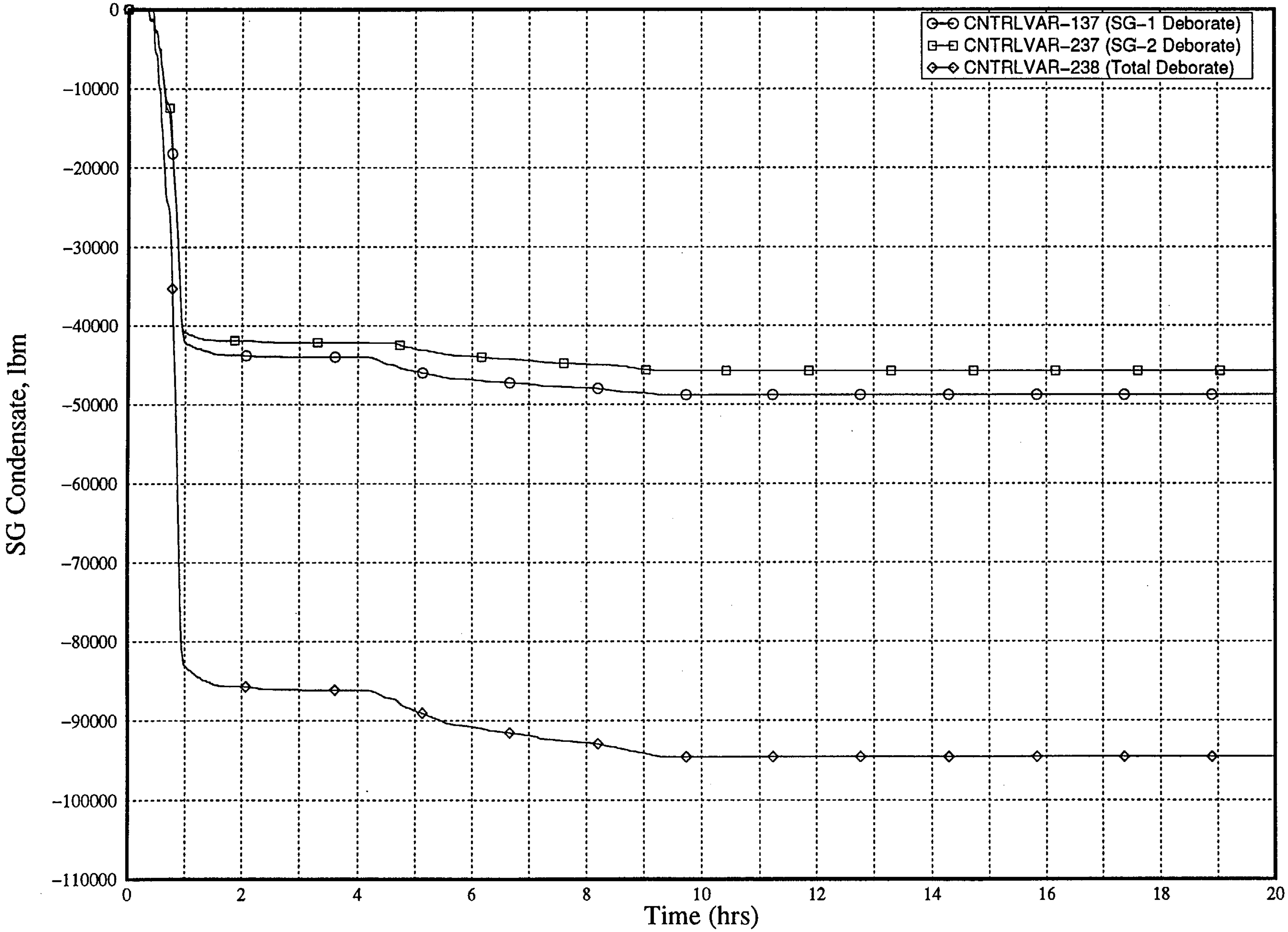


FIGURE A.5.1 : 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

System Pressures

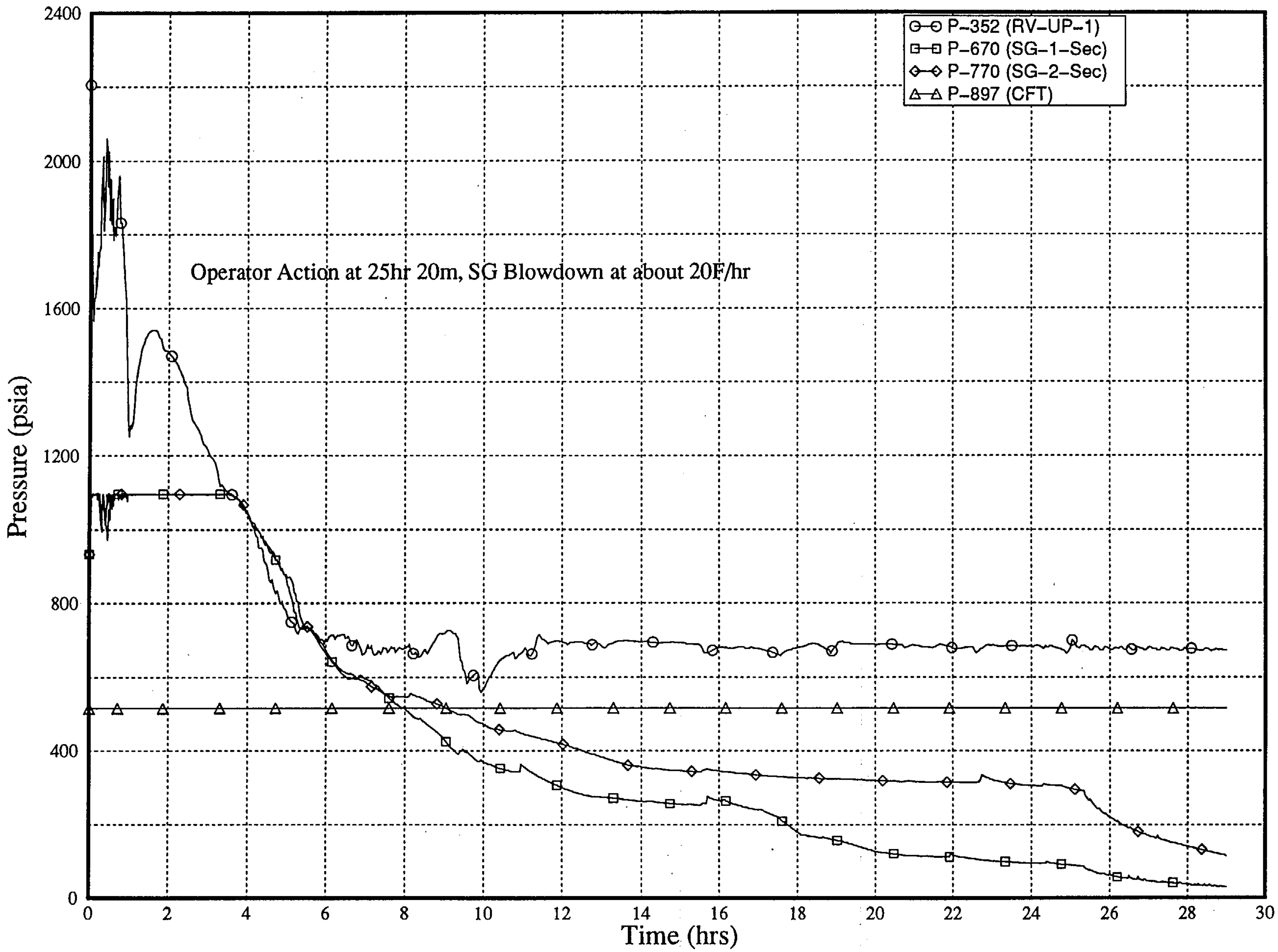


FIGURE A.5.2 : 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Intact Loop Collapsed Liquid Elevations

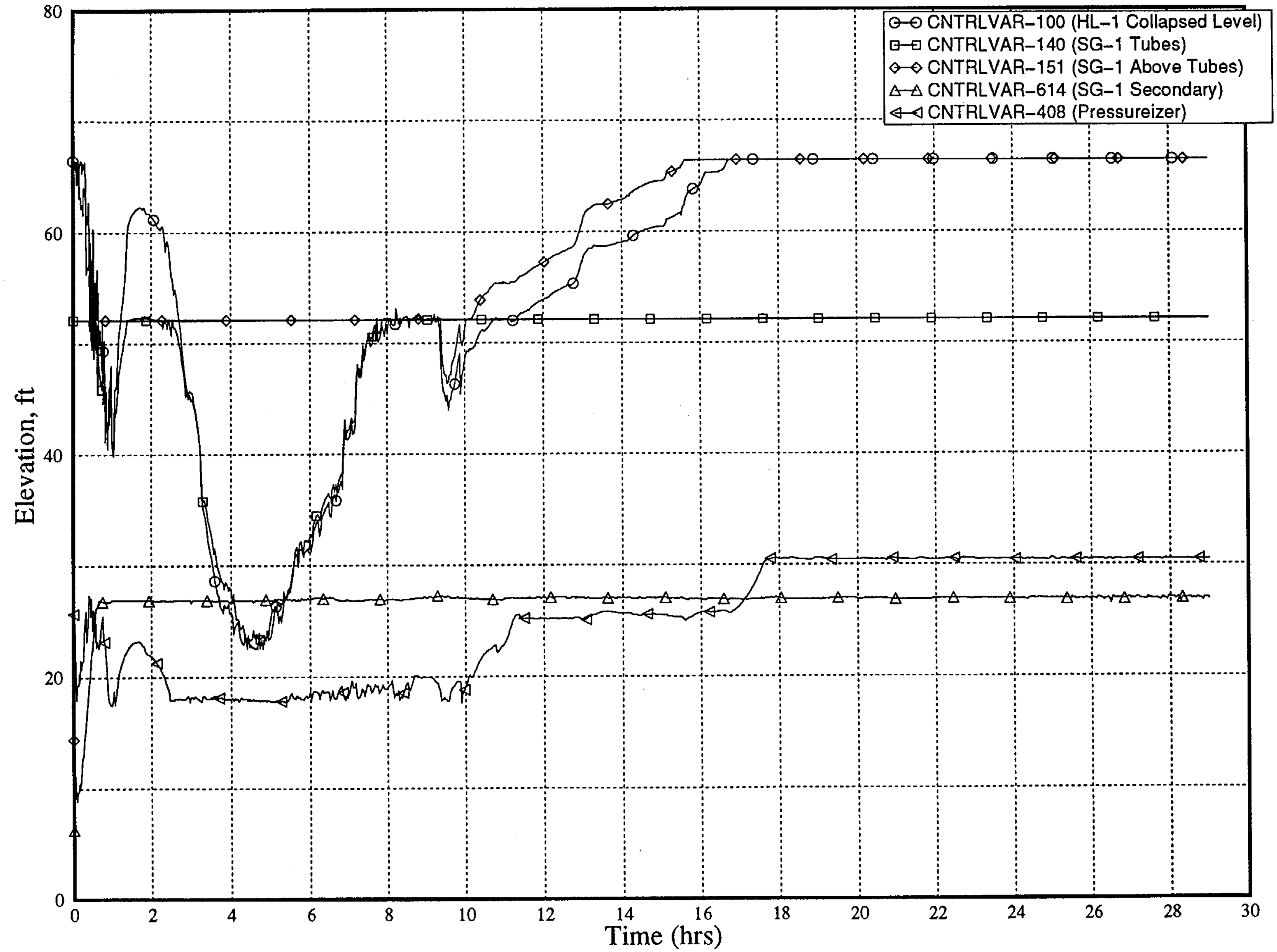


FIGURE A.5.3 : 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Broken Loop Collapsed Liquid Elevations

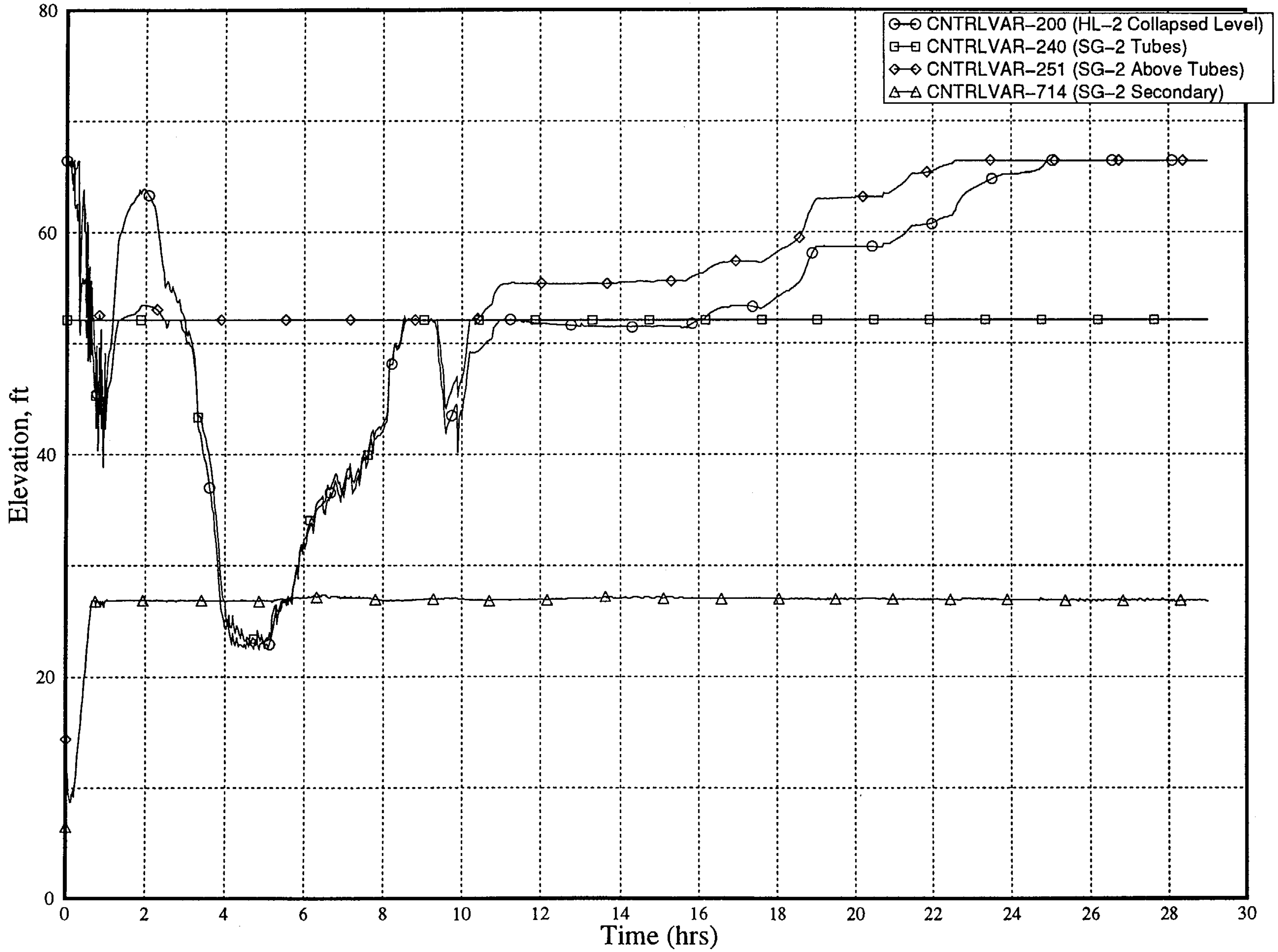


FIGURE A.5.4 : 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

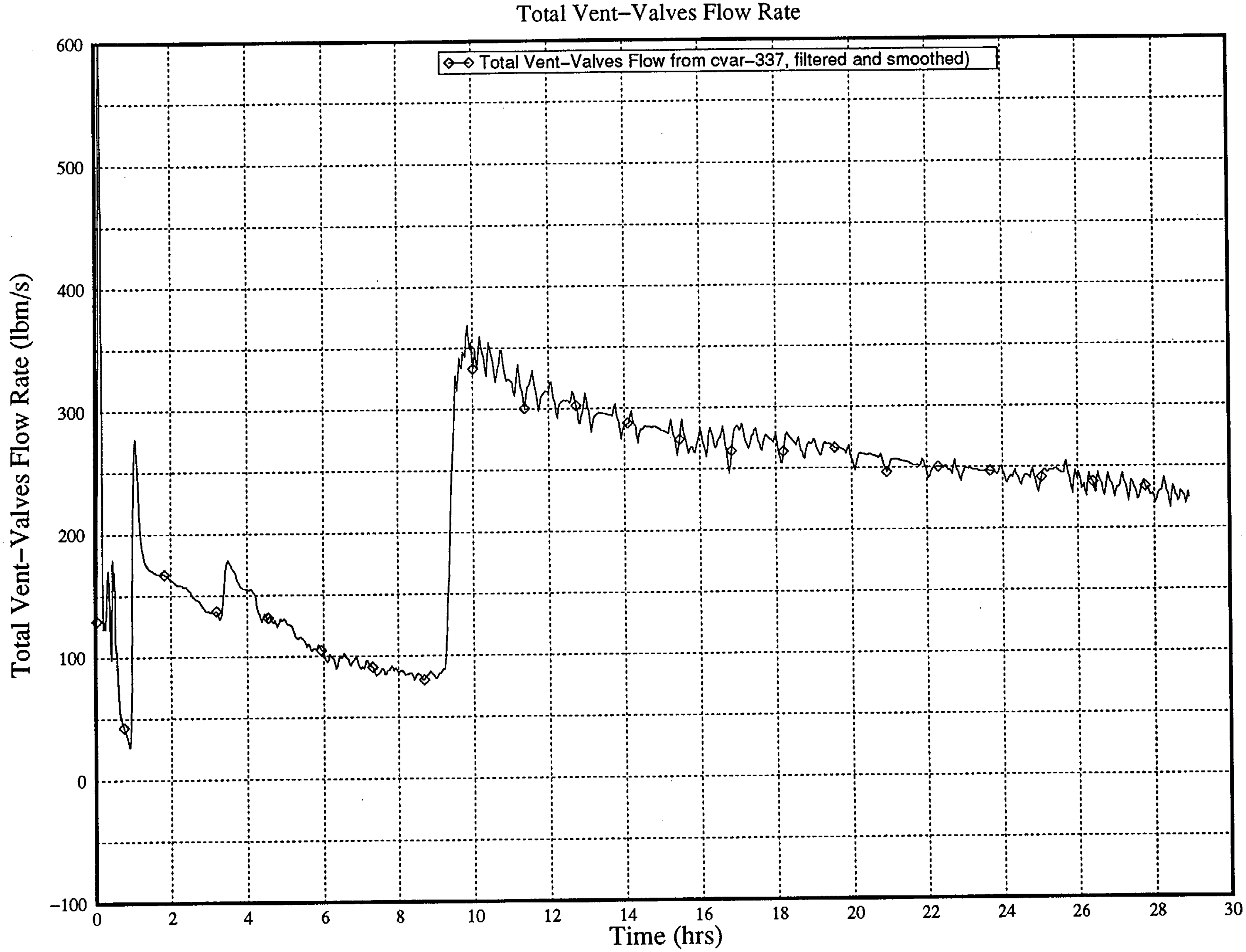


FIGURE A.5.5 : 0.007 ft² Cold Leg Break, Late Operator Action (at 25h 20m).

Vent Valve, Upper Plenum, Upper Head Voiding

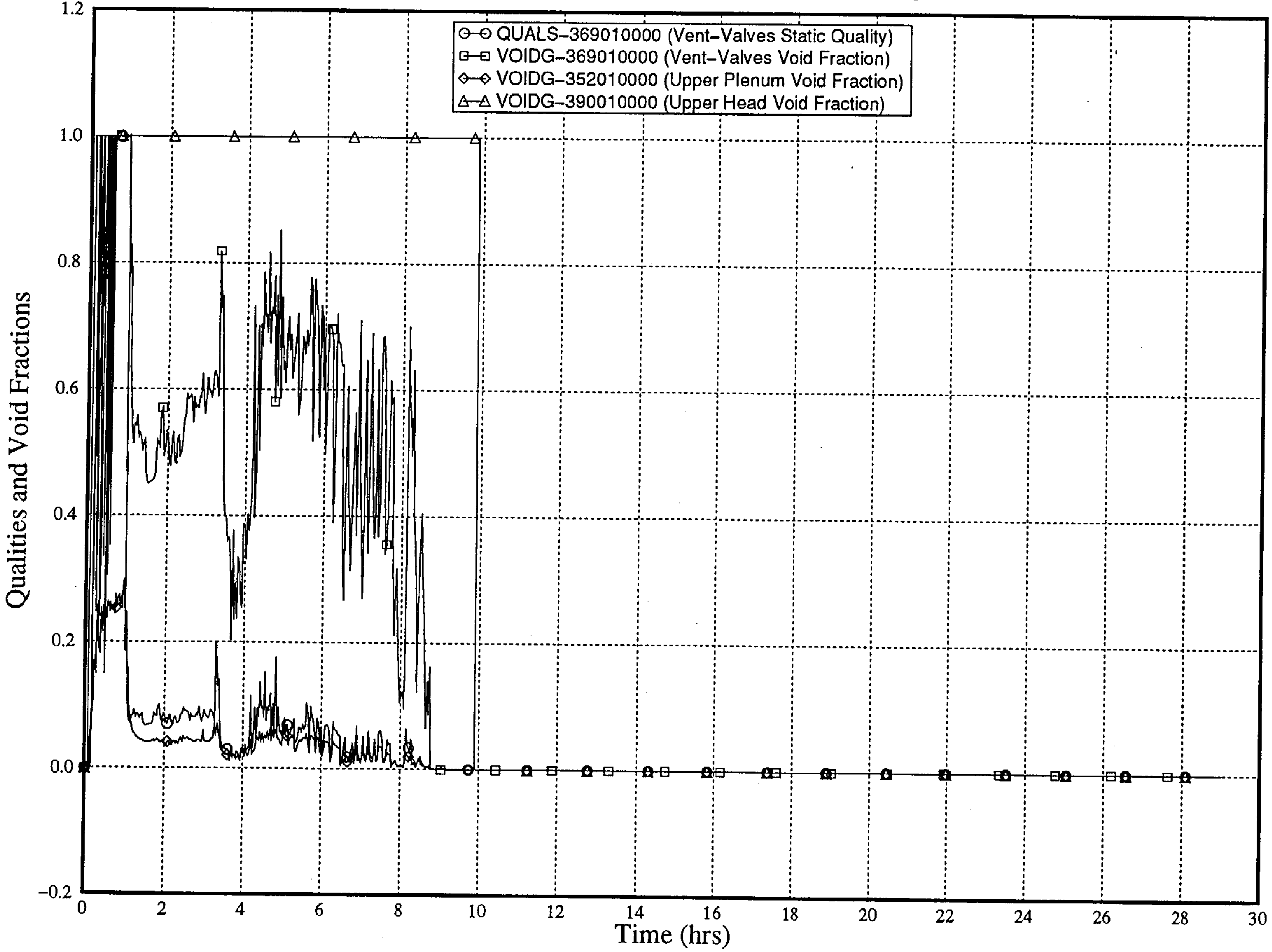


FIGURE A.5.6 : 0.007 ft² Cold Leg Break, Late Operator Action (at 25h 20m).

Total ECCS and Break Flow

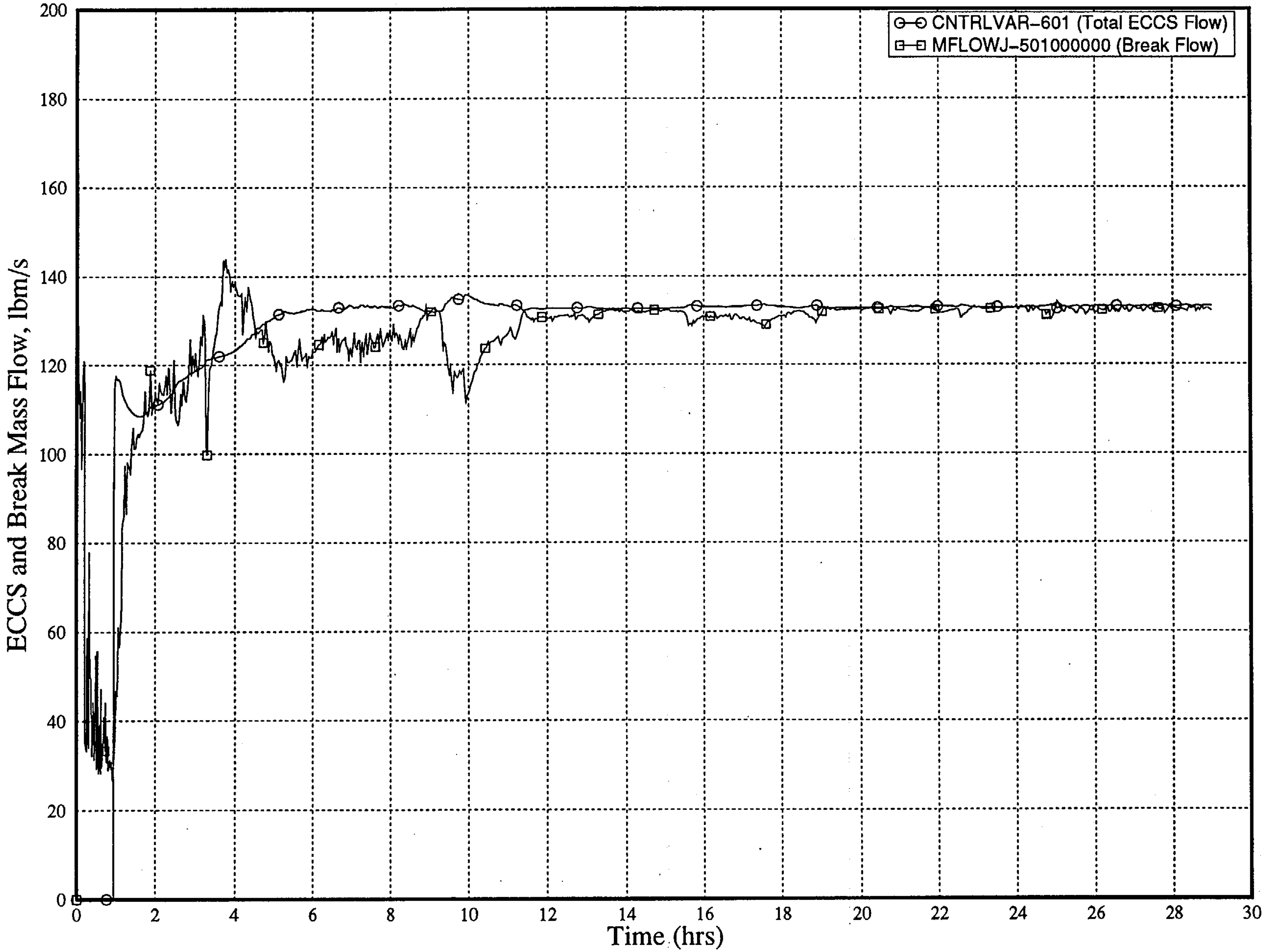


FIGURE A.5.7 : 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Break Flow Quality

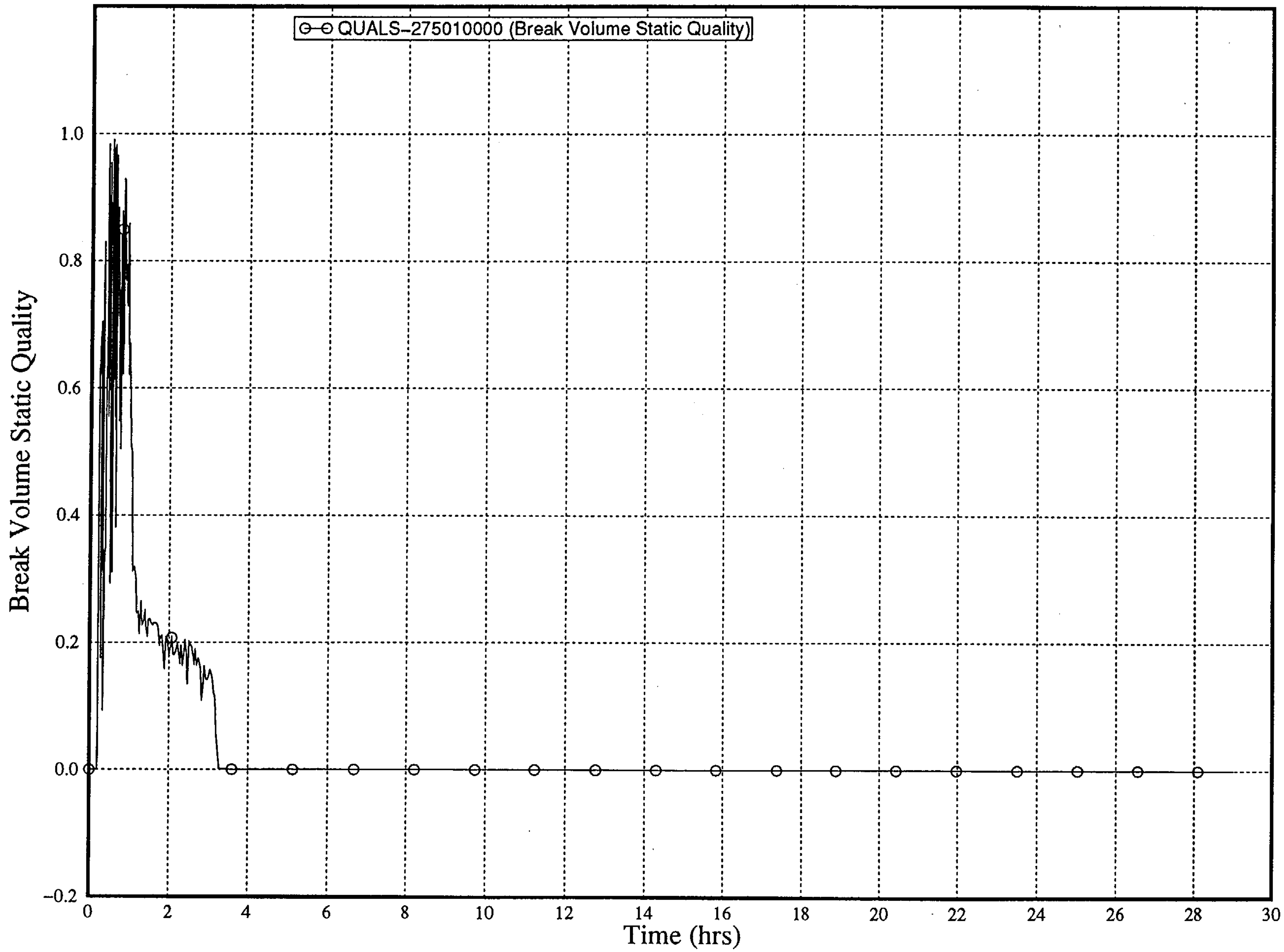


FIGURE A.5.8 : 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Break Flow Temperature

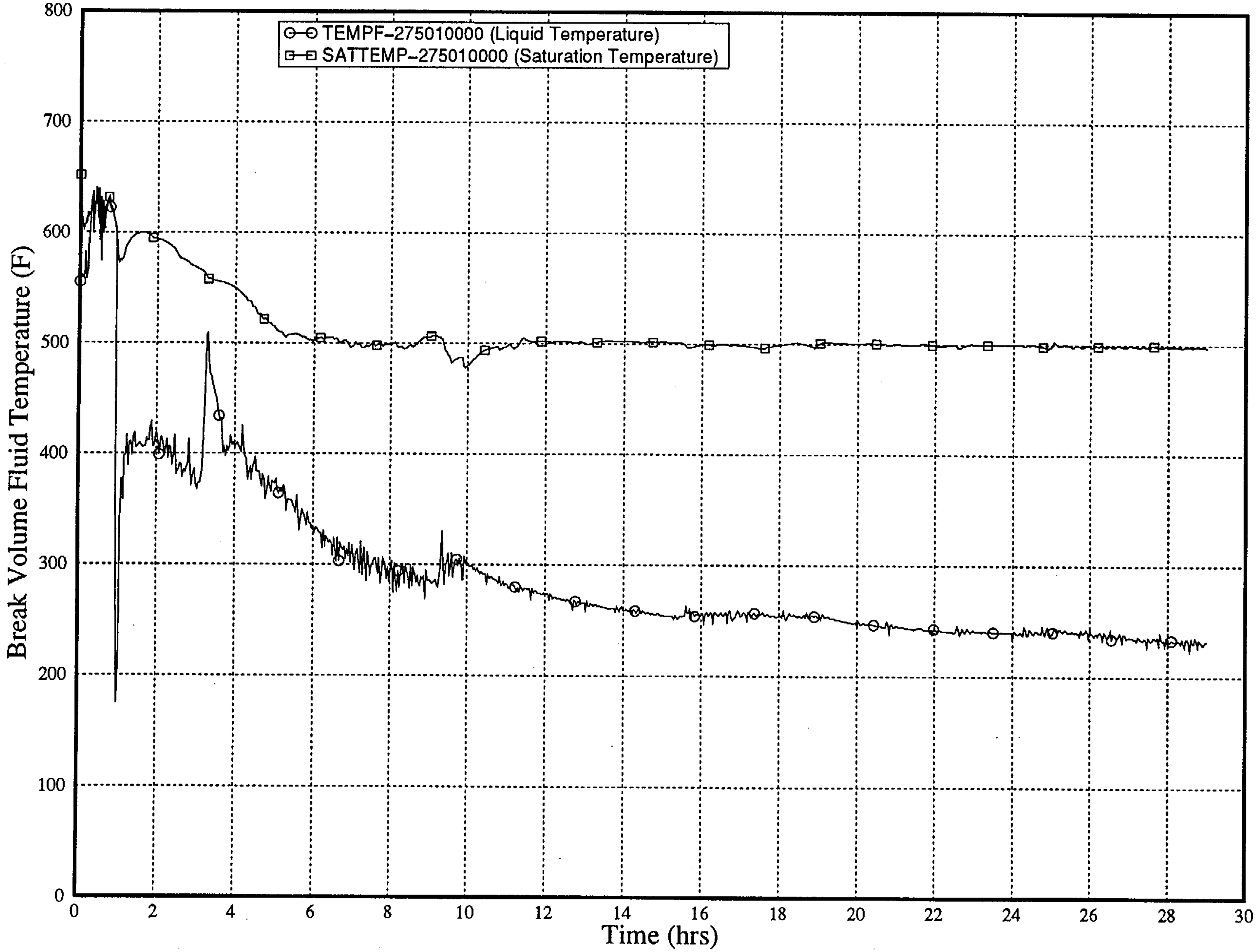


FIGURE A.5.9 : 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Intact Loop Cold Leg Flow Rates

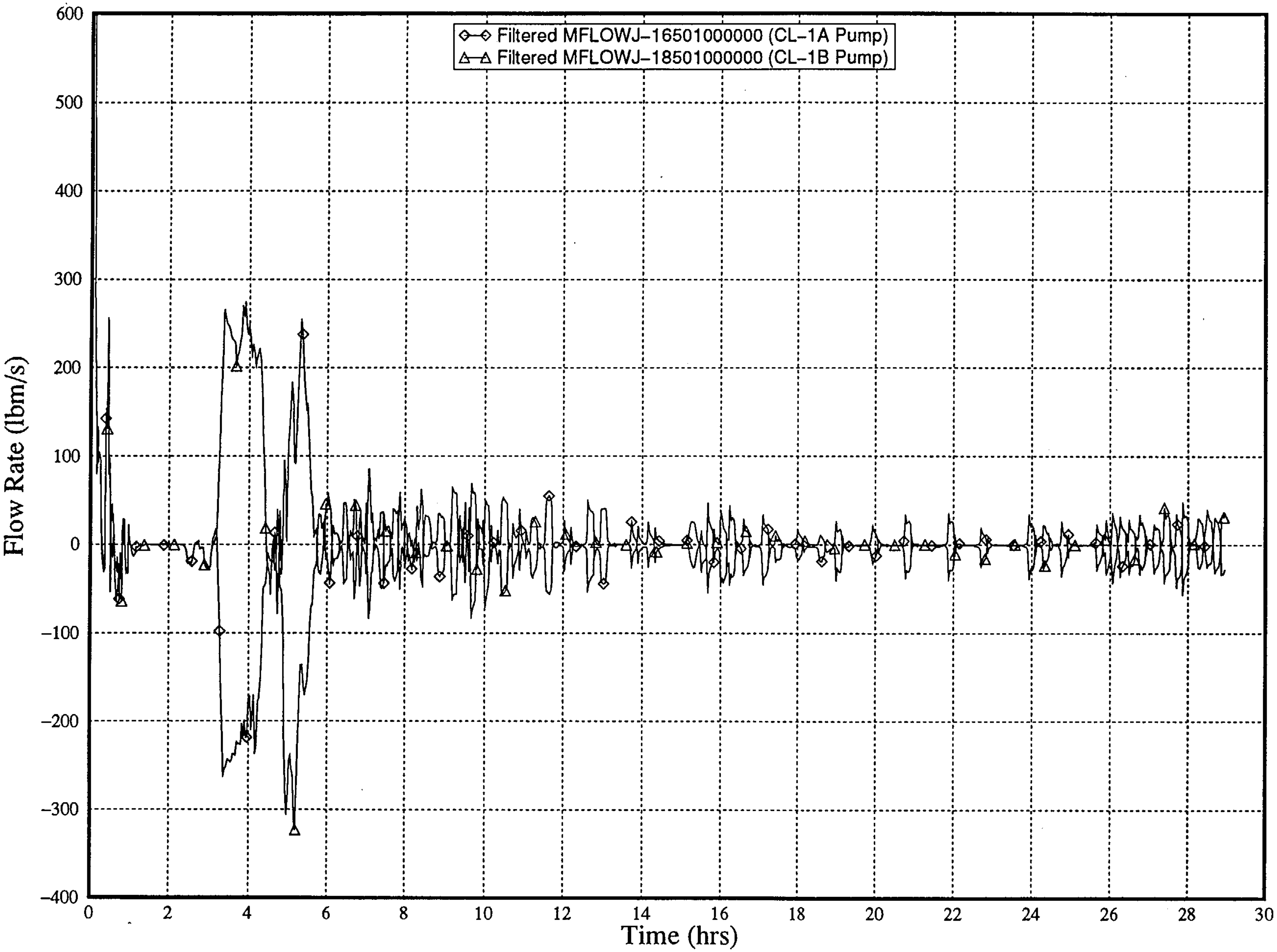


FIGURE A.5.10: 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Broken Loop Cold Leg Flow Rates

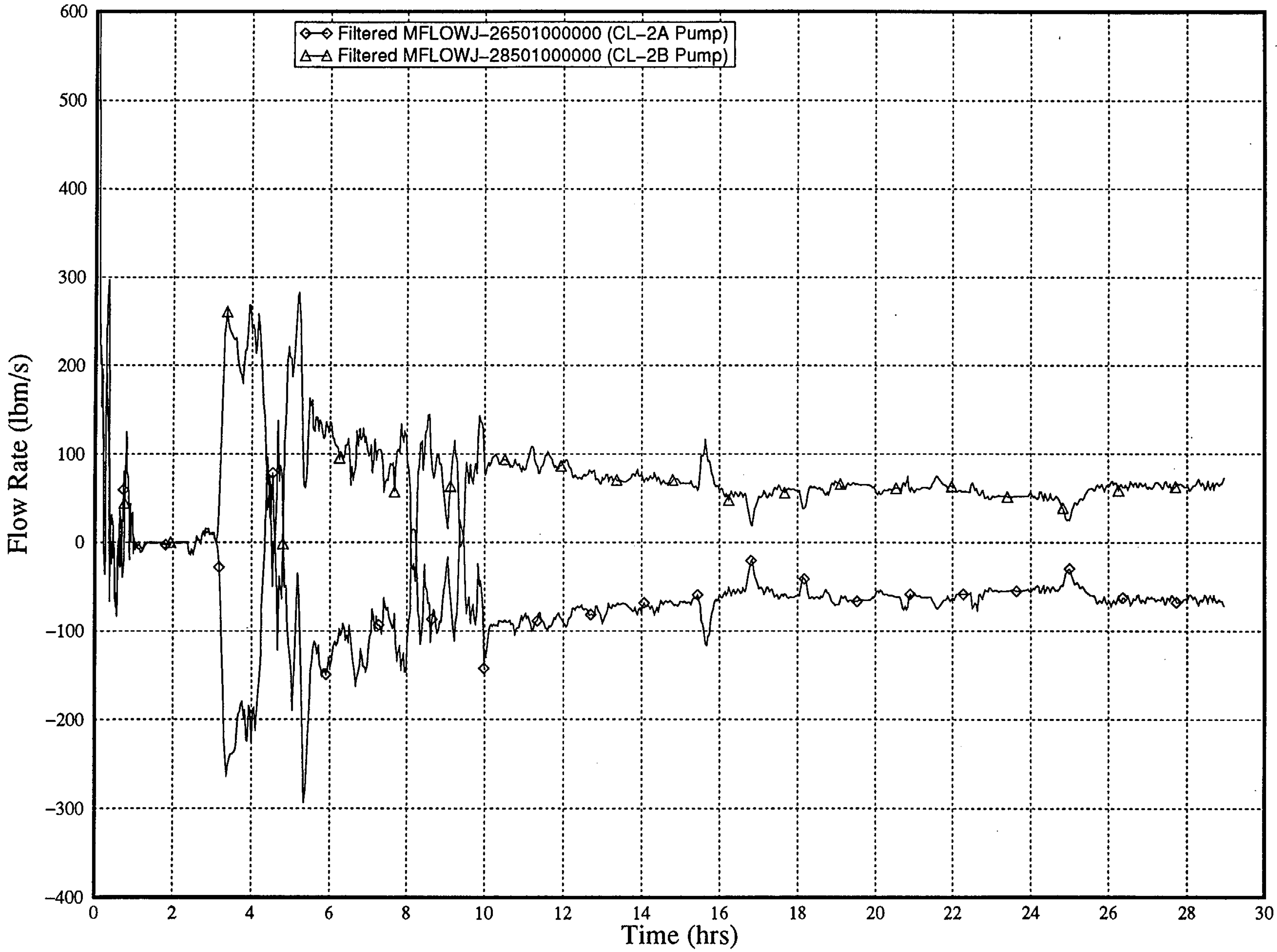


FIGURE A.5.11: 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Loop Circulation and Vent–Valve Flow Rates

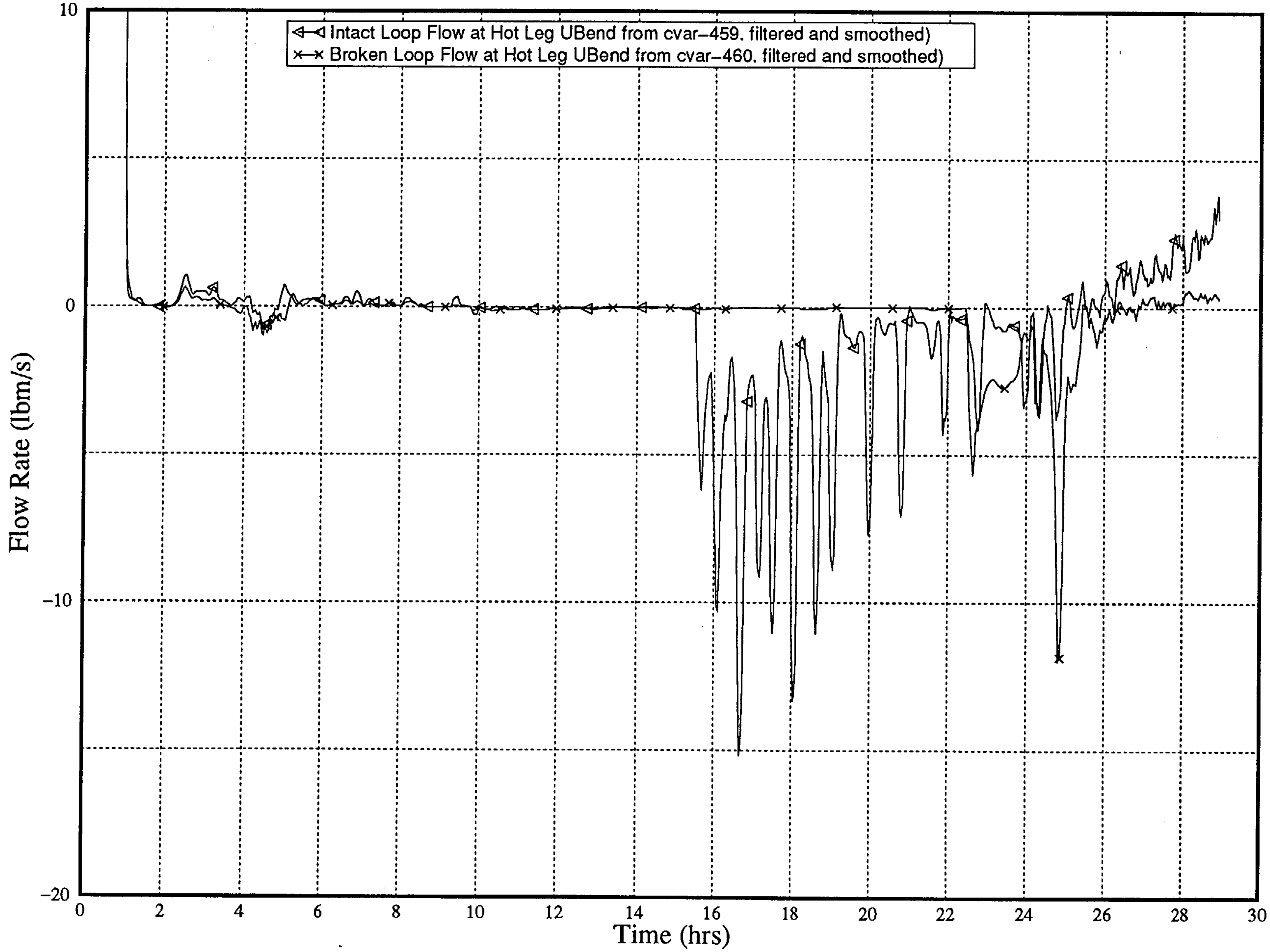


FIGURE A.5.12: 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Core Inlet Flow

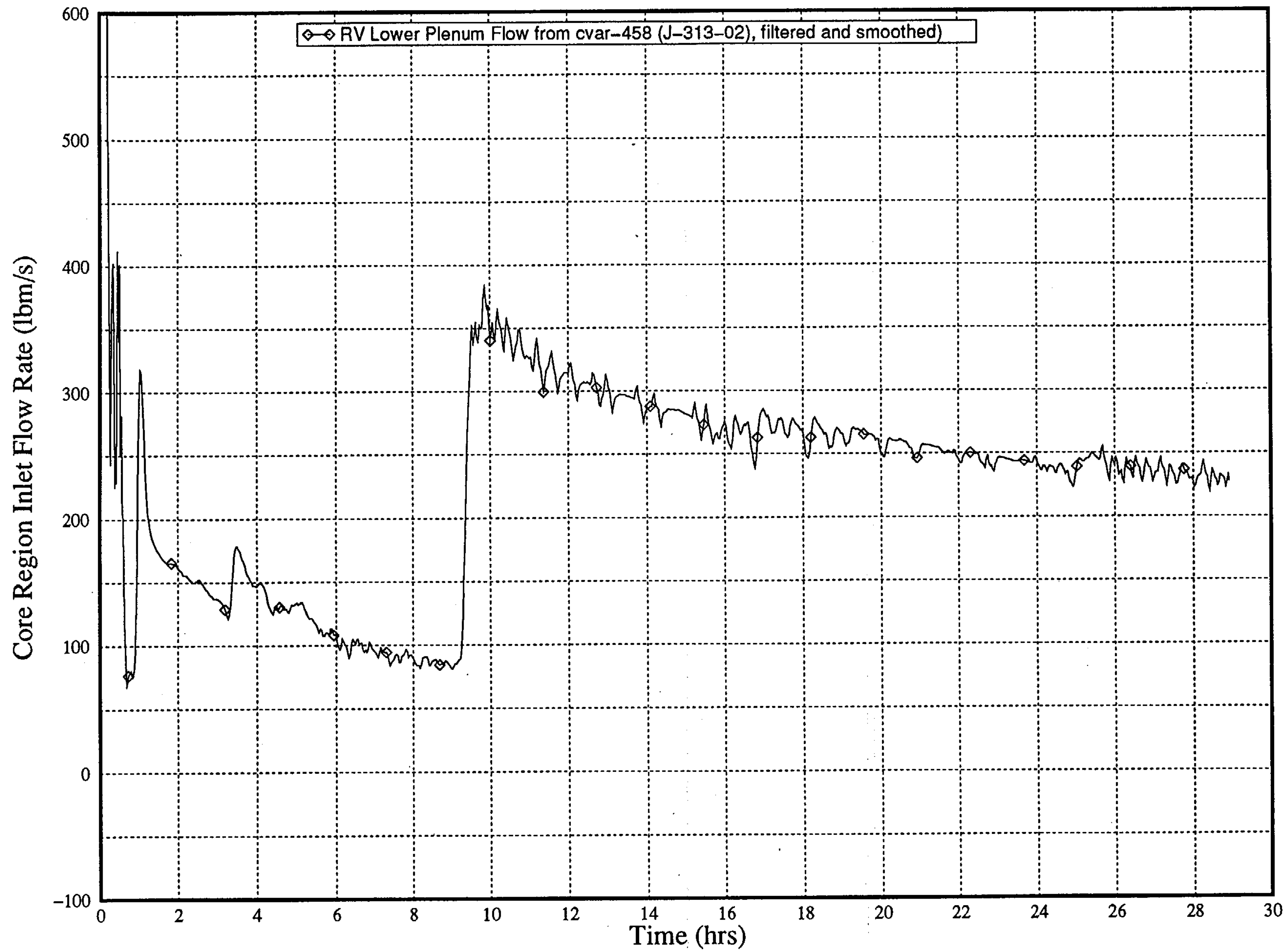


FIGURE A.5.13: 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Reactor Vessel Temperature Distribution

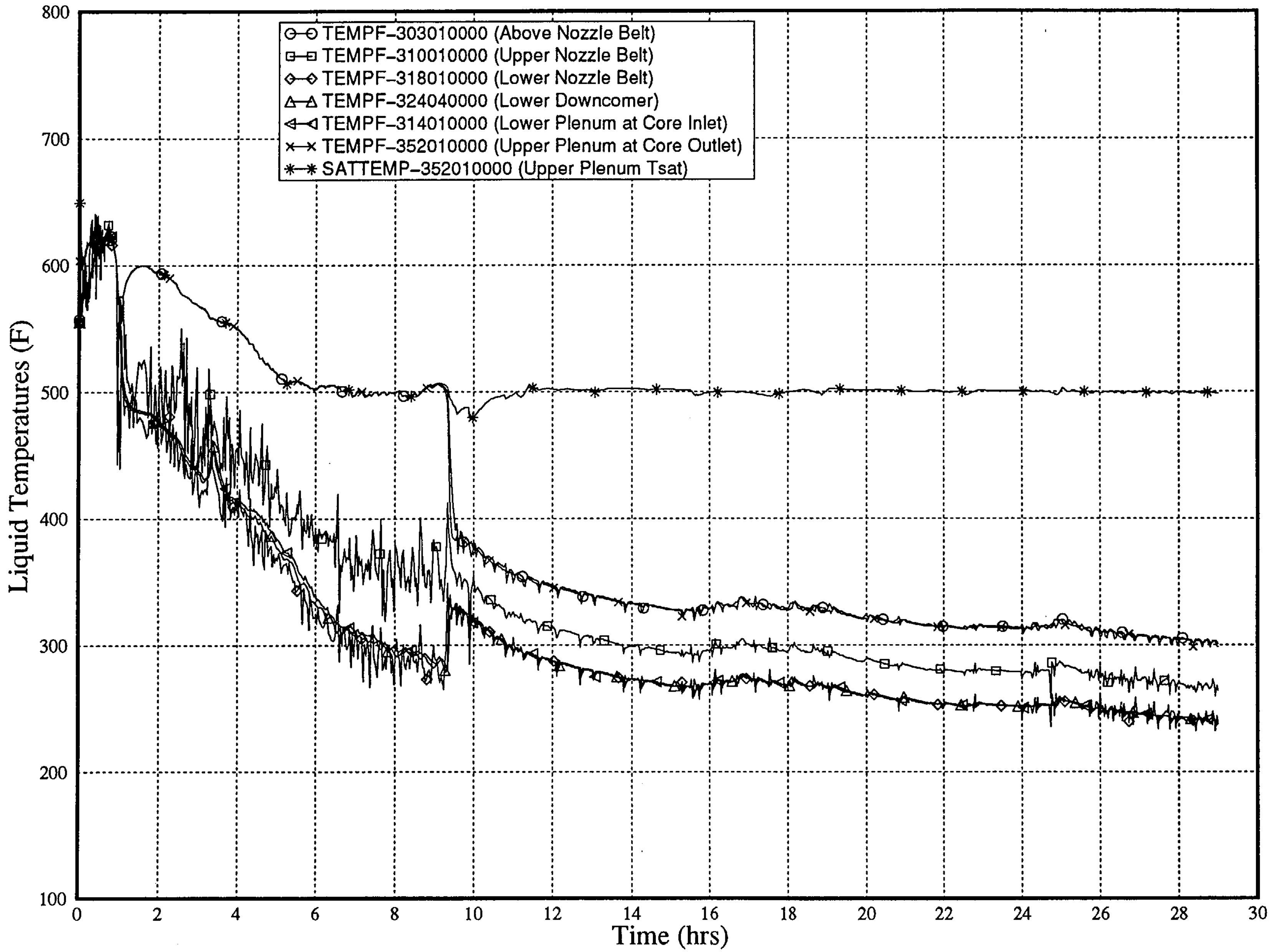


FIGURE A.5.14: 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Normalized Core Power Generation

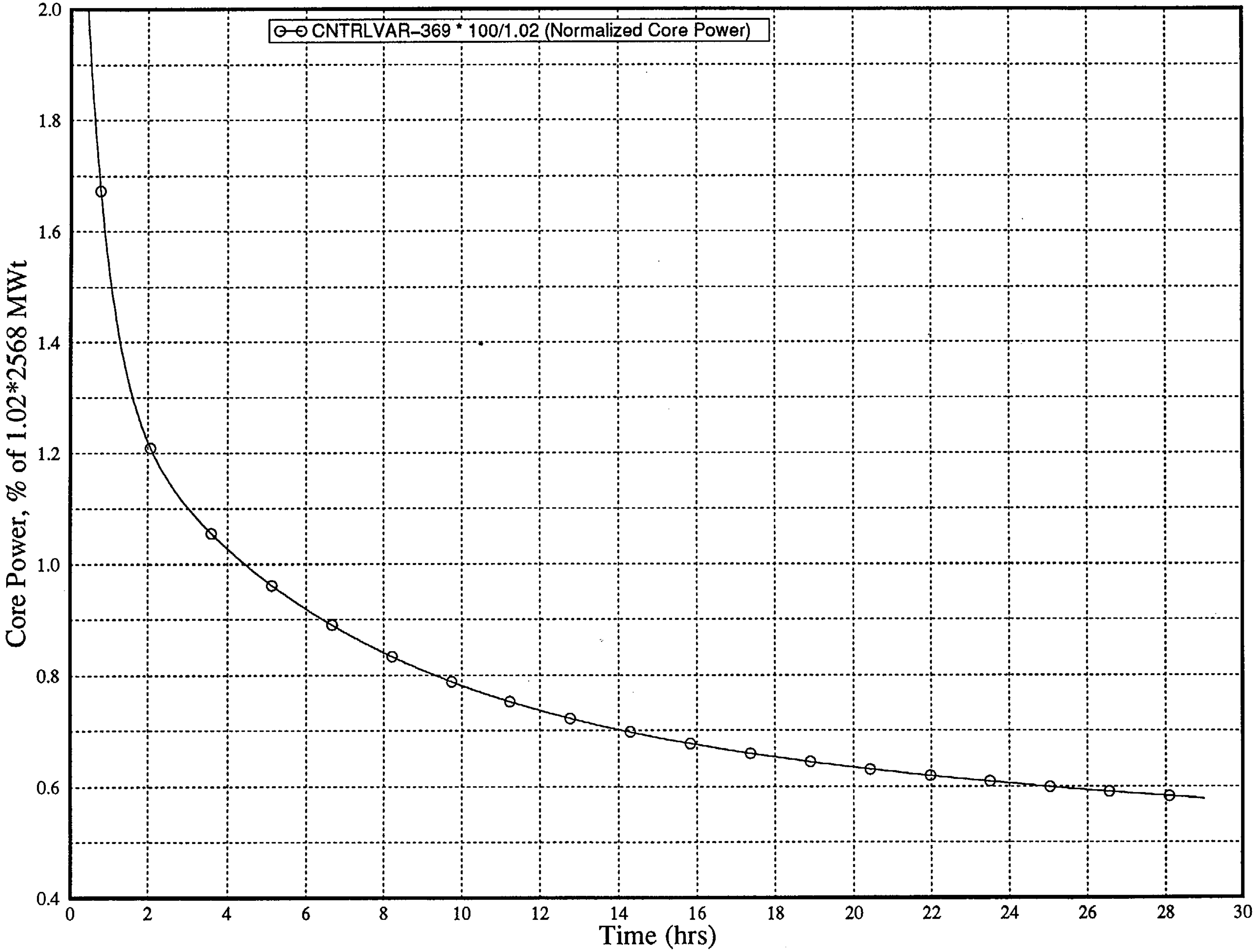


FIGURE A.5.15: 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

Deborate Accumulation Due to Steam Condensation in SG

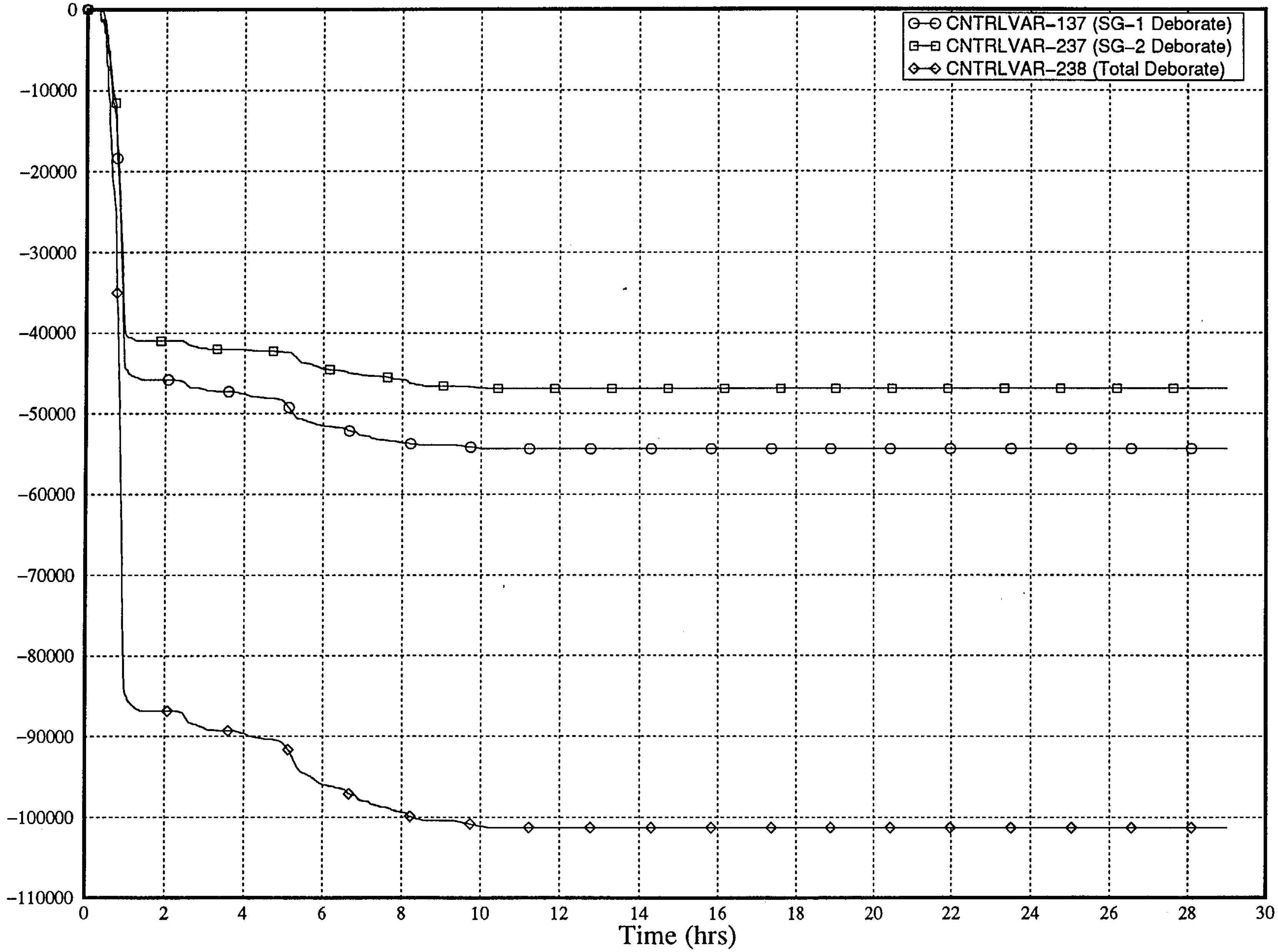


FIGURE A.5.16: 0.007 ft^2 Cold Leg Break, Late Operator Action (at 25h 20m).

RV Upper Plenum to SG–Secondary Delta–T

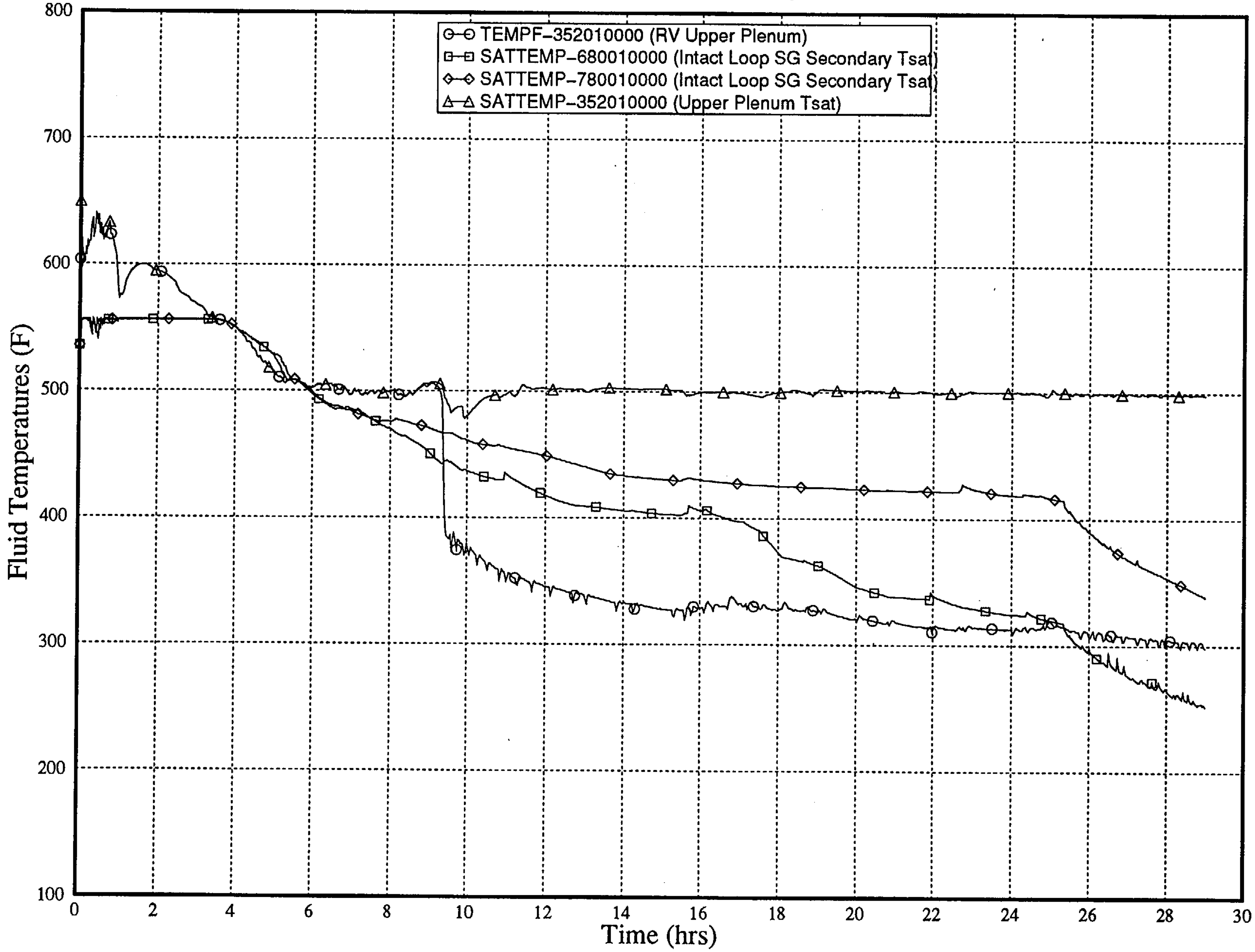


FIGURE A.6.1 : 0.007 ft² Cold Leg Break, Early Operator Actions.

System Pressures

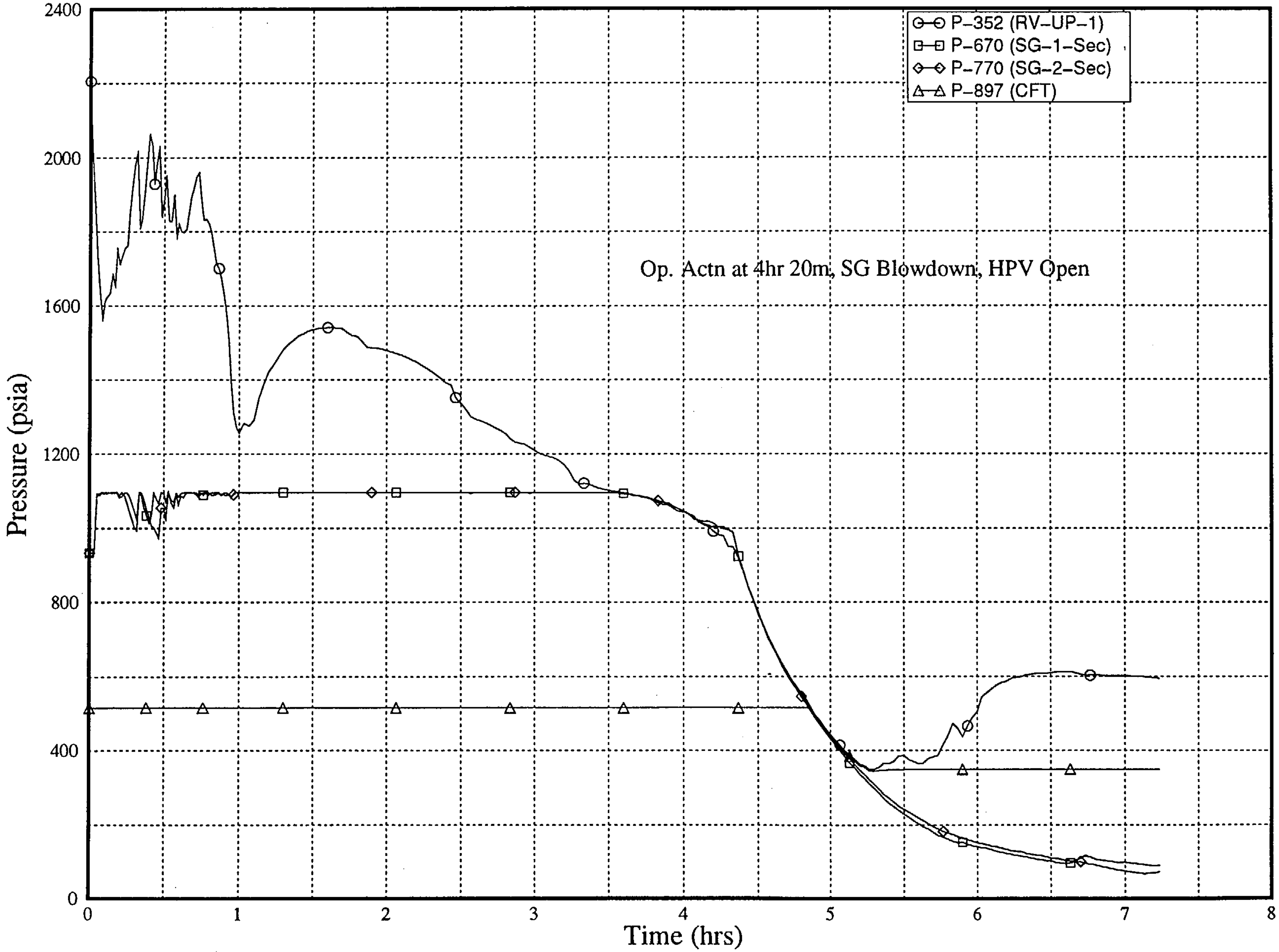


FIGURE A.6.2 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Intact Loop Collapsed Liquid Elevations

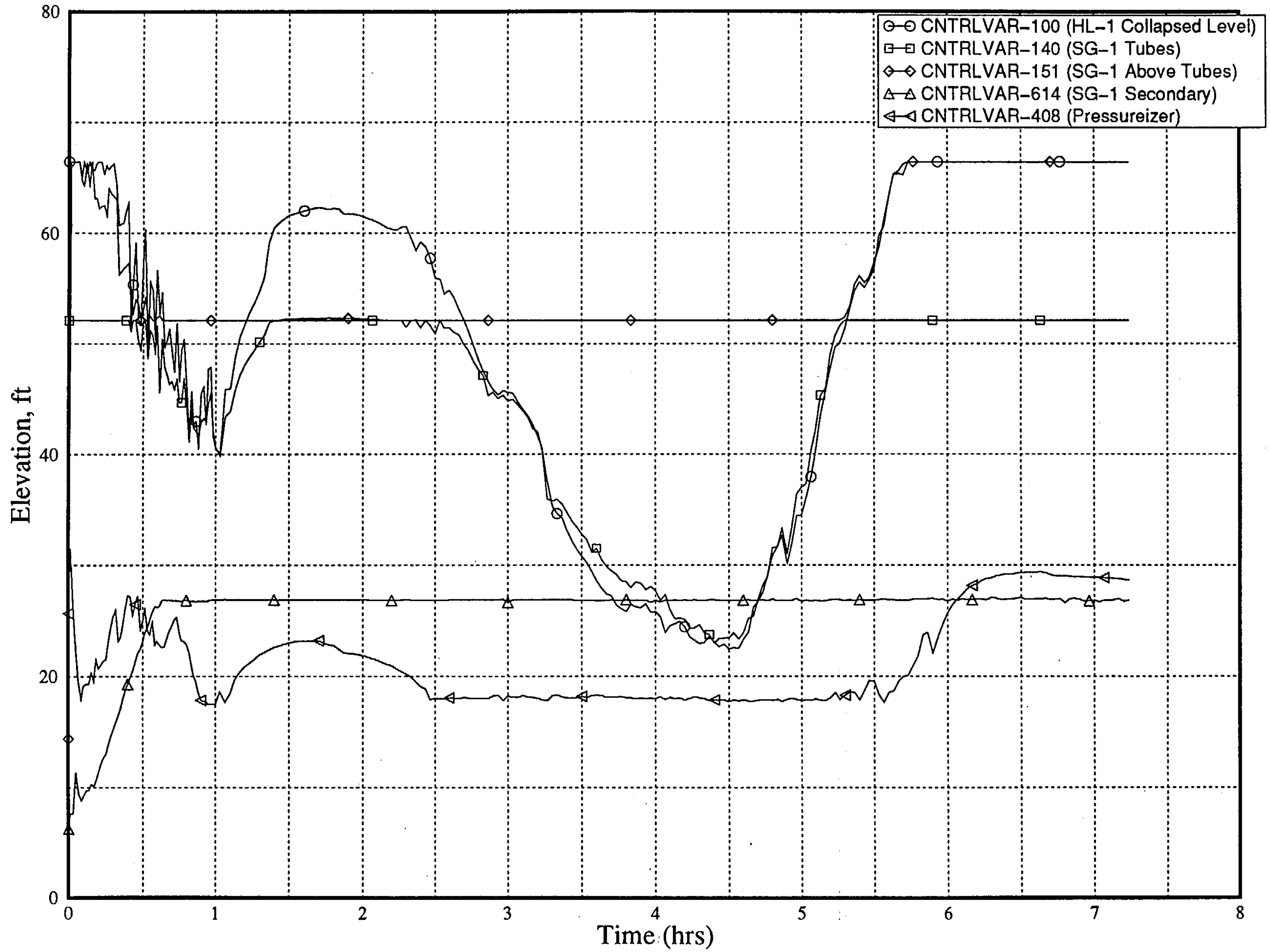


FIGURE A.6.3 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Broken Loop Collapsed Liquid Elevations

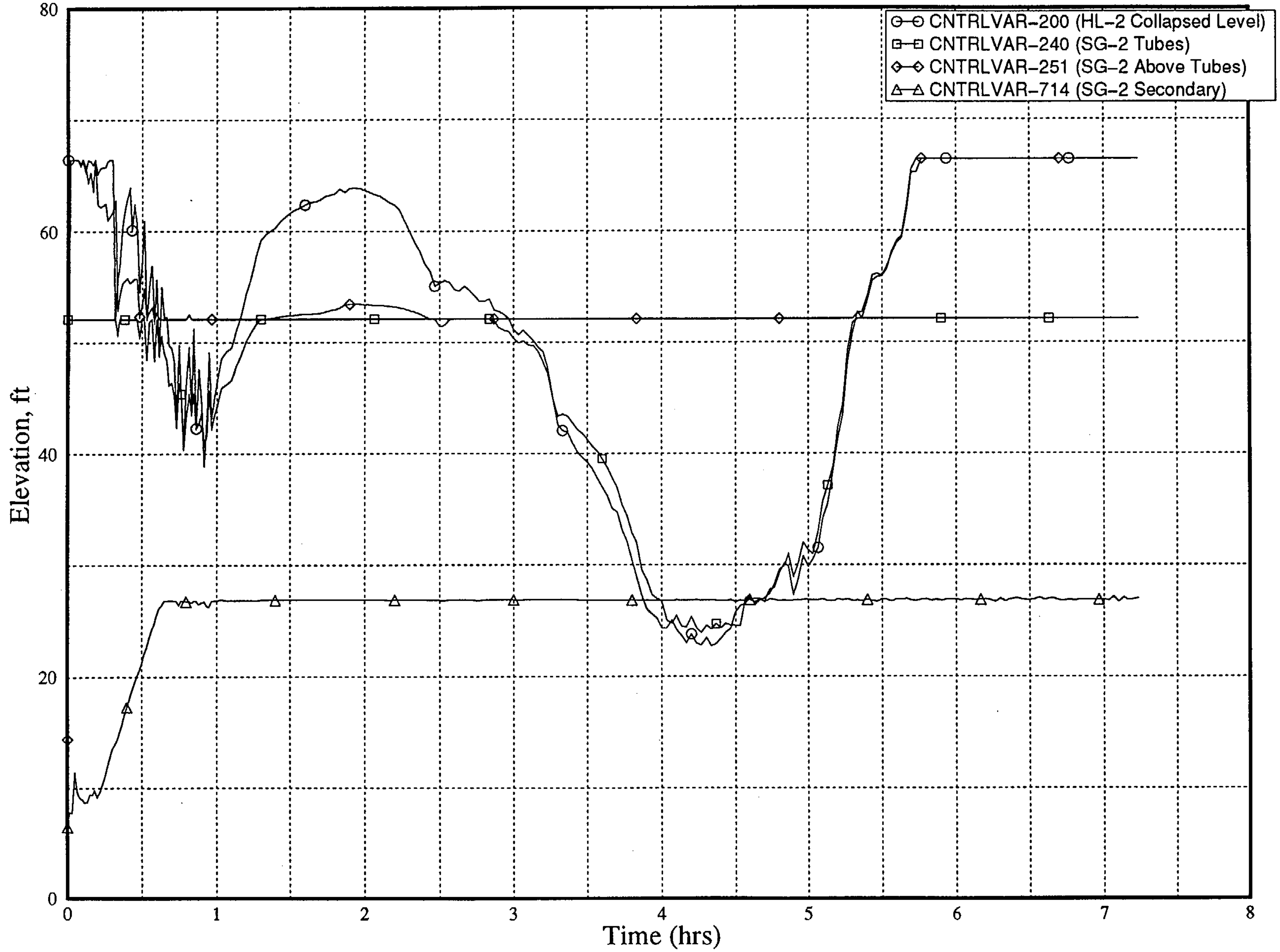


FIGURE A.6.4 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

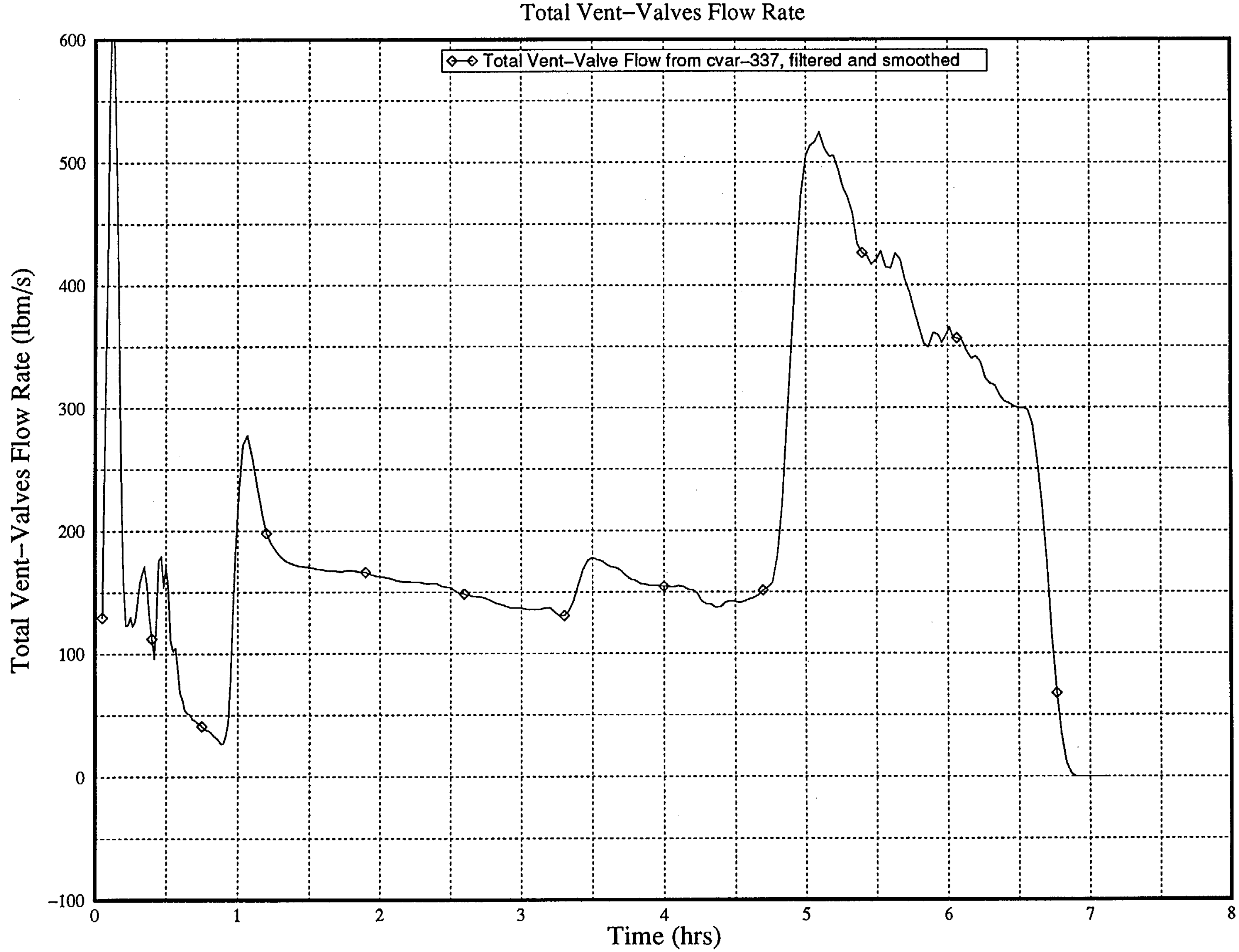


FIGURE A.6.5 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Vent Valve, Upper Plenum, Upper Head Voiding

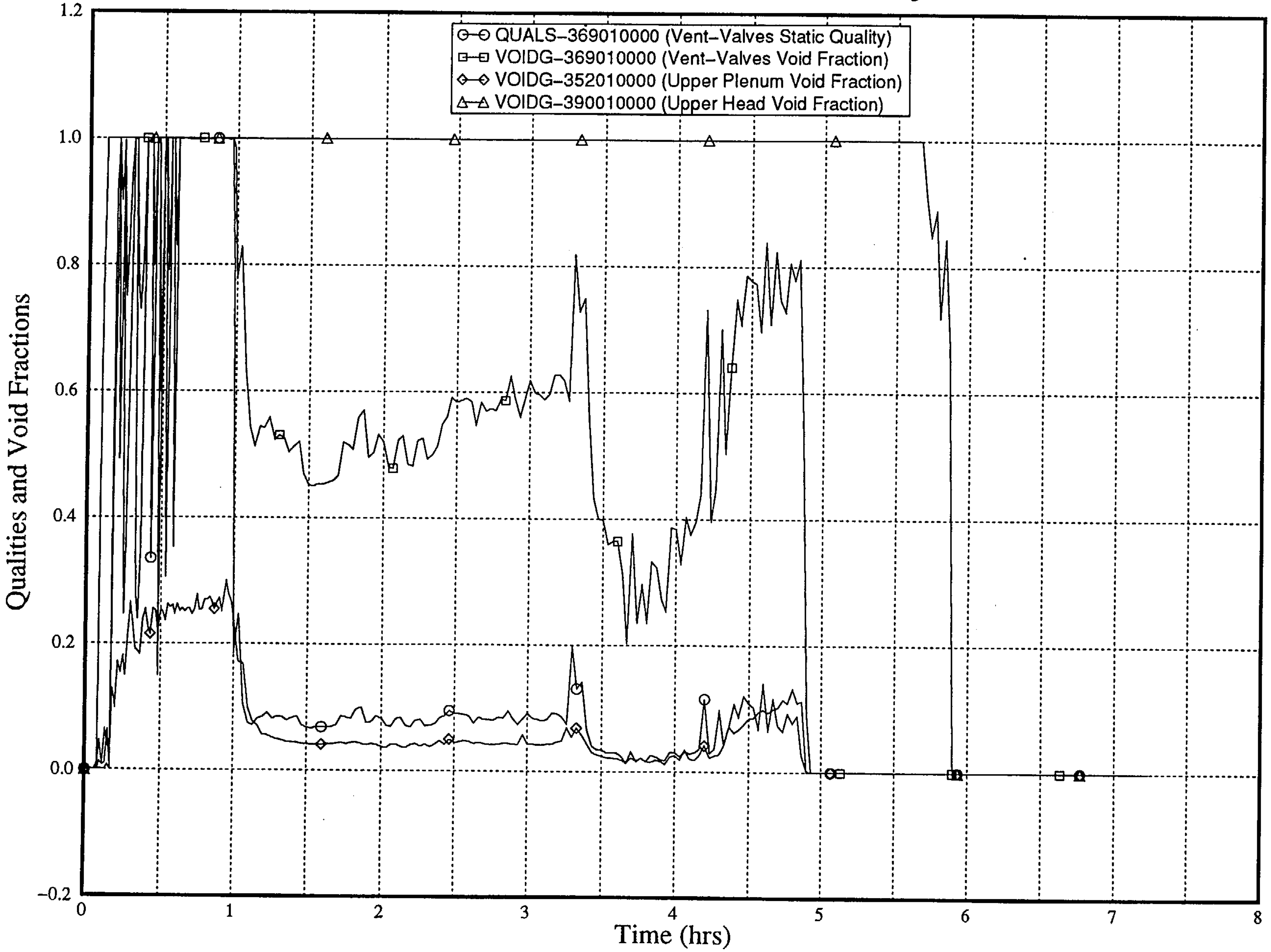


FIGURE A.6.6 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Total ECCS and Break Flow

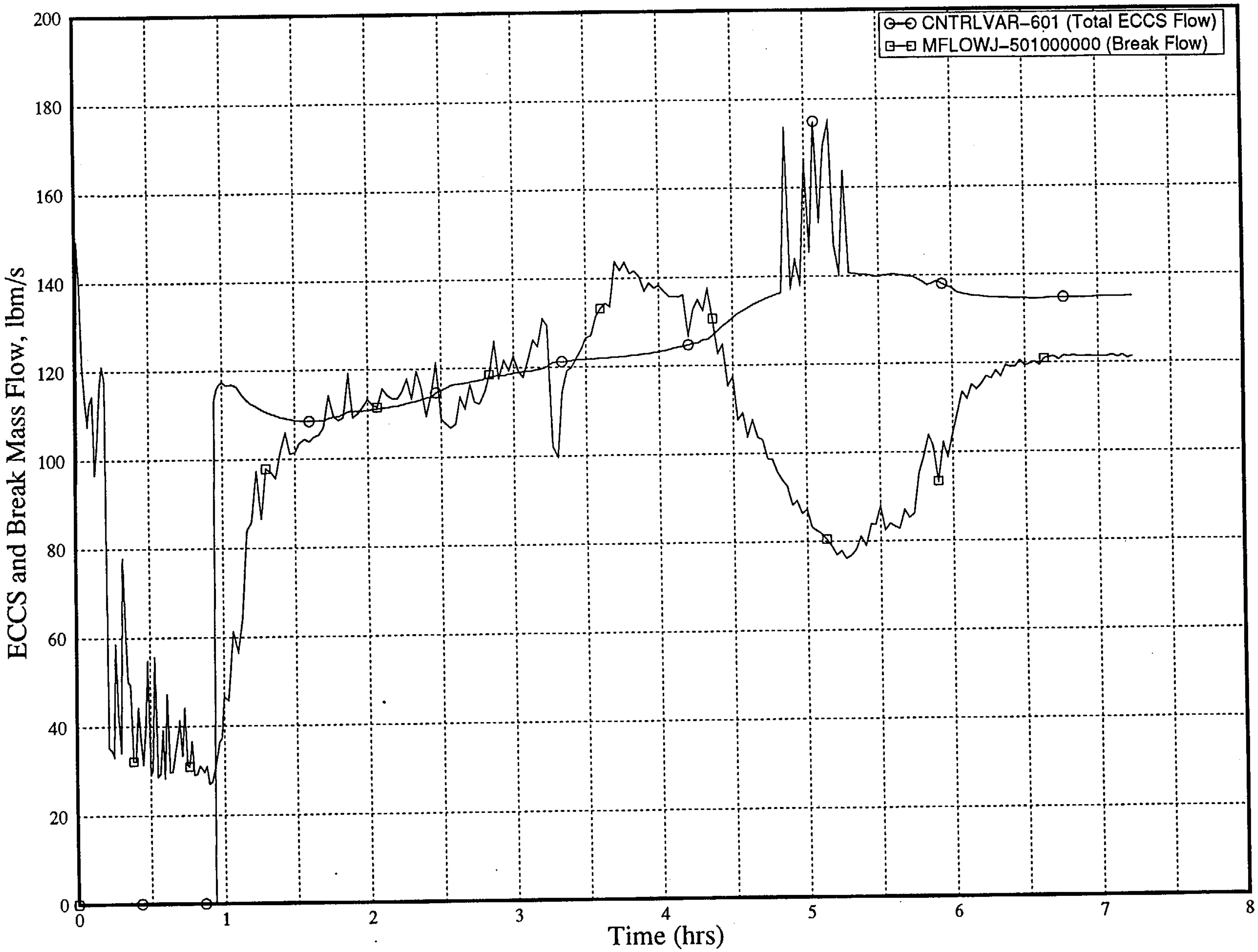


FIGURE A.6.7 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Break Flow Quality

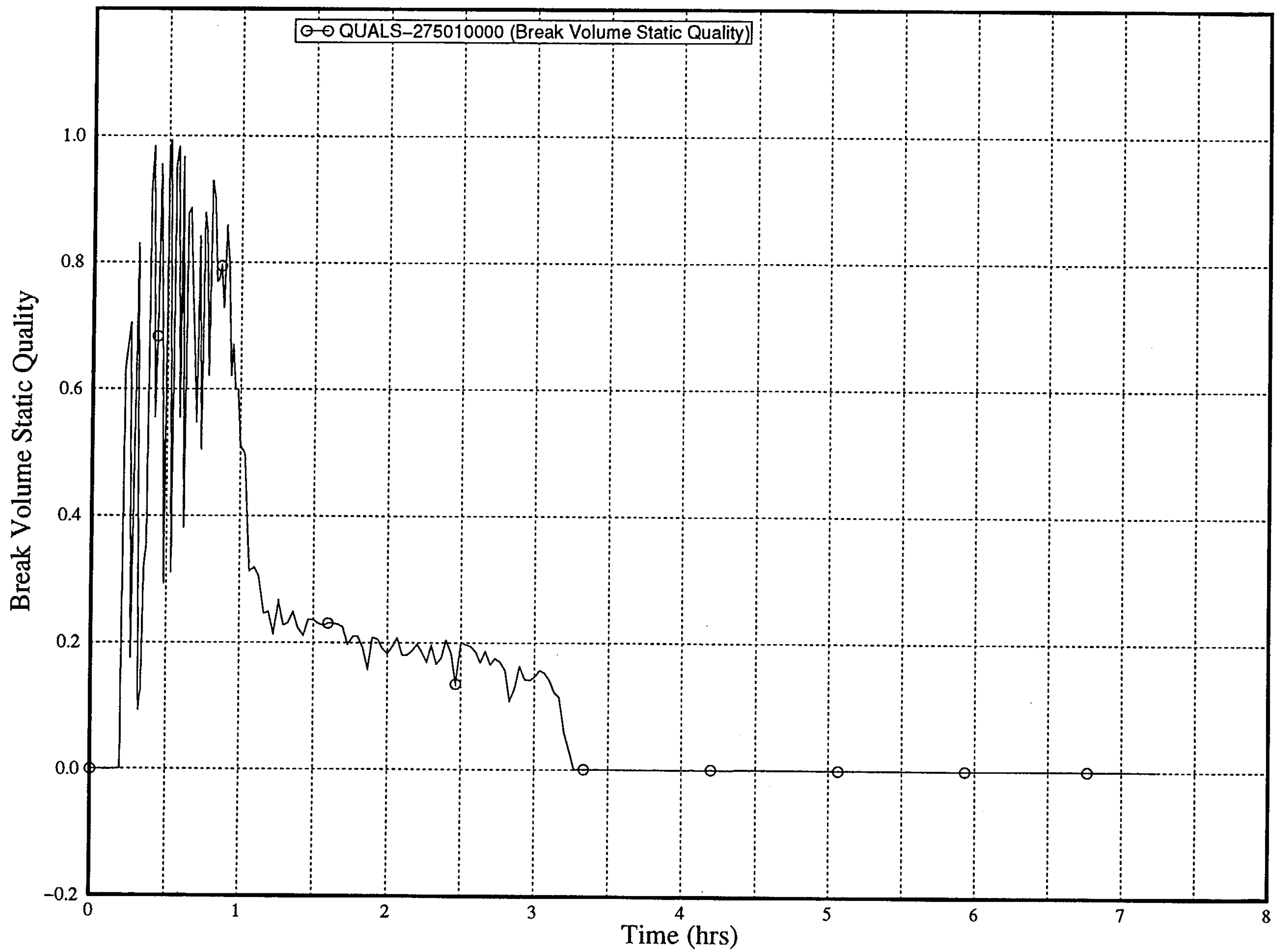


FIGURE A.6.8 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

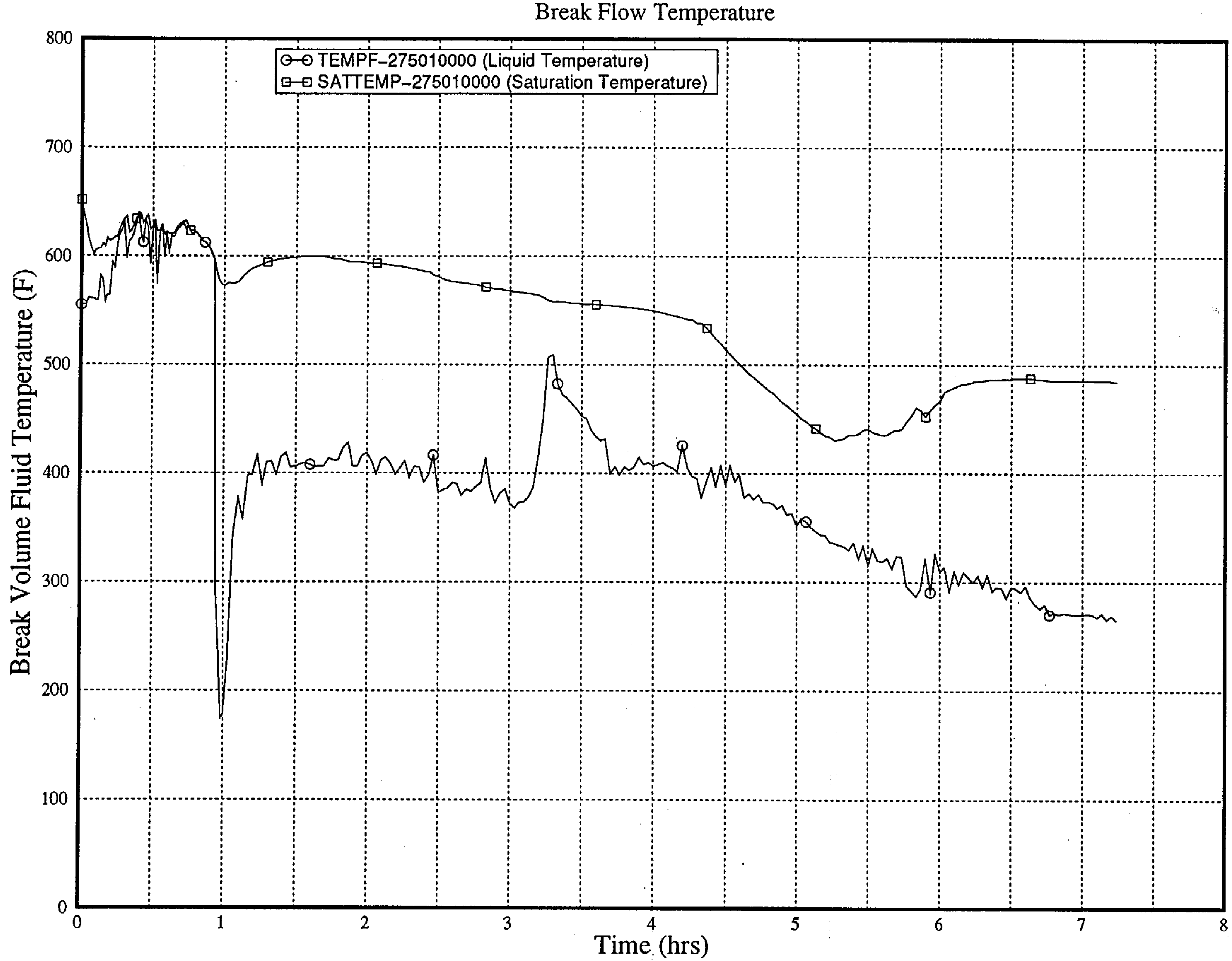


FIGURE A.6.9 : 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Intact Loop Cold Leg Flow Rates

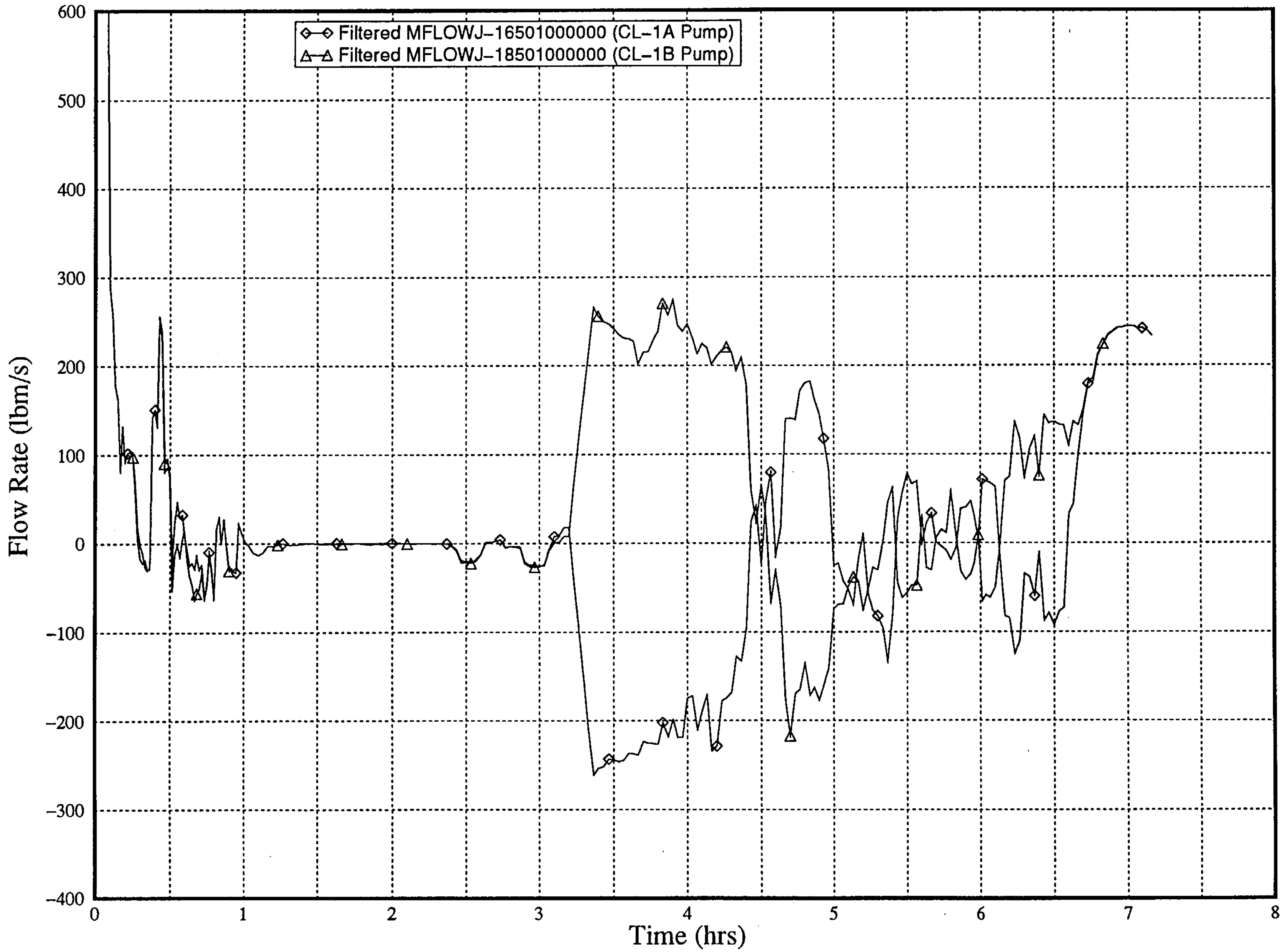


FIGURE A.6.10: 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Broken Loop Cold Leg Flow Rates

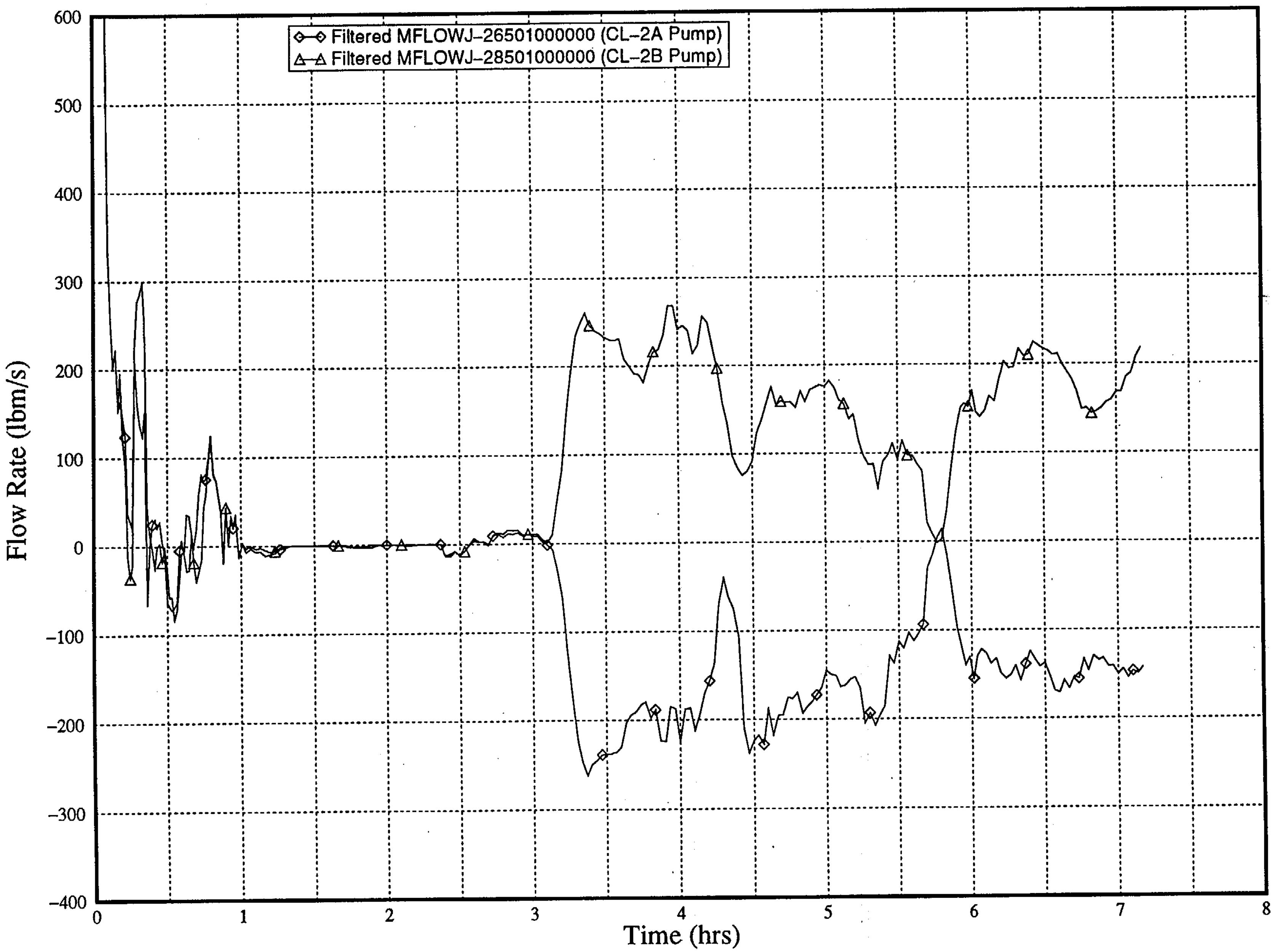


FIGURE A.6.11: 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Loop Circulation and Vent–Valve Flow Rates

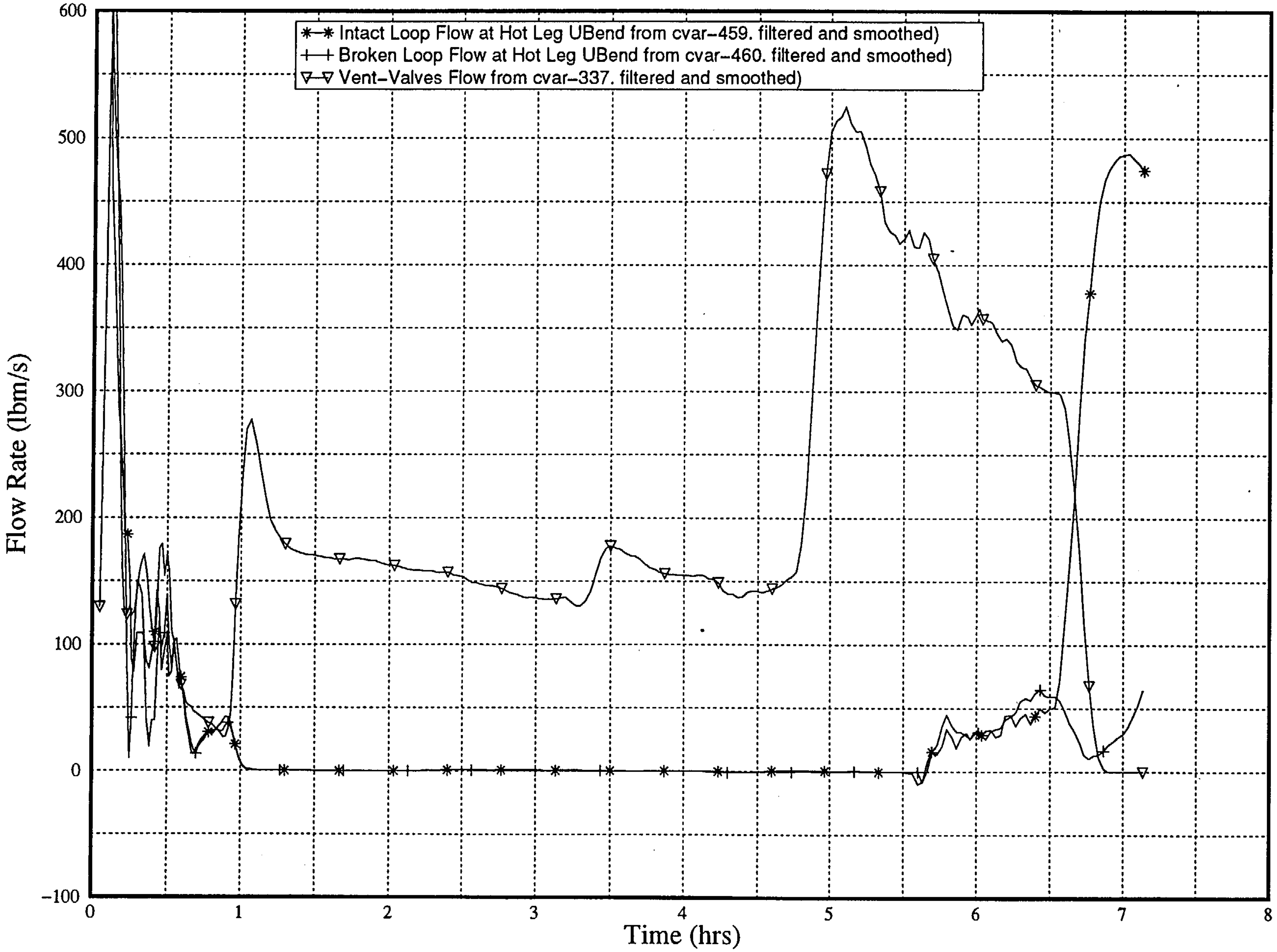


FIGURE A.6.12: 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Core Inlet Flow

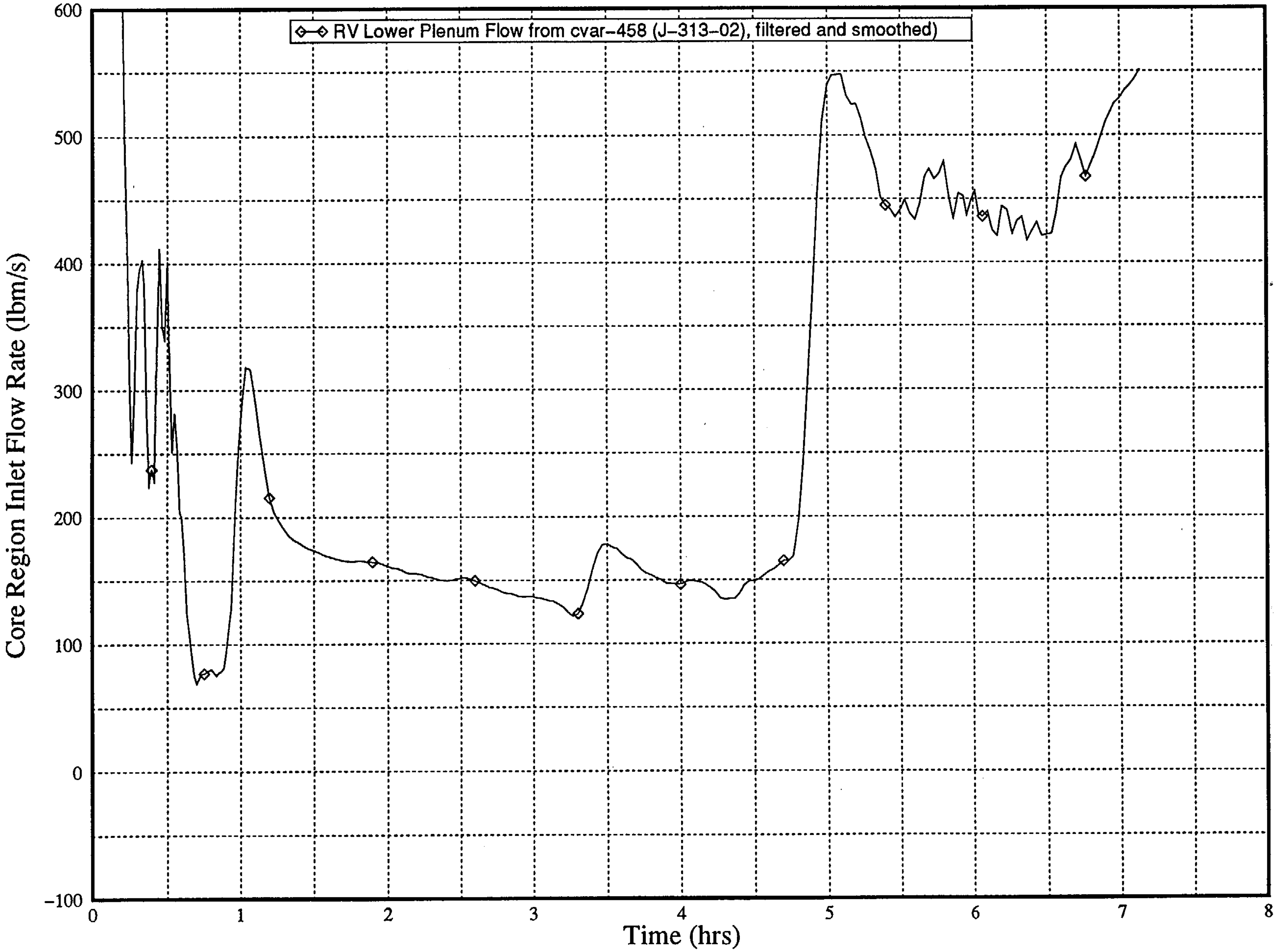


FIGURE A.6.13: 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Reactor Vessel Temperature Distribution

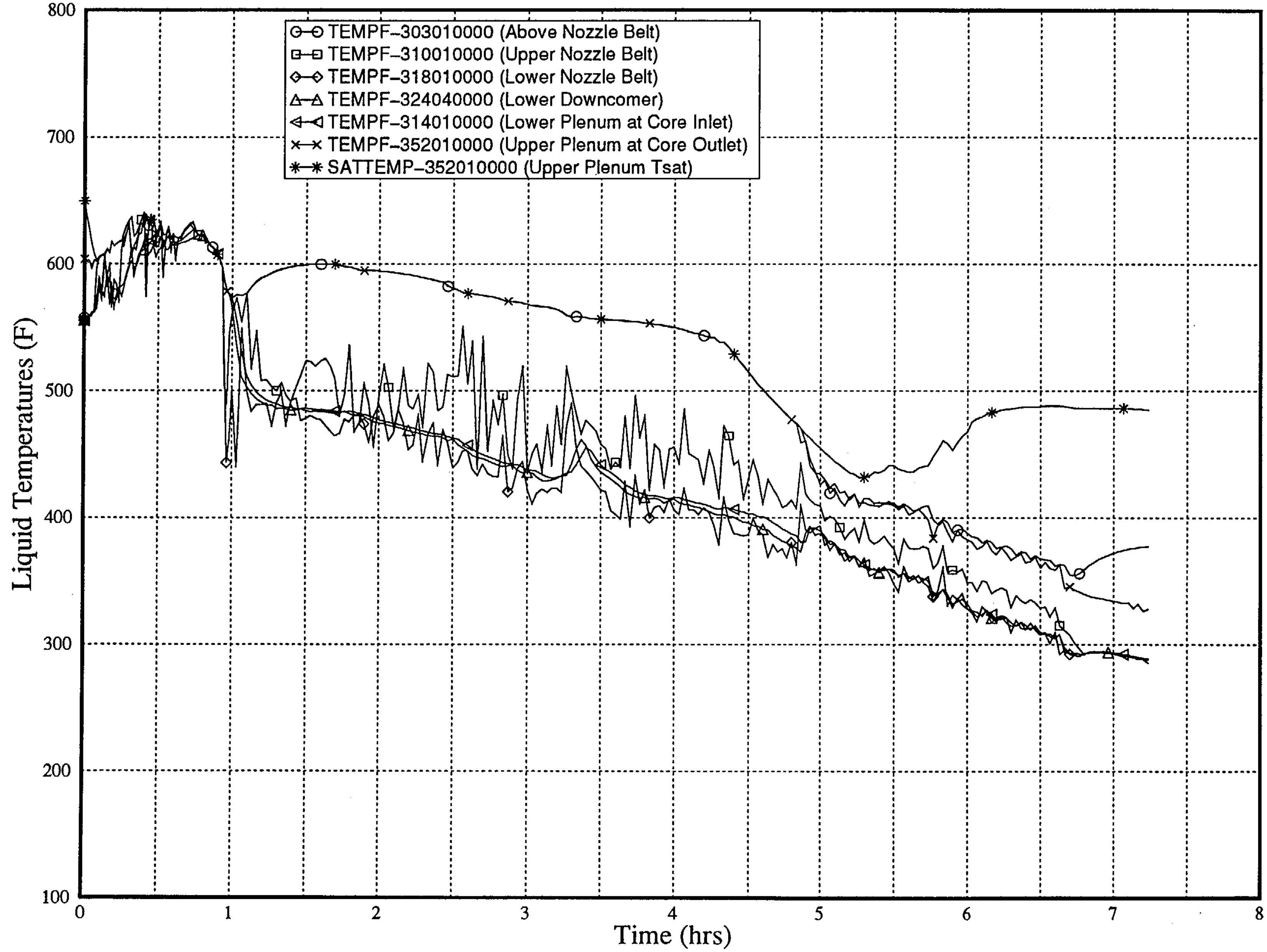


FIGURE A.6.14: 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Normalized Core Power Generation

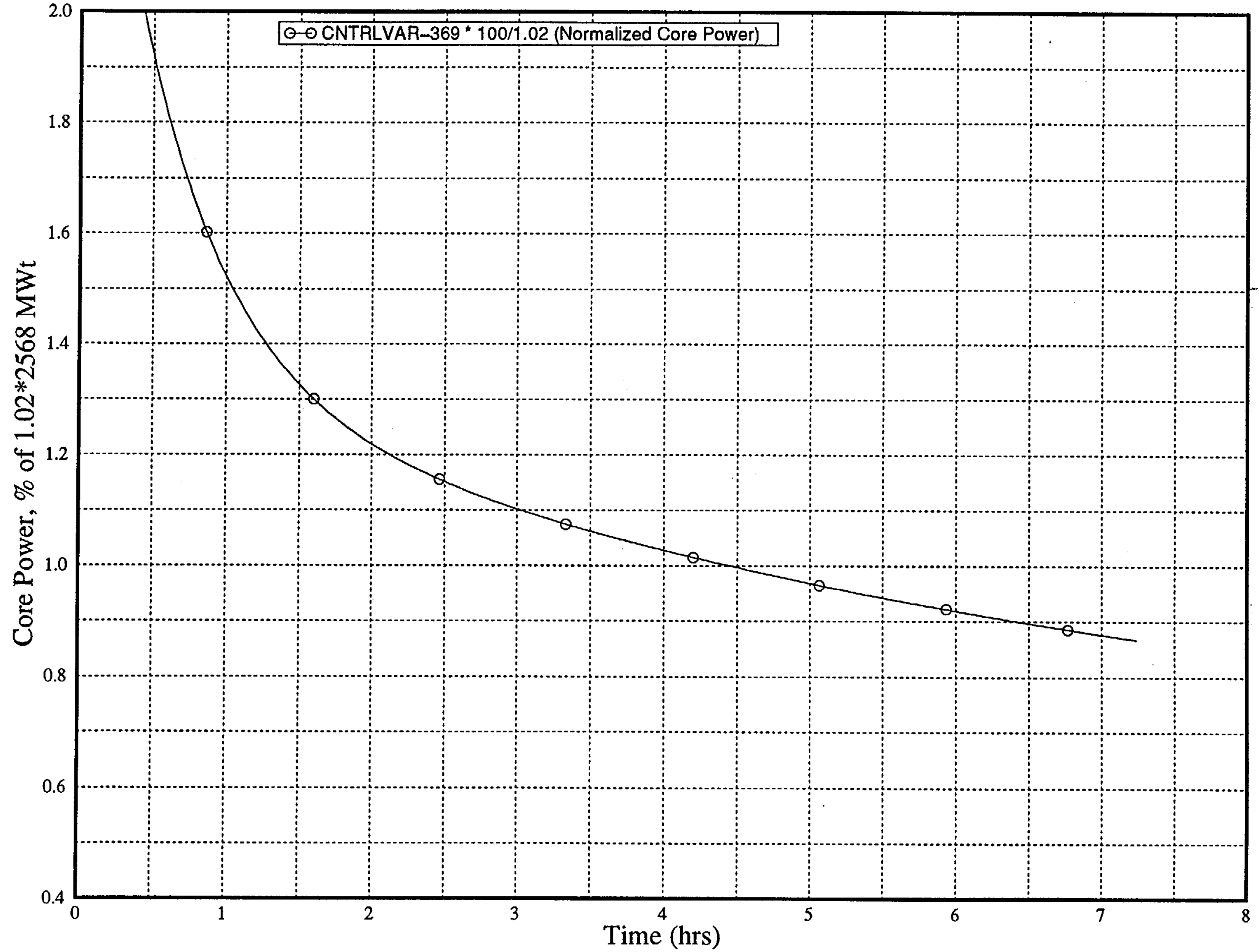
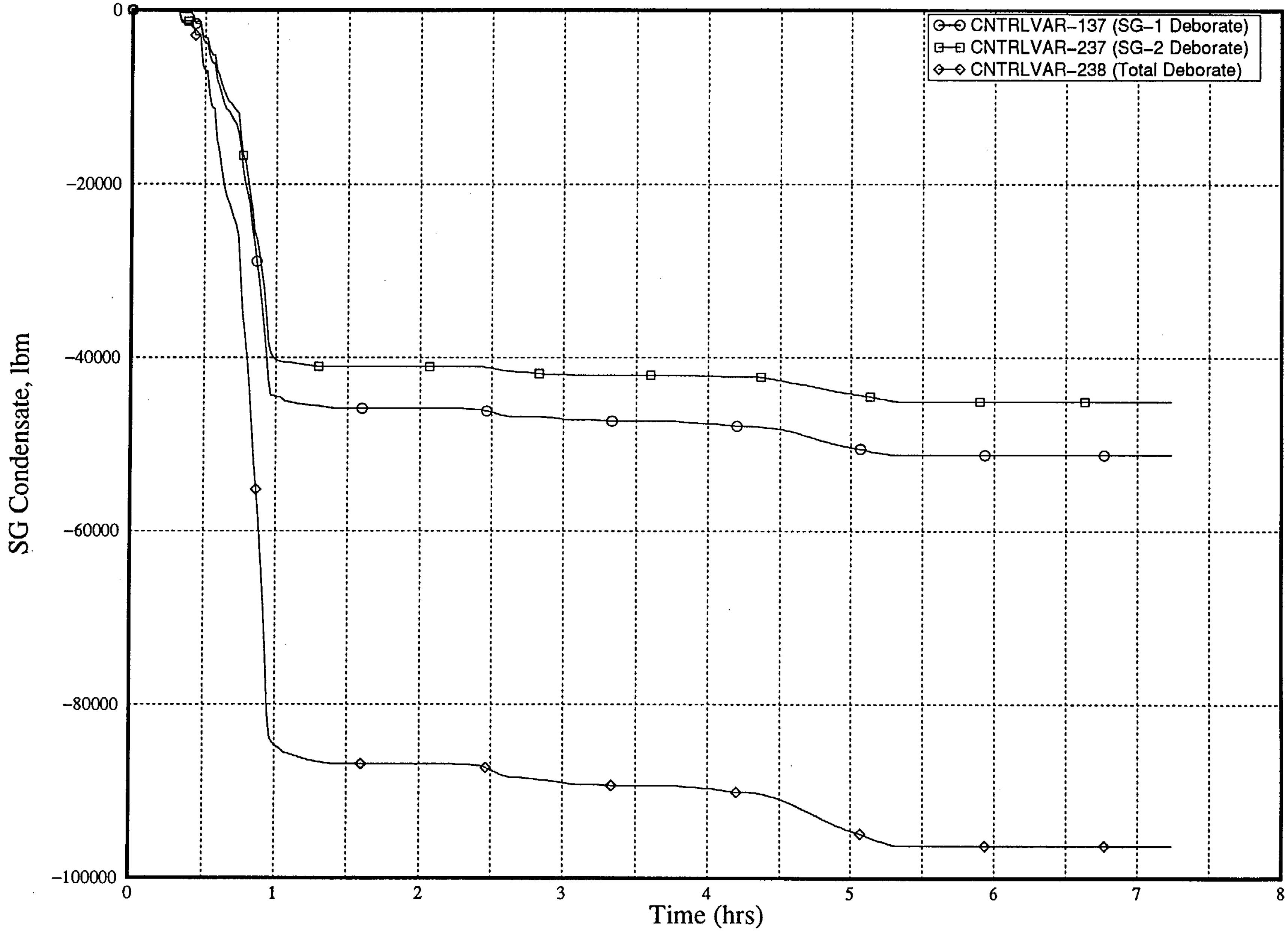


FIGURE A.6.15: 0.007 ft^2 Cold Leg Break, Early Operator Actions.

Deborate Accumulation Due to Steam Condensation in SG



RELAP5/MOD2 B&W V20HP

FIGURE A.6.16: 0.007 ft^2 Cold Leg Break, Early Operator Actions.

RV Upper Plenum to SG–Secondary Delta–T