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Analysis of Natural-Convection Phenomena in a 3-Loop PWR during a TMLB' Transient Using the COMMIX Code

by H. M. Domanus and W. T. Sha

Argonne National Laboratory, Argonne, Illinois 60439
operated by The University of Chicago
Prepared for the Office of Nuclear Regulatory Research
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ANALYSIS OF NATURAL-CONVECTION PHENOMENA IN A 3-LOOP PWR DURING A TMLB' TRANSIENT USING THE COMMIX CODE

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Analytical Thermal Hydraulic Research Program
Materials and Components Technology Division

January 1988

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ABSTRACT

A numerical simulation of the multidimensional thermal-hydraulic characteristics in a 3-loop PWR during a hypothetical TMLB' accident scenario has been performed by means of the COMMIX computer code. The operating conditions, as well as the modeling approaches used in the simulation, are discussed. Selected results, which show the natural circulation phenomena and compare the thermal-hydraulic behavior in the different loops, are presented.

FIN No.	Title
A2255	COMMIX PWR Calculations

CONTENTS

FIGURES

EXECUTIVE SUMMARY

The TMLB' is one of the postulated reactor accidents that is currently being investigated by the U.S. Nuclear Regulatory Commission (NRC). In this accident, several different significant events and physical phenomena occur. During the progression of the TMLB' accident scenario, there is a time when the hot leg dries out and the core becomes uncovered. From that time on, multidimensional natural-circulation phenomena play an important role in heat transport and the heat-up of the various components in a reactor system.

Natural circulation, one of the phenomena in TMLB', is important because the amount of decay heat being transported to different internal structures (e.g., upper internals, steam generator tubes) depends upon the natural-circulation flow pattern that is established during the accident. To save computer storage and computer running time, system analyses are performed under the assumption that flow phenomena are generally one-dimensional. However, the natural-convection phenomena, which are probable in the TMLB' scenario, e.g., countercurrent flow in the hot leg, are multidimensional. Therefore, the flow patterns, temperature distributions, and steam generator heat transfer rates resulting from the multidimensional calculation, as performed here, can provide very useful guidance for simulation of one-dimensional systems. Hence, our task here is to perform multidimensional analysis of natural-circulation phenomena and to generate data that are needed to support the system analyses being performed at Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), and Idaho National Engineering Laboratory (INEL).

In the transient that we simulated, the entire system at time $t = 0$ was isothermal, i.e., it contained saturated steam at $p = 1.61 \times 10^7$ Pa. For time $t > 0$, decay heat was added to the core. With the addition of decay heat to the core, natural convection began. While the natural-convection flow pattern was being established, the system was being perturbed by the opening and closing of the PORV.

We have performed the present analysis by using a PORV model that was at the end of the surge line that was connected to the pressurizer. The results of the analysis confirm that COMMIX is capable of analyzing multidimensional natural-convection phenomena and generating data required for system analysis. Also, the results agree qualitatively with available experimental data.

1. OBJECTIVE

The objectives of the research program are to

1. study multidimensional natural-circulation phenomena,
2. predict heat transfer rates to various internal structures, and
3. examine the recirculating-flow pattern in a reactor system in general, and in the hot legs in particular,

during the postulated TMLB' accident. This report also examines the asymmetry that is caused by the opening and closing of the PORVs and the effects of the opening-closing of the PORVs on the natural-convection flow pattern and heat transfer to various components.

2. INTRODUCTION

The TMLB' is one of the postulated reactor accidents that is currently being investigated by the U. S. Nuclear Regulatory Commission (NRC). In this accident, several different significant events and physical phenomena occur [1]. During the progression of the TMLB' accident scenario, there is a time when the hot leg dries out and the core becomes uncovered. From that time on, multidimensional natural-circulation phenomena play an important role in heat transport and the heat-up of the various components in a reactor system. Figure 1 shows some system modeling results that were generated by INEL for the Seabrook Plant [2]. Key events are indicated, and the time window for the current analysis is shown.

Our major goal in the present analysis was to determine how much energy is transported to different internal structures (steam generator tubes, upper-plenum structures, etc.) and also to determine the magnitude of the hot-leg-countercurrent flow and steam generator circulation. We therefore have simulated a transient based on the recommendation of J. Dallman and P. Bayless-INEL, and R. Henninger-LANL [3].

To date, several simulations have been performed, each being more complete than the previous. The first simulation was a two-dimensional model that assumed 1/4-plant symmetry and constant exit pressure [4]. The second simulation was a three-dimensional model that assumed 1/2 symmetry of a 3-loop plant and introduced a pressure-dependent-valve model for the PORV exit [5]. The simulation reported here extends the 3-loop plant model. The additional models included in the current work are

1. surge line pipe length connected to the left hot leg and the PORV placed at the end of the modeled length,

2. thermal aspects of surge line pipe wall,

3. thermal aspects of left and back hot-leg pipe wall,

4. thermal aspects of left and back steam generator tube sheet,

5. full 2000-s transient time with transient decay heat source. For the first 1000 s, the decay heat source was constant (1.04% of $Q_{full\ power}$). Between 1000 and 1500 s, the decay heat source linearly increased to 1.1 times the constant value. From 1500 to 2000 s, the decay heat source linearly increased to 1.3 times the constant value.

In this simulated transient, the entire system at time $t = 0$ was isothermal, i.e., it contained saturated steam at $p = 1.61 \times 10^7$ Pa. For time $t > 0$, decay heat was added to the core. With the decay heat addition in the core, natural convection began. While the natural-convection flow pattern was being established, the system was being perturbed by the opening and closing of the PORV.

The objectives of the analysis were to

1. demonstrate the capability of COMMIX [6] to analyze multidimensional natural-convection and recirculating-flow phenomena that are encountered in a PWR during the TMLB' accident scenario with PORV cycling,

2. calculate and compare the rates of heat transfer to the different hot-leg loops, and

3. determine and compare the countercurrent flow in the different hot-leg loops.

The present analysis was specifically designed to determine the natural-convection phenomena after the time when the hot leg dries out. During this time,

1. the system pressure was cycling because the PORV open/close set pressures were 2350/2280 psia,

2. the secondary side of the steam generator had dried out and was assumed to be a negligible heat sink, and

3. the only heat sinks were the internal structures (e.g., steam generator tubes, upper internals, pipe walls, and core internals).

We have performed the analysis with a PORV model that is at the end of the surge line that is connected to the pressurizer. The results of the analysis confirm the capability of COMMIX to analyze multidimensional natural-convection phenomena and generate data required for system analysis.

3. NUMERICAL MODEL

3.1 BACKGROUND

To simulate a reactor system and to save computer running time, the present analysis has been performed under the assumption of 1/2 symmetry of a 3-loop power plant. However, we have used the same hot-leg characteristics that were used in the earlier two-dimensional Zion calculations [4]. Important dimensions and features of the vessel are described in Ref. 4.

3.2 IMPORTANT CONSIDERATIONS

With the objectives stated in Section 1 as a guide, the following factors were considered in the development of the present model.

1. We have assumed 1/2 symmetry in the plant. Therefore, 1-1/2 loops are present. Results from each of the 2 loops can be compared to determine the differences between them.

2. In the TMLB' scenario, the reactor coolant pumps are not operating. The primary loop is a closed system, and natural convection is the only driving force. The possible natural-convection currents therefore, are (a) between the steam generator and reactor vessel, and (b) inside the reactor vessel.

3. The open/close set points of the PORV keep the system pressure cycling between the specific limits. A valve model has been used to account for the PORV cycling. The valve was either open or closed. When the valve was open, the flow rate was a constant equal to the PORV capacity. When the valve was closed, there was no flow. The valve opened when the pressure rose above the PORV high-set point and closed when the pressure dropped below the low-set point.

3.3 GEOMETRIC DESCRIPTION OF THE MODEL

The geometric layout of the three-dimensional model is shown in Figs. 2 through 5. To distinguish the two loops, the hot leg with the surge line and PORV, shown in Fig. 2, is referred to as the left hot leg. The back hot leg has no PORV.

Figures 2 through 5 show the partitionings of the model. We have used a model with a total of 947 computational cells. The geometric obstructions to fluid flow by internal solid structures were accounted for by implementing appropriate volume porosities and directional surface porosities in the input data.

The thermal inertia of all internal solids, e.g., fuel rods and support columns, was considered by modeling these thermal structures and employing the properties of appropriate material (stainless steel, Zircaloy, uranium dioxide, silver alloy, inconel). Heat transfer correlations and force structures were used in the model to calculate appropriate heat transfer and friction coefficients [4].

3.4 SURGE LINE MODEL

The surge line was a horizontal (K = 12) pipe which connected the left hot leg to the pressurizer as shown in Fig. 2. The pipe had a 0.2667-m (10.5-in.) inside diameter and was 17.56 m (57.6 ft.) long. At the end of this length the pipe turned upward. The PORV model was placed at this point, before the exit and pressurizer.

The 0.0287-m- (1.13-in.-) thick surge line pipe wall was modeled as a thermal structure. Heat losses from the outer surface of the surge line pipe wall were assumed to be negligible.

3.5 HOT-LEG PIPE WALL MODEL

The pipe walls of the left and back hot legs were accounted for in the current simulation. The hot leg pipes were 0.7366 m (29 in.) in diameter and 0.08128 m (3.2 in.) thick. The pipe walls were modeled as thermal structures interacting thermally with each of the fluid cells in the hot leg.

3.6 STEAM GENERATOR TUBE SHEET MODEL

The steam generator tube sheets in the left and back steam generators were accounted for in the current simulation. The tube sheet was 0.5334 m (21 in.) thick and 3.286 m (129.38 in.) in diameter. It had 6776 holes in it to accomodate 3388 U tubes. The tubes had an inside diameter of 0.019685 m (0.775 in.). The solid portion of the plate occupied 3.424 cu m. The tube sheet was modeled as thermal structures interacting with the fluid cells at K = 22 of the left and back steam generators as shown in Figs. 2 and 3.

4. OPERATING CONDITIONS

At time t = 0 s, the entire system contained 19,251 kg of saturated steam at a uniform temperature of 350°C. The vertical static pressure distribution was initialized with reference to p = 16.10 MPa at the junction of the surge line and pressurizer.

It was assumed that no heat was transferred from the steam generator tubes to the secondary side. A 2000-s transient calculation was performed with a transient decay heat source. For the first 1000 s the decay heat source was constant at 1.04% of $Q_{\text{full power}}$ (Q_o = 34 MW). To approximately account for the increased heat that was generated in the core owing to the start of cladding oxidation at 1000 s, the decay heat source linearly increased to 1.1 Q_o by 1500 s. From 1500 to 2000 s, the decay heat source linearly increased to 1.3 Q_o.

5. CALCULATION RESULTS AND OBSERVATIONS

5.1 PRESENTATION OF RESULTS

During the 2000-s transient, the valve cycled 34 times. When the valve opened, the flow and temperature fields were perturbed. After the valve closed, the flow and temperature fields returned rapidly to more modestly changing natural-circulation patterns. Because of this cyclic behavior in addition to a more gradual transient, selected results for the overall transient are presented, and summarized in tabular form. Finally, the flow field is presented for several times during the transient at a point in the cycle just before the valve opened. Where appropriate, values are presented for the whole plant. The left hot leg contains the surge line and PORV.

5.2 RESULTS OVER THE WHOLE TRANSIENT

The function of the PORV can be seen by examining the variation in system pressure illustrated in Fig. 6 which shows 34 valve open/close cycles. The pressure increased until the high-set point was reached, at which time the valve opened. With the valve open, the system depressurized until the pressure fell below the low-set point, at which time the valve closed. While the valve was open, mass left the system through the valve as shown in Fig. 7.

Mass flows at selected locations are presented in Figs. 8 through 11. These figures can be compared with one another and similarities can be noted. For example, the steam generator tube flows for the left and back steam generators behaved quite similarly (compare Figs. 8 and 9), whereas the left and back hot-leg flows show more difference (compare Figs. 10 and 11), particularly when the valve was open. The results are consistent with the notion that mass is drawn toward the open valve.

Heat transfer to key system components is shown in Figs. 12 through 15. Heat transfer to the steam generator tube sheet is combined with the tube information. Figure 14 shows that more heat was transferred to the left than to the back steam generator tubes. Furthermore, for a short period of time during a cycle there was a net heat transfer back to the steam from the tubes. This is due to the isentropic expansion of the steam as the system became depressurized when the valve was open.

Temperatures at various locations around the system are presented in Figs. 16 through 27. The highest temperatures in the system are shown in Fig. 16; the hot spot was at the top center of the core. The temperature of the clad reached 1000 K (727°C) when oxidation began at 987 s. Figures 20 and 21 indicate that the left steam generator was somewhat hotter than the back steam generator, and also, that the full lengths of the steam generator tubes were participating after approximately 600 s, as is indicated by the exit warm-up. Figures 22 and 23 indicate that there was more slugging action in the left hot leg than in the back hot leg. Whereas the temperatures in the center and side of the core differed by up to 360°C (Fig. 25), the difference in temperature between the center and side of the upper plenum was less than 110°C (Fig. 26). Temperatures along the steam generator tubes are shown in Figs. 26a through 27d. After the natural circulation flow was completely set up and during a period after the valve opened, the steam temperatures fell below the temperatures of the inner tube all along the steam generator tubes. At that time, net heat was transferred back to the steam from the tubes. Similar results were observed in the back steam generator tubes.

Figure 28 shows the cumulative steam mass that had left the system through the PORV.

Figures 29 to 31 show the cumulative heat that was deposited onto important system components. The curves in these figures represent the cumulative effects of the instantaneous data presented in Figs. 13 to 15.

A summary of the important system quantities for the entire 2000-s transient is presented in Table 1. By 2000 s, 51.9% of the initial steam mass had left the system through the valve. Of the 72,250 MJ of decay heat, 54.4% was deposited onto the core internals. More heat (5.9%) was deposited in the left steam generator than in the back steam generator.

5.3 FLOW DISTRIBUTION

The flow fields at three different times into the transient, for the left hot leg and the back hot leg, are presented in Figs. 32a-c and 33a-c, respectively. In all cases, the time was at the point in a cycle just before the valve opened. The first time (593 s) corresponds to a time when the natural-circulation patterns were clearly developed and the entire length of the steam generator tubes began to participate thermally. The second time (979 s) corresponds to the time when clad oxidation began. The final time (1957 s) was near the end of the simulation. Similarities between the flow patterns of

Table 1. Selected Quantities for the Overall Transient

Mass lost	9985 kg	51.9%
Energy Transferred (MJ, %)		
Decay heat	72.25E3	
Core internals	39.31E3	54.4
Plenum internals	12.83E3	17.8
Left steam generators	2.51E3	3.5
Back steam generators	2.37E3	3.3
All steam generators	7.25E3	10.0
Left pipe wall	0.46E3	0.6
Back pipe wall	0.40E3	0.6
Surge line wall	0.11E3	0.2
All pipe walls	1.37E3	1.9
Steam	11.49E3	15.9

early and late times indicate the persistance of the natural-convection phenomena.

6. CONCLUSIONS

A numerical simulation of a 3-loop PWR has been performed for a portion of a TMLB' accident sequence by means of the COMMIX computer code. Significant new aspects of the model were

1. surge line pipe length connected to the left hot leg and the PORV placed at the end of the modeled length.

2. thermal aspects of surge line pipe wall.

3. thermal aspects of left and back hot leg pipe wall.

4. thermal aspects of left and back steam generator tube sheet.

5. full 2000-s transient time with transient decay heat source. For the first 1000 s, the decay heat source was constant (1.04% of $Q_{full\ power}$). Between 1000 and 1500 s, the decay heat source linearly increased to 1.1 times the constant value. From 1500 to 2000 s, the decay heat source linearly increased to 1.3 times the constant value.

Three key observations were made.

1. A natural-circulation flow pattern reestablished very rapidly after PORV was closed.

2. More heat was transported to the steam generator tubes in the loop with the PORVs.

3. When the valve opened, its pressure impulse was felt everywhere immediately, and flow reversal occurred not only in the neighboring steam generator, but in all steam generators.

All of the above observations are in agreement with the Westinghouse experiments [7-10].

A natural-circulation flow pattern developed, permitting heat transport between the core and the hot-leg structures. While the flow field was significantly perturbed when the valve opened, it was quickly reestablished after the valve closed.

Because steam was drawn into the hot leg that contained the PORV when the valve was open, somewhat higher temperatures were calculated in the steam generator tubes in the valve loop. Over the course of the entire transient, 5.9% more heat was deposited in the steam generator tubes in the loop that contained the PORVs than in the steam generator tubes of the other loops.

The temperature at which the clad starts to oxidize (1000 K) was reached in the upper center of the core 987 s into the transient. This time is somewhat later than but consistent with the previous calculation since more solid structures were modeled.

During a portion of the PORV open/close cycle, reverse heat transfer was observed in the steam generator tubes. This reverse heat transfer was due to the isentropic expansion of the steam in the system when the PORVs opened.

Results and observations from this simulation are currently being applied to the system models that are used to analyze the complete TMLB' sequence.

ACKNOWLEDGMENT

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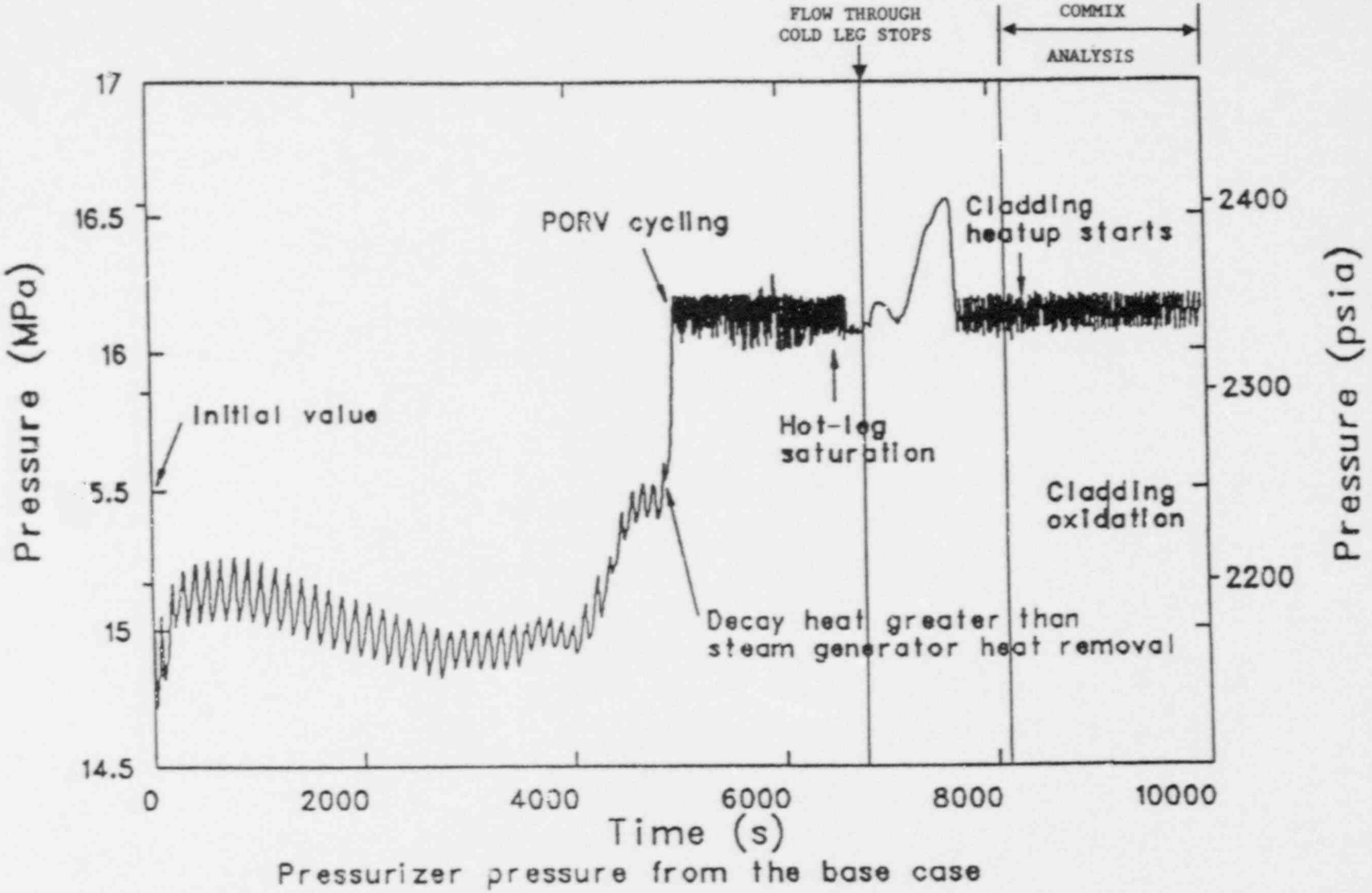

Fig. 1. Characteristic Events During the TMLB' Scenario

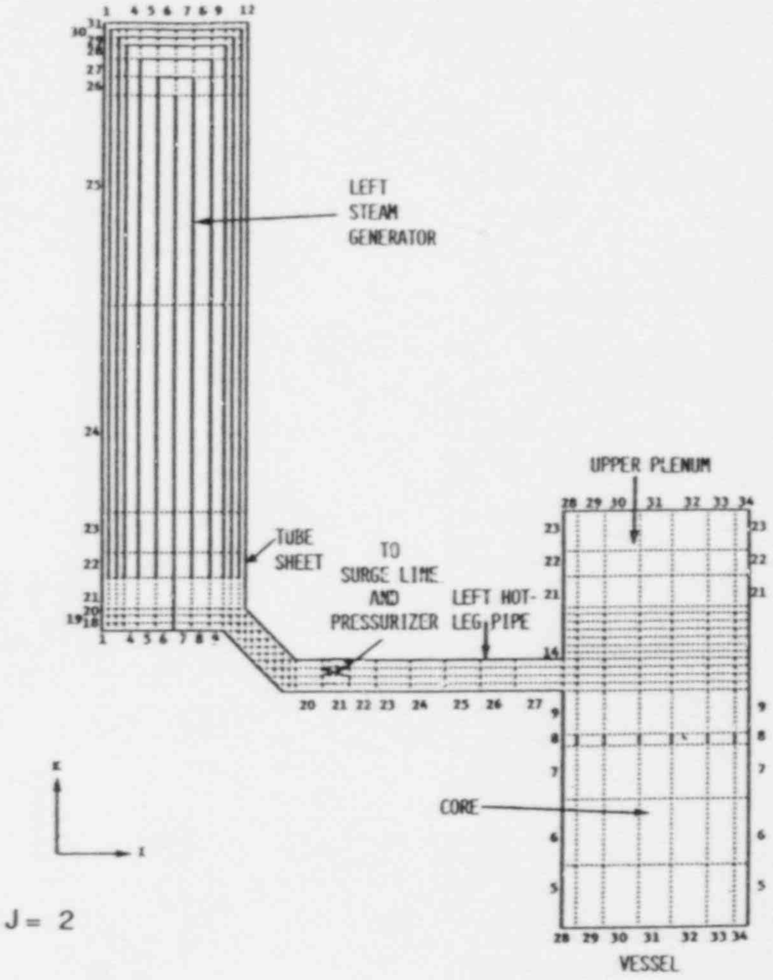

Fig. 2. Vessel and Left Hot Leg

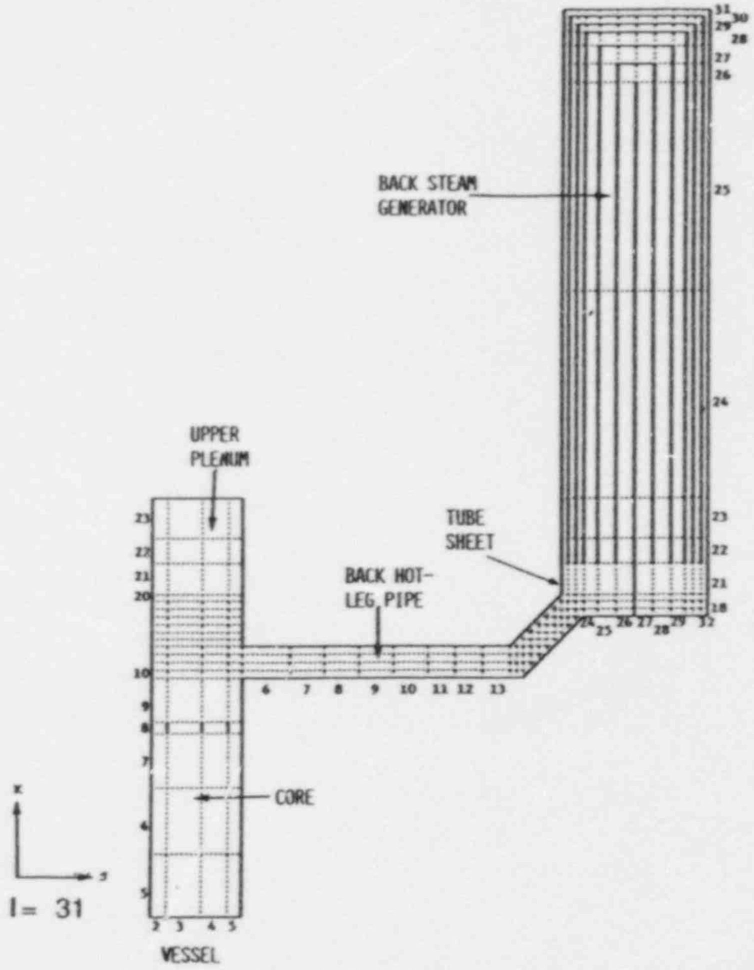

Fig. 3. Vessel and Back Hot Leg

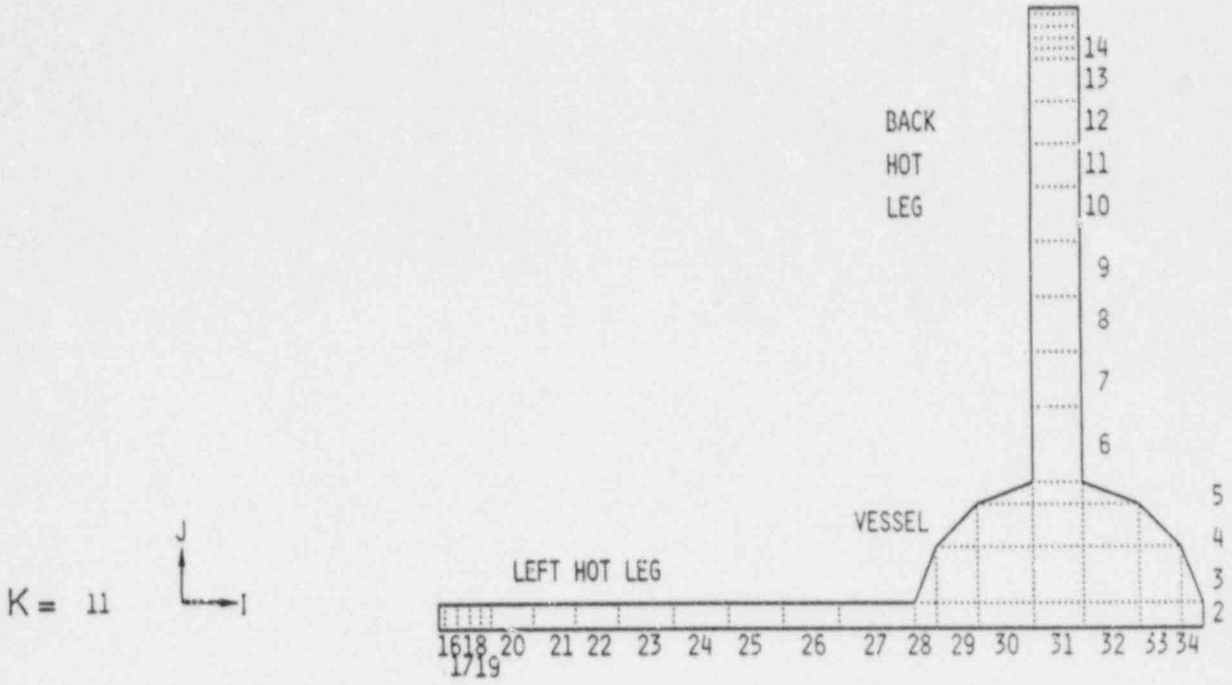

Fig. 4. Plant 1/2 Symmetry - Vessel and Hot Legs

Fig. 5. Plant 1/2 Symmetry - Vessel and Steam Generators

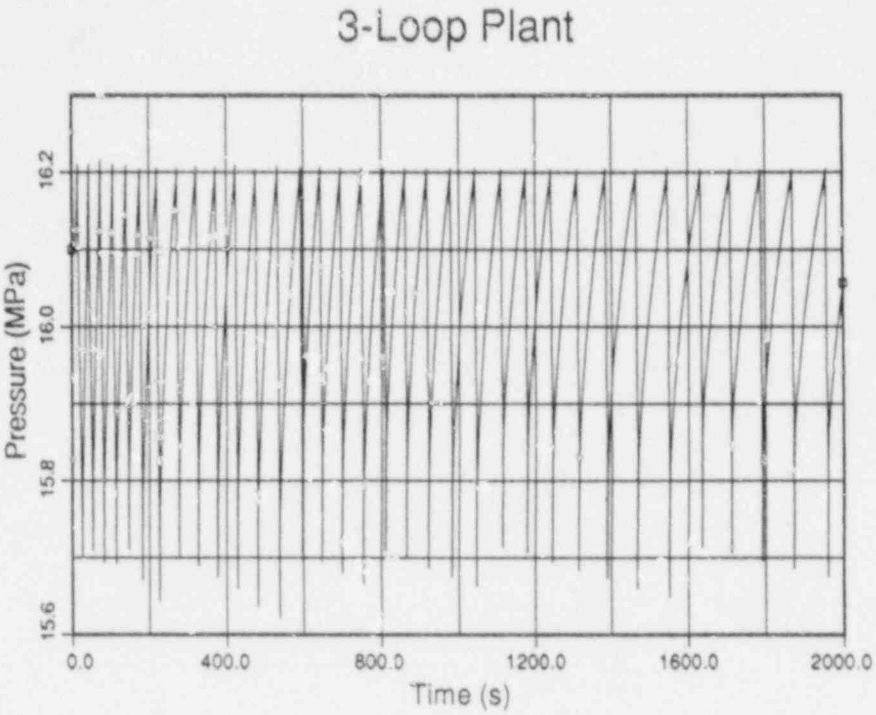

Fig. 6. System Pressure Variation Near Valve Exit

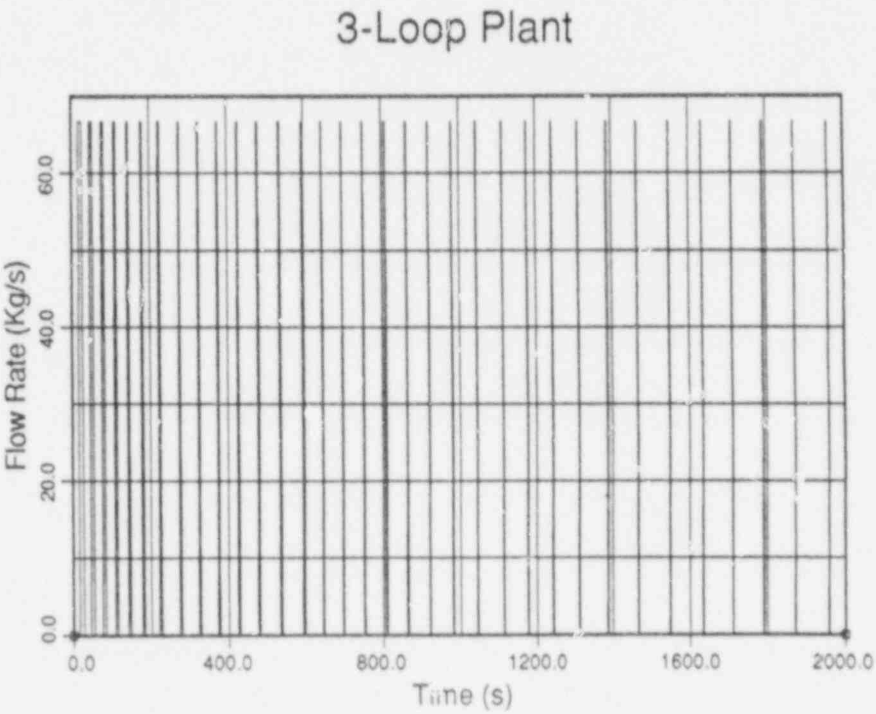

Fig. 7. Mass Flow Through Valve Exit

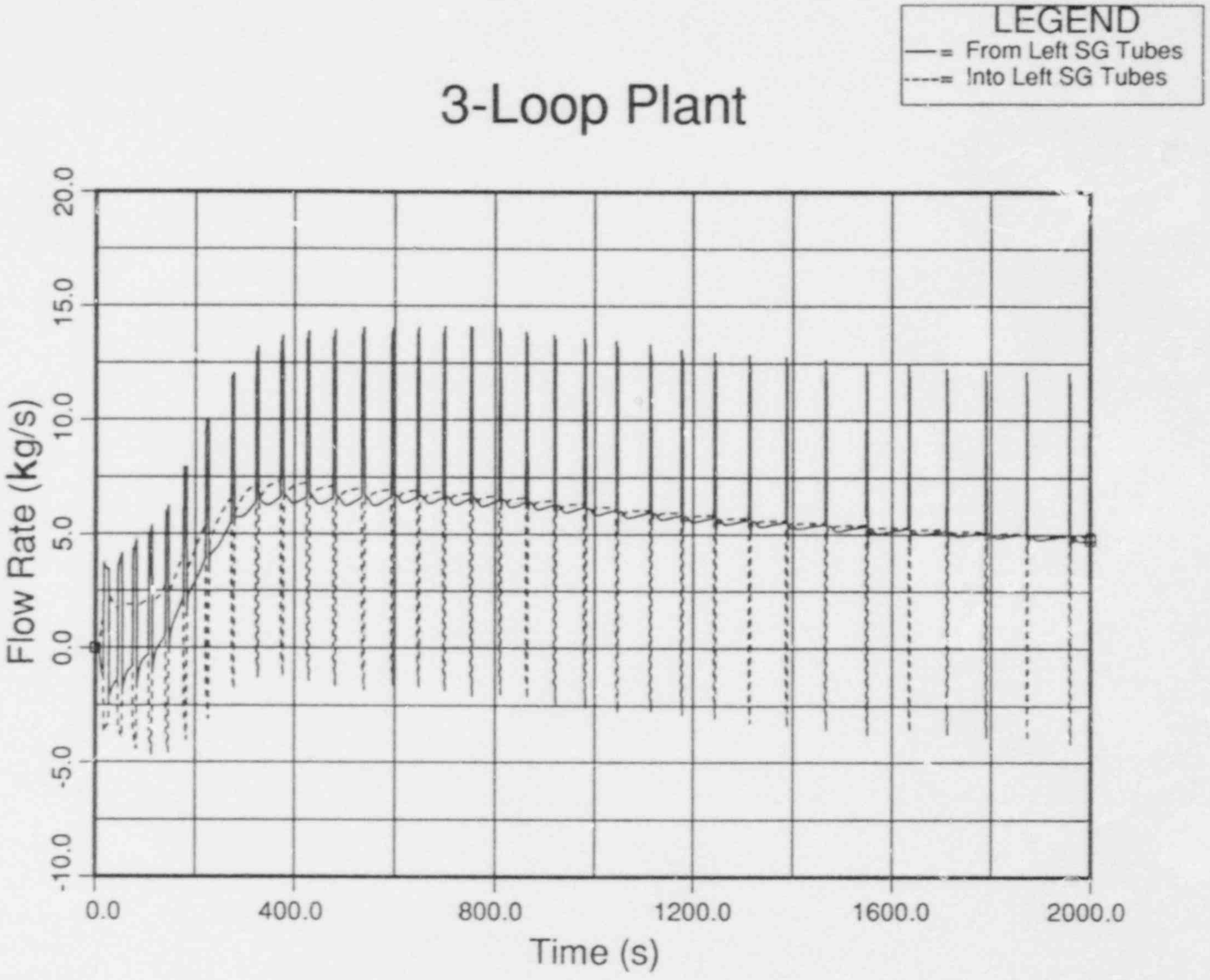

Fig. 8. Left Steam Generator (SG) Tube Flow

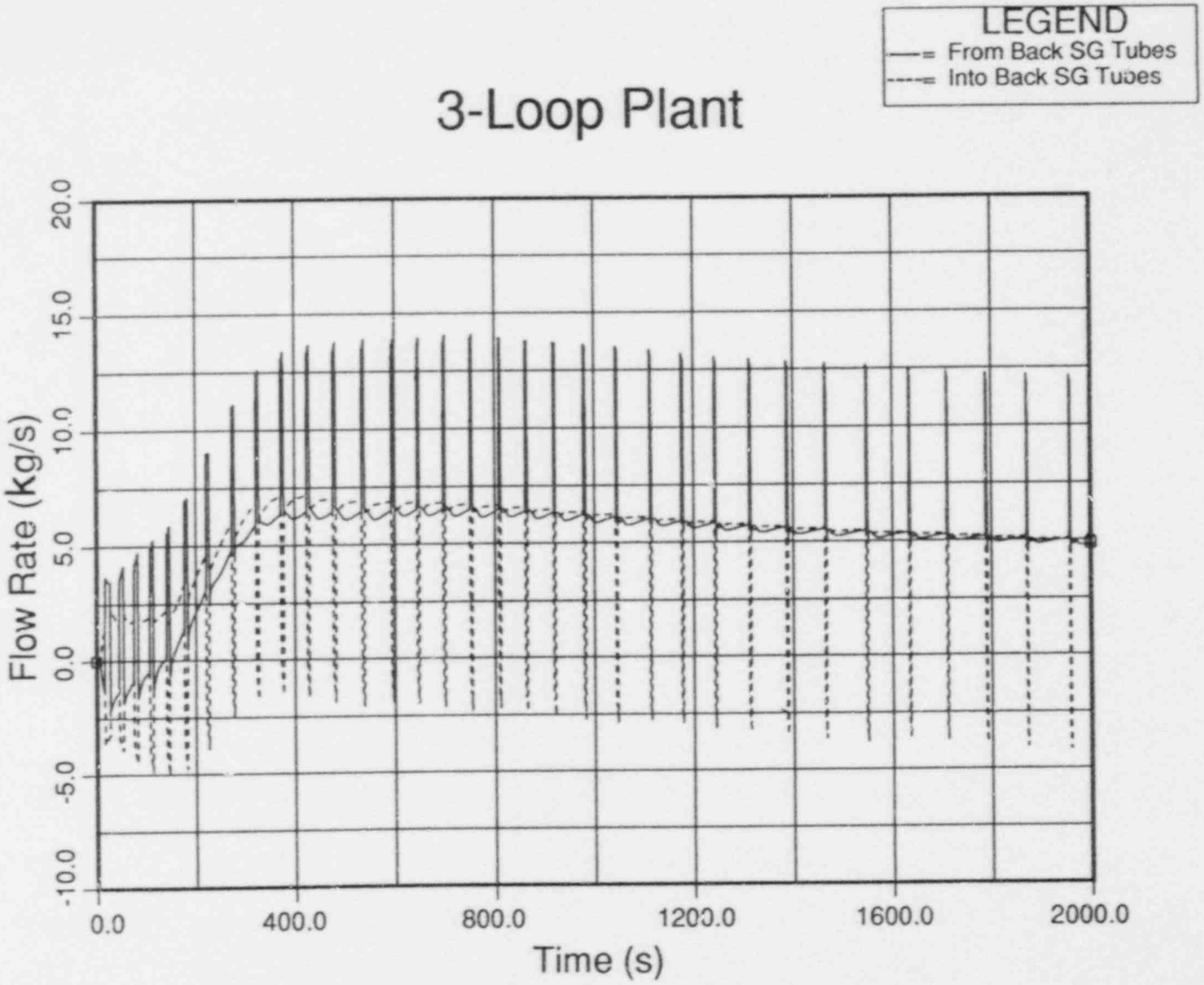

Fig. 9. Back Steam Generator Tube Flow

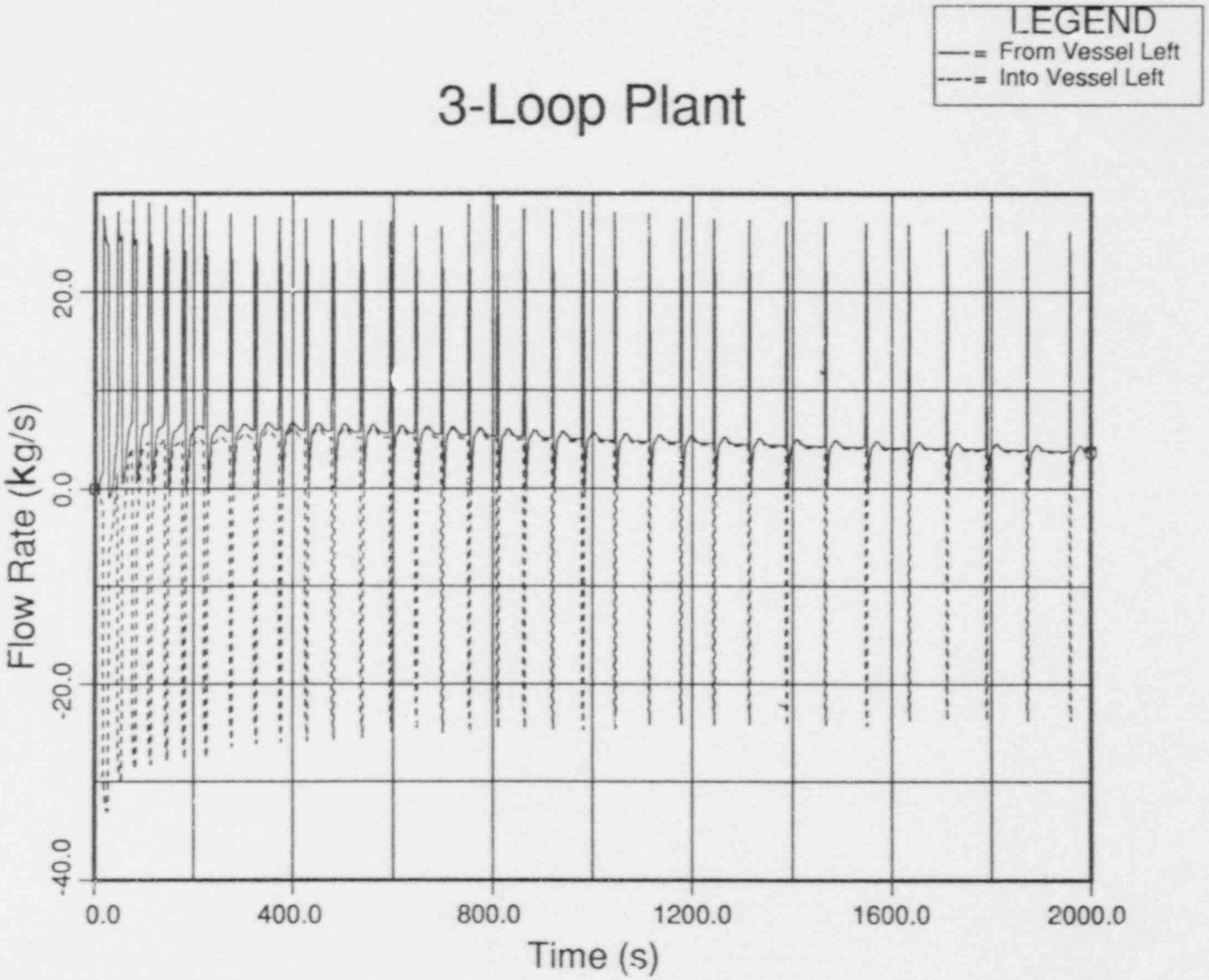

Fig. 10. Left Hot-Leg Flow

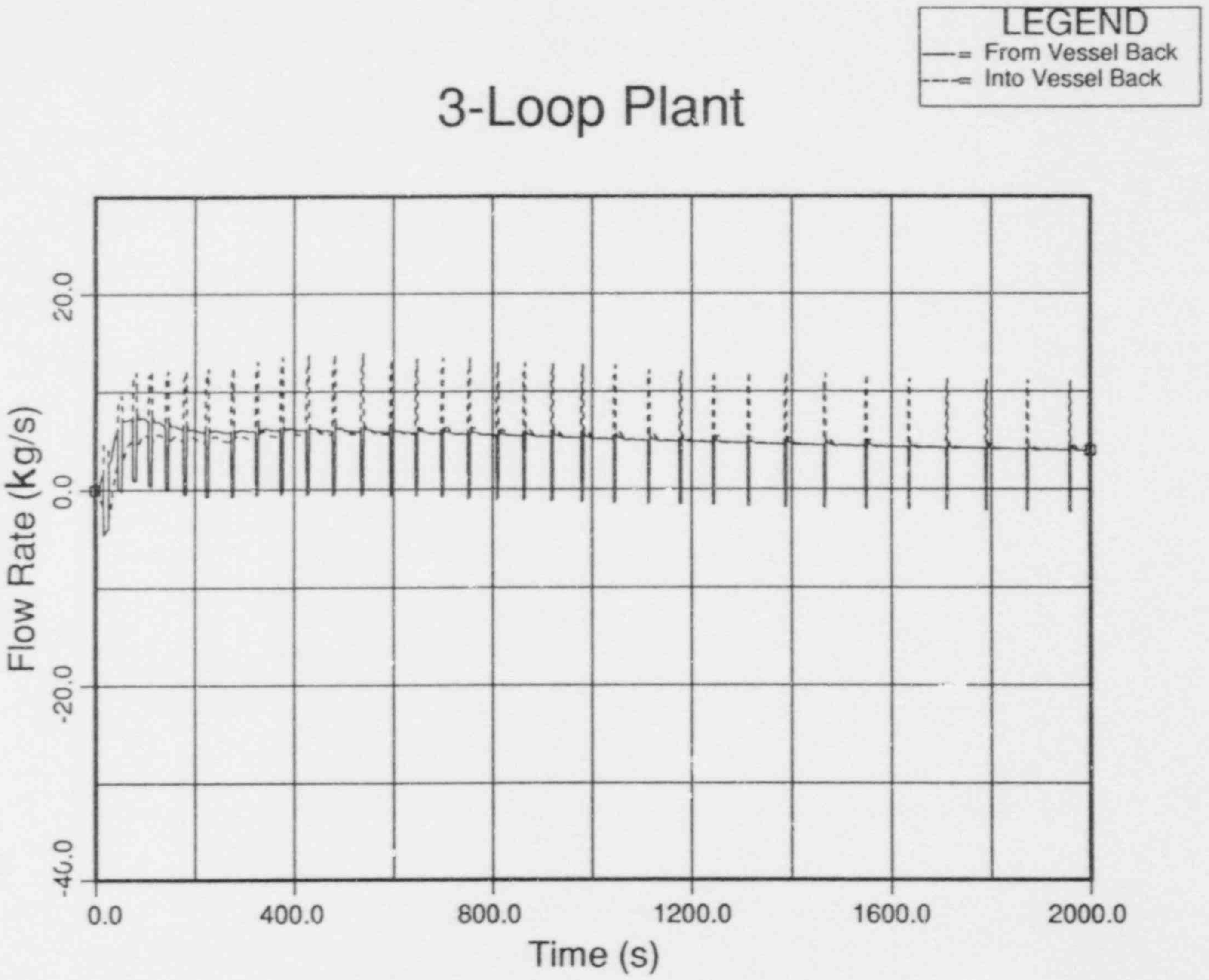

Fig. 11. Back Hot-Leg Flow

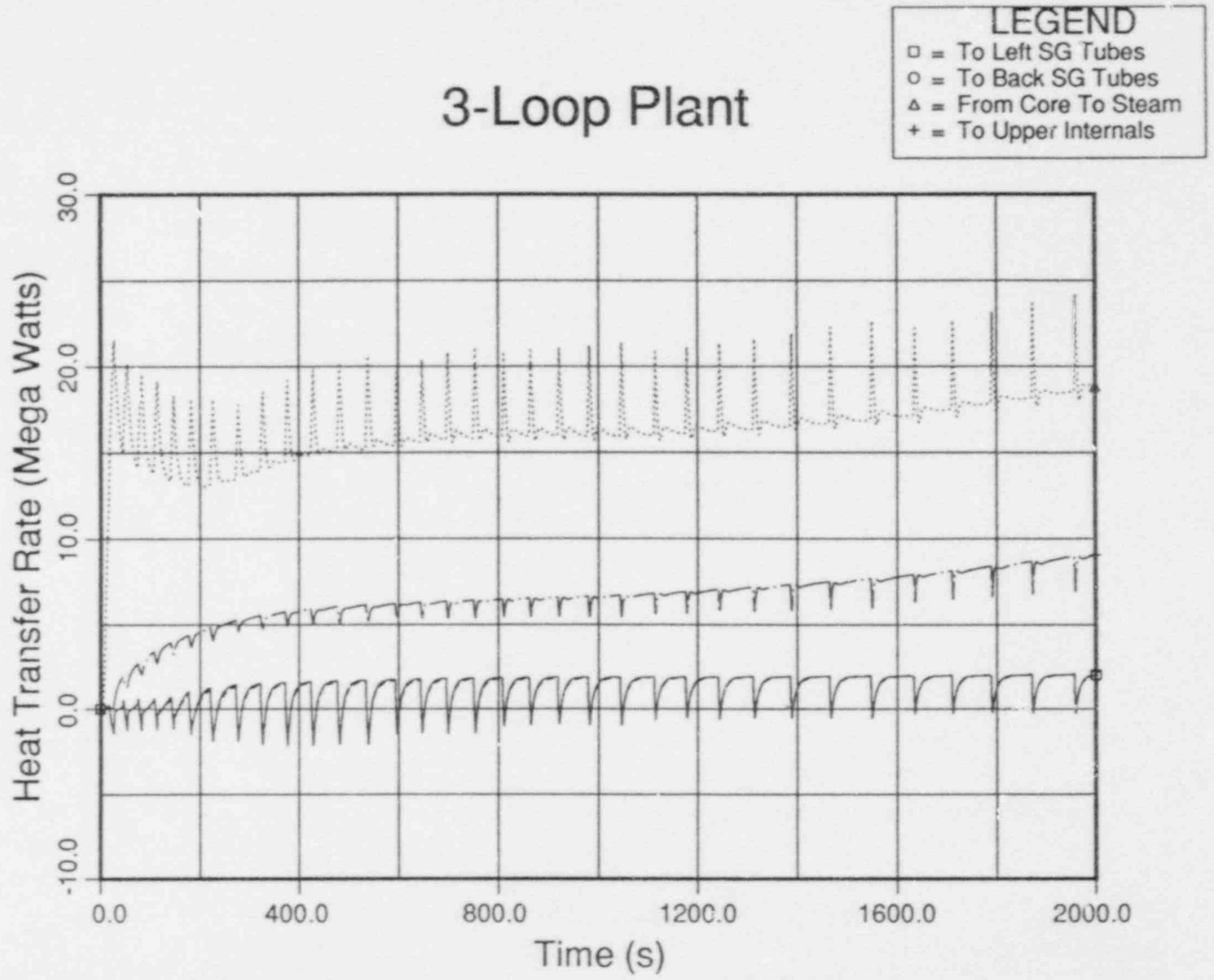

Fig. 12. Selected System Heat Transfer to Solids

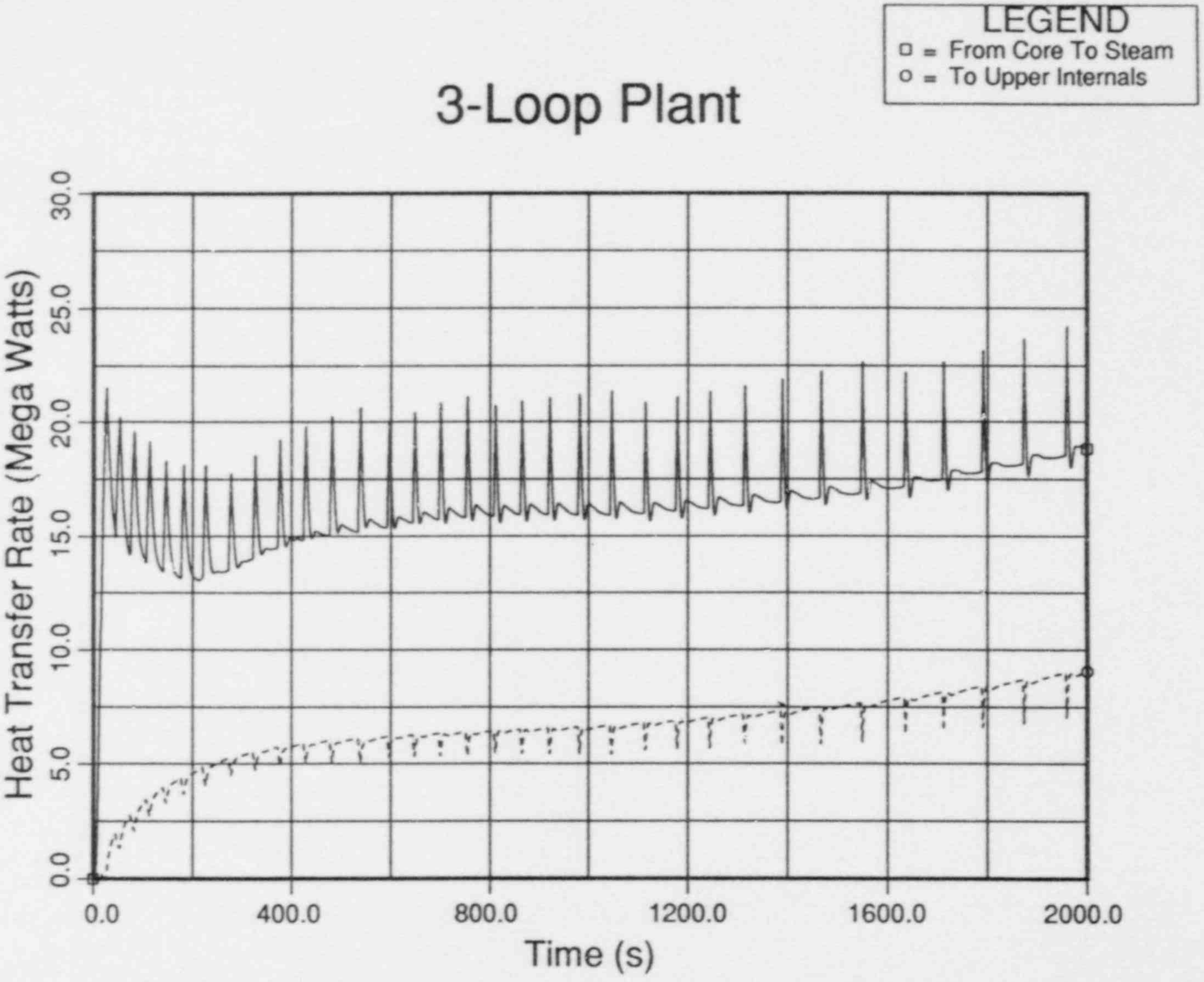

Fig. 13. Vessel Heat Transfer to Solids

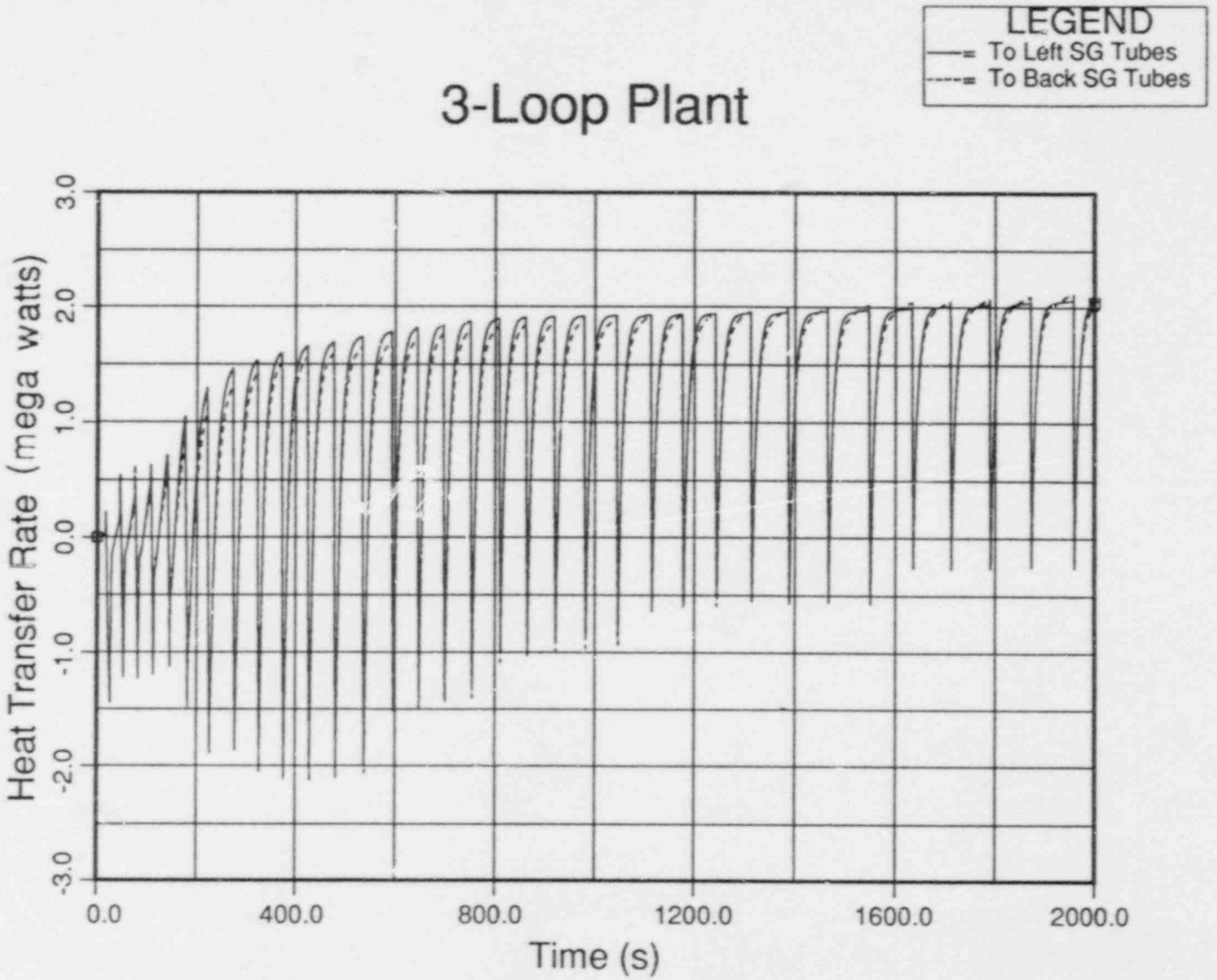

Fig. 14. Heat Transfer to Steam Generator Tubes

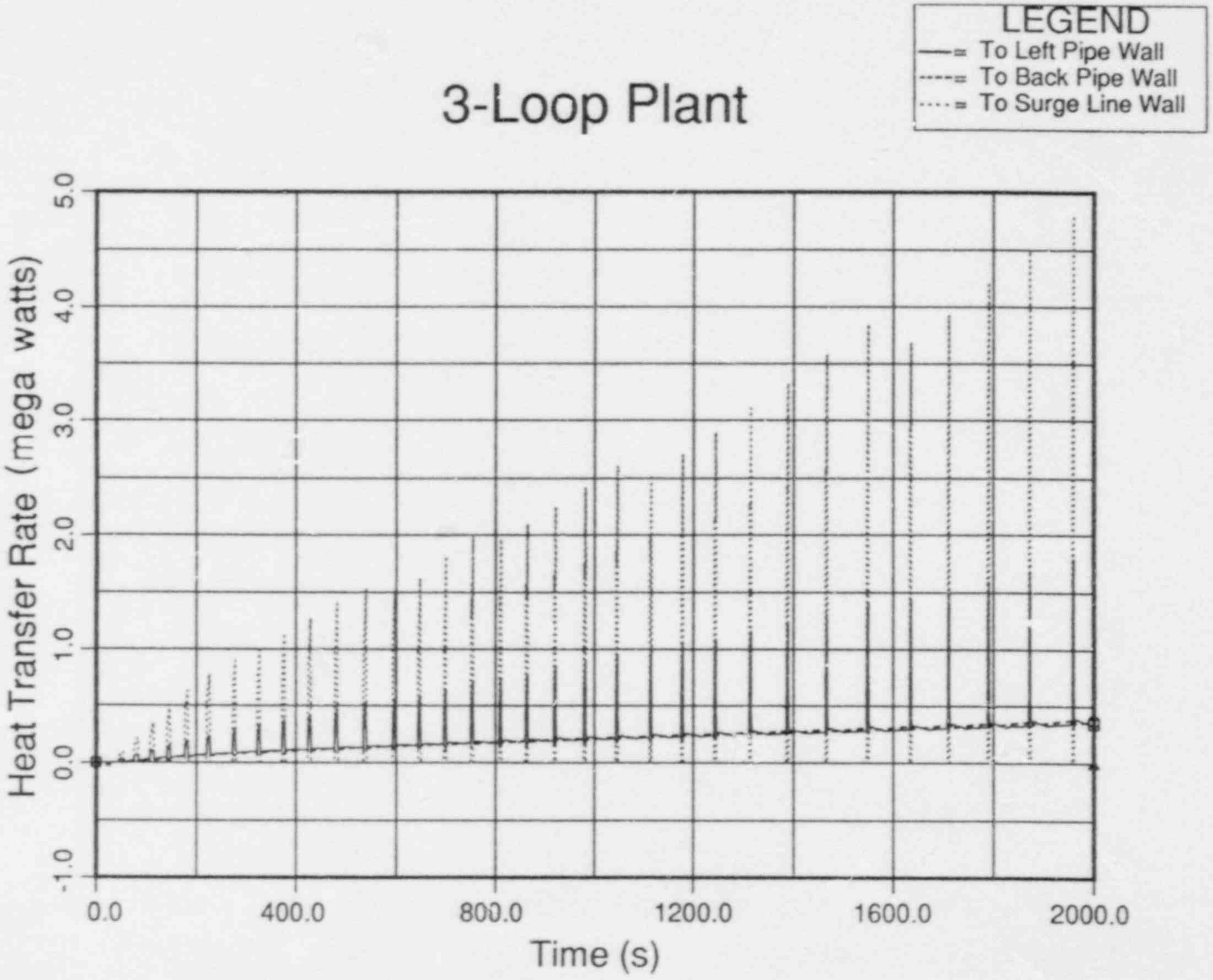

Fig. 15. Heat Transfer to Pipe Walls

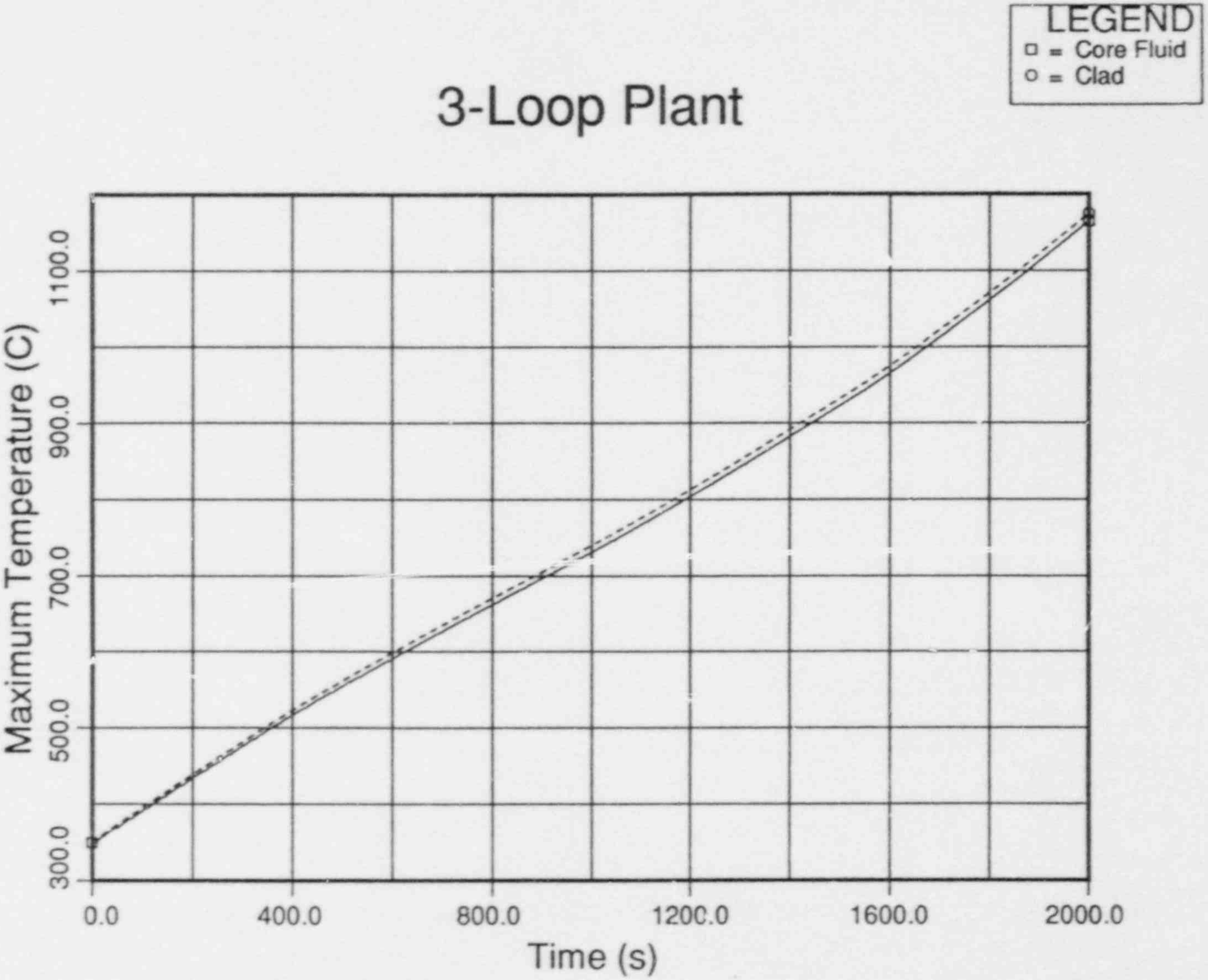

Fig. 16. Hot Spot Temperatures

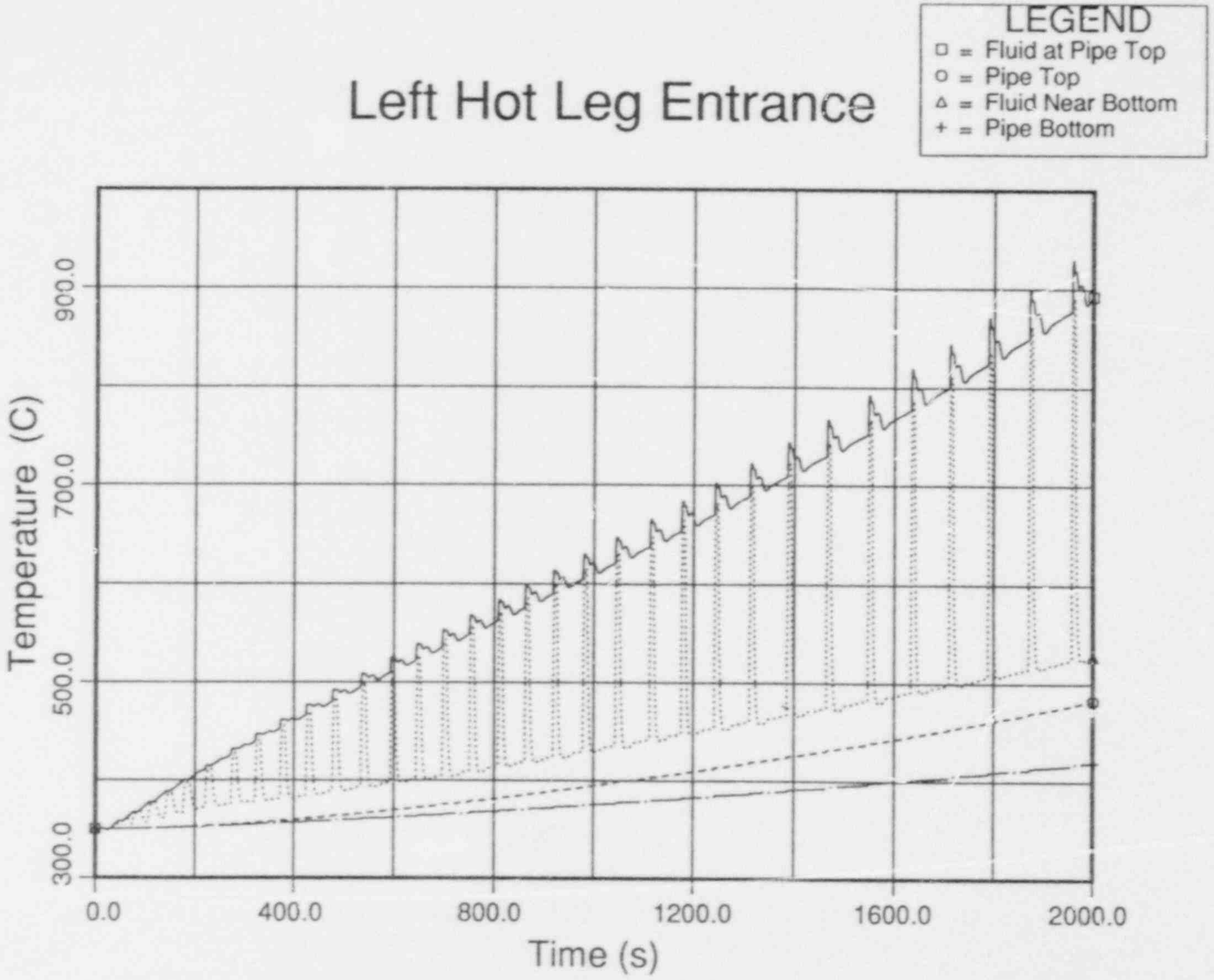

Fig. 17. Temperatures at Entrance of Left Hot Leg

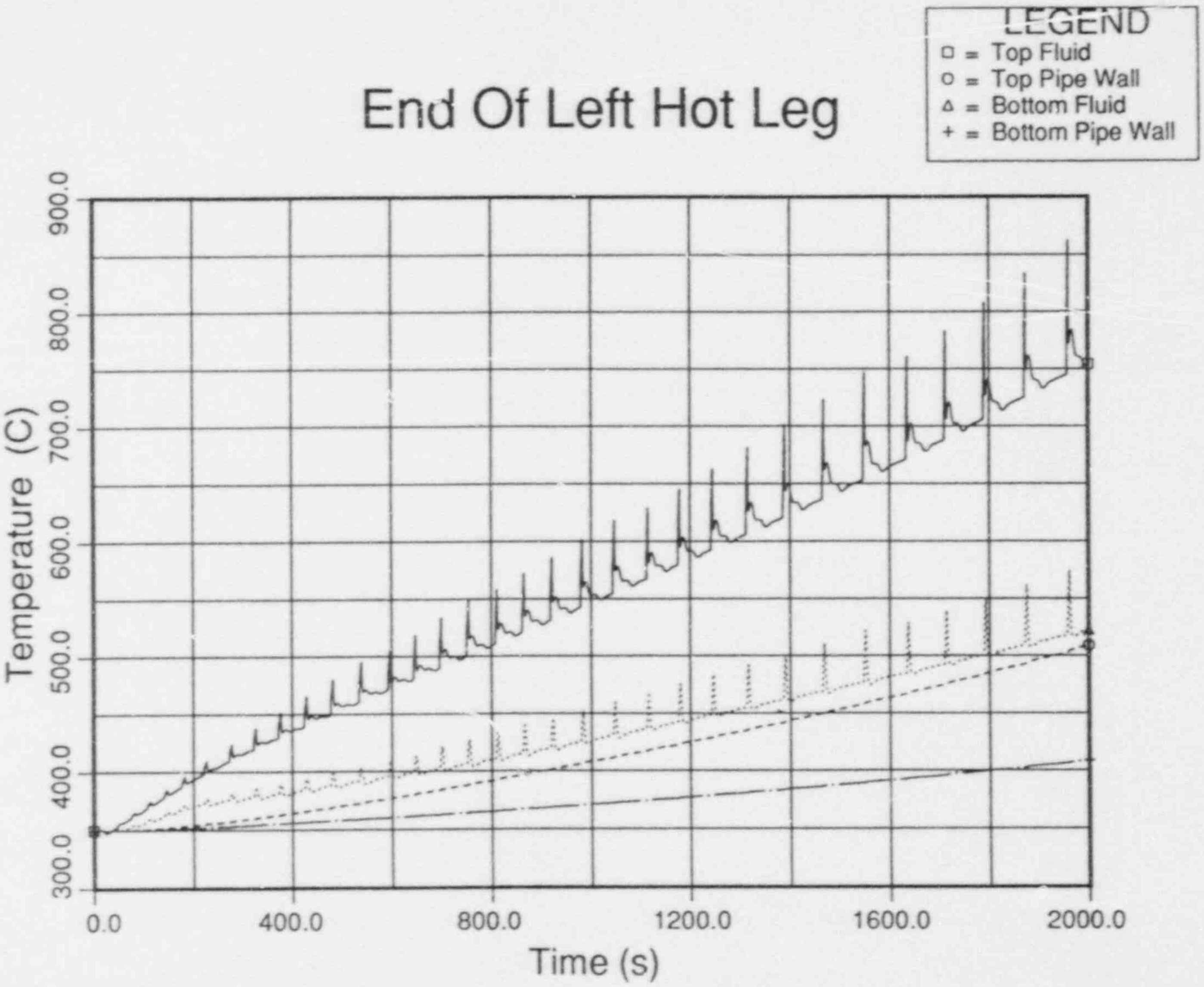

Fig. 18. Temperatures at End of Left Hot Leg (I = 20)

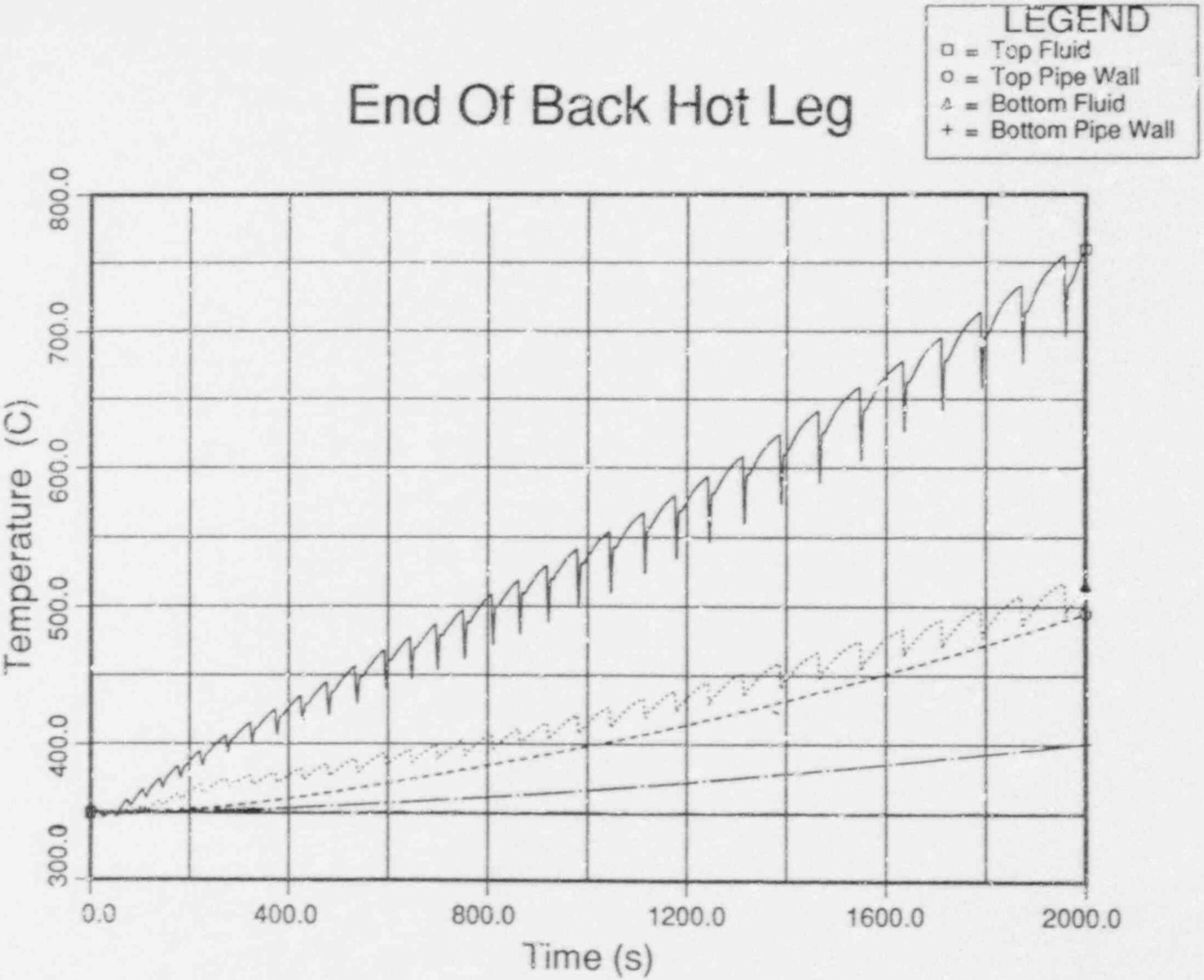

Fig. 19. Temperatures at End of Back Hot Leg (J = 13)

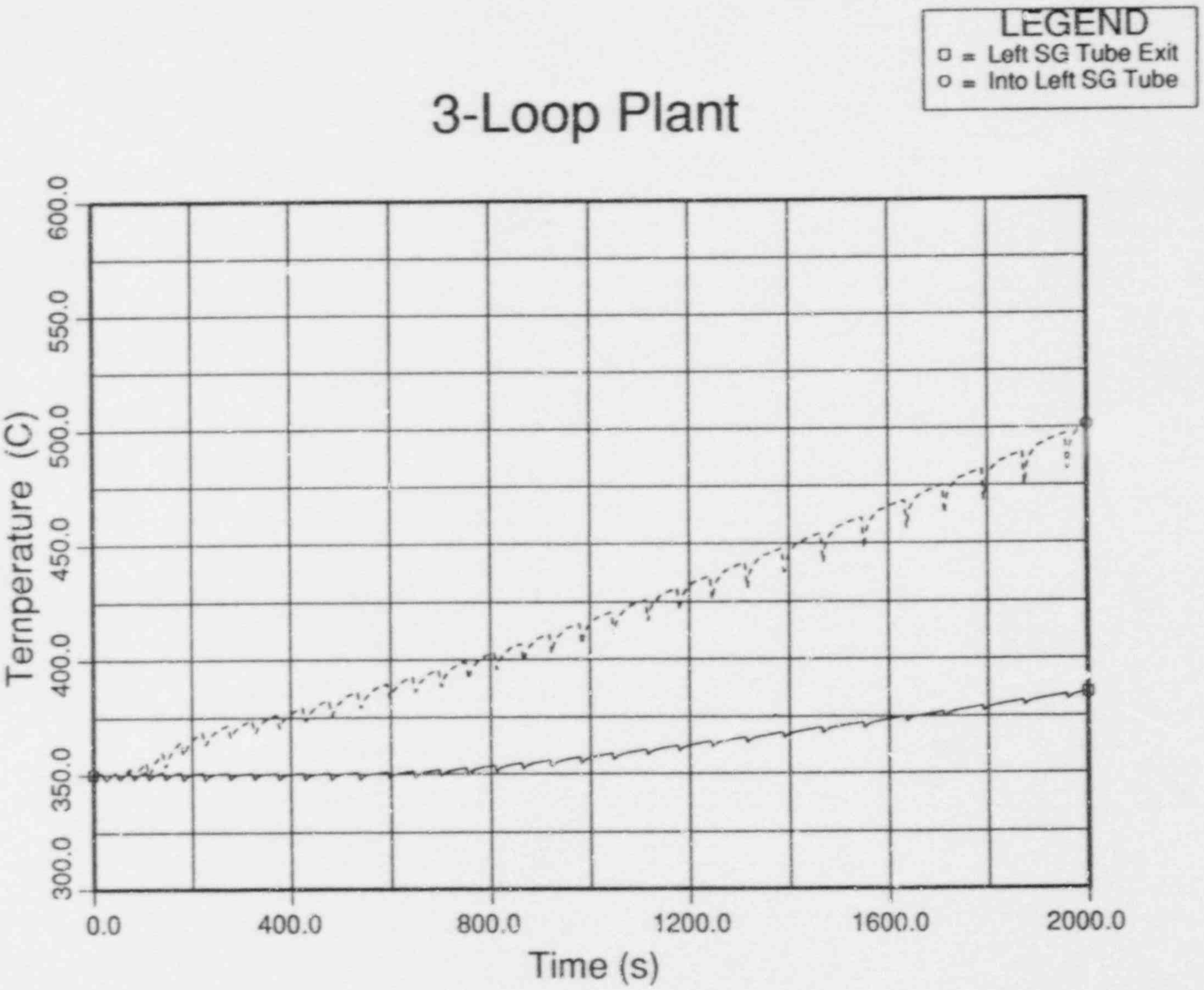

Fig. 20. Steam Temperature in Left Steam Generator

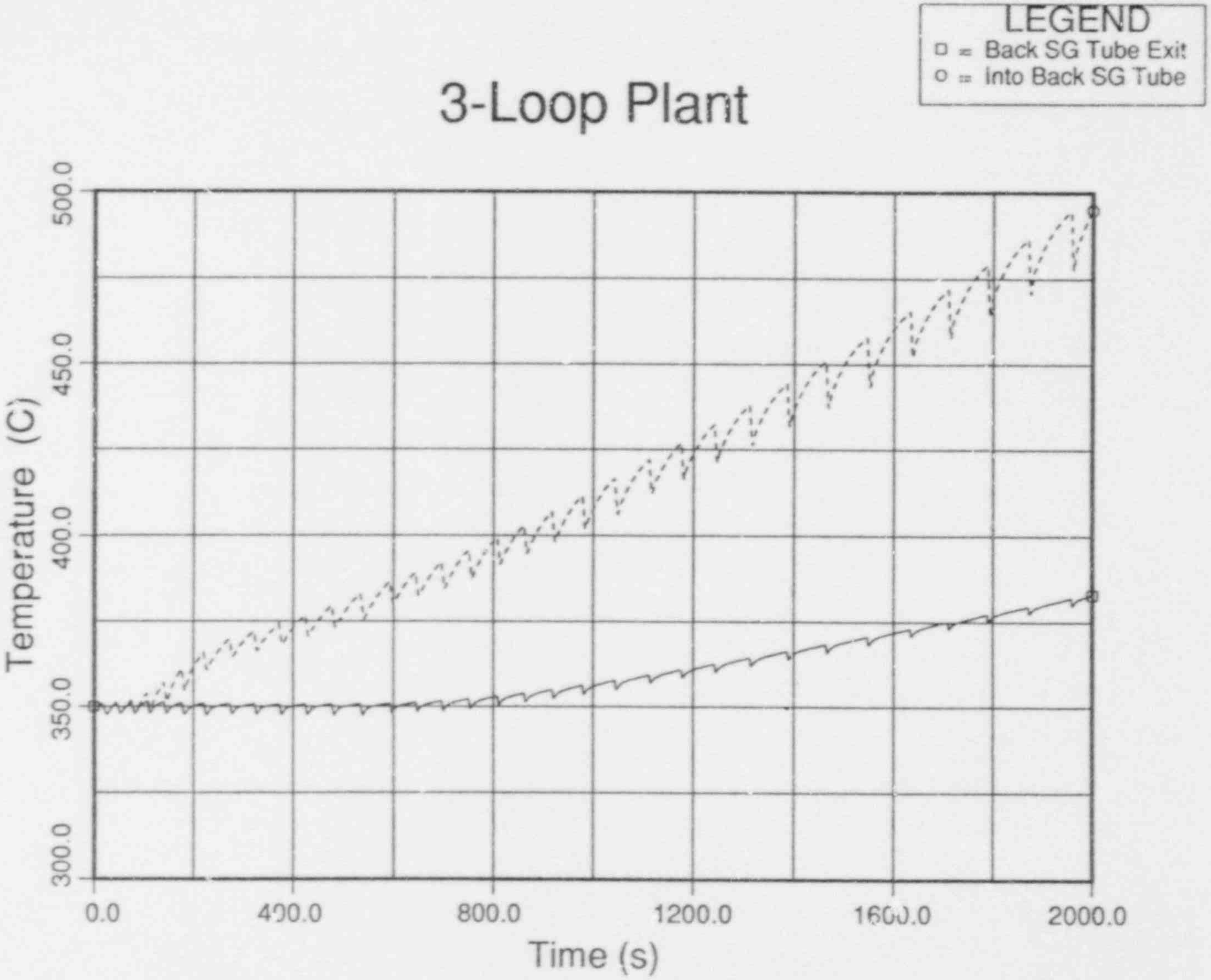

Fig. 21. Steam Temperature in Back Steam Generator

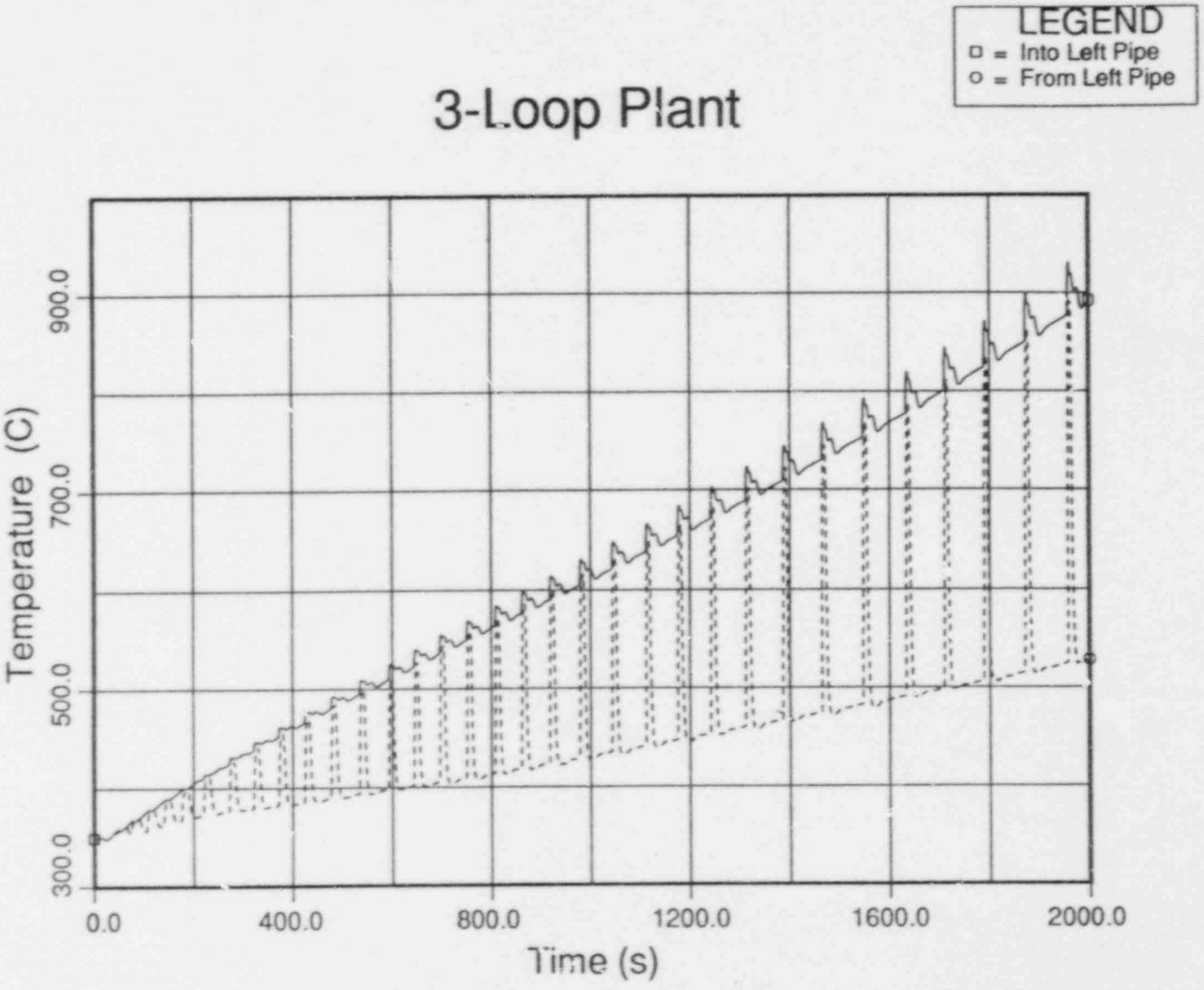

Fig. 22. Steam Temperature in Left Hot Leg

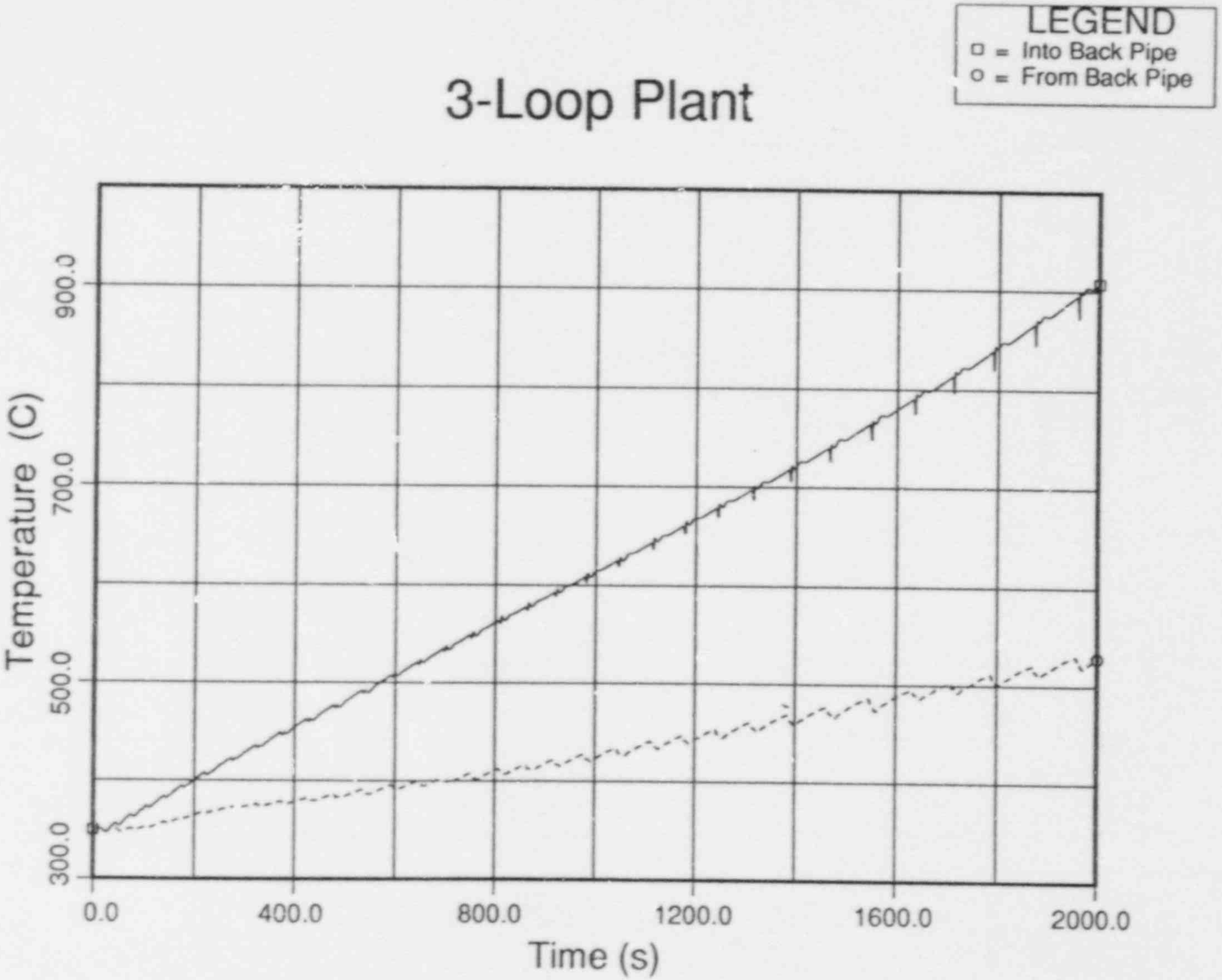

Fig. 23. Steam Temperature in Back Hot Leg

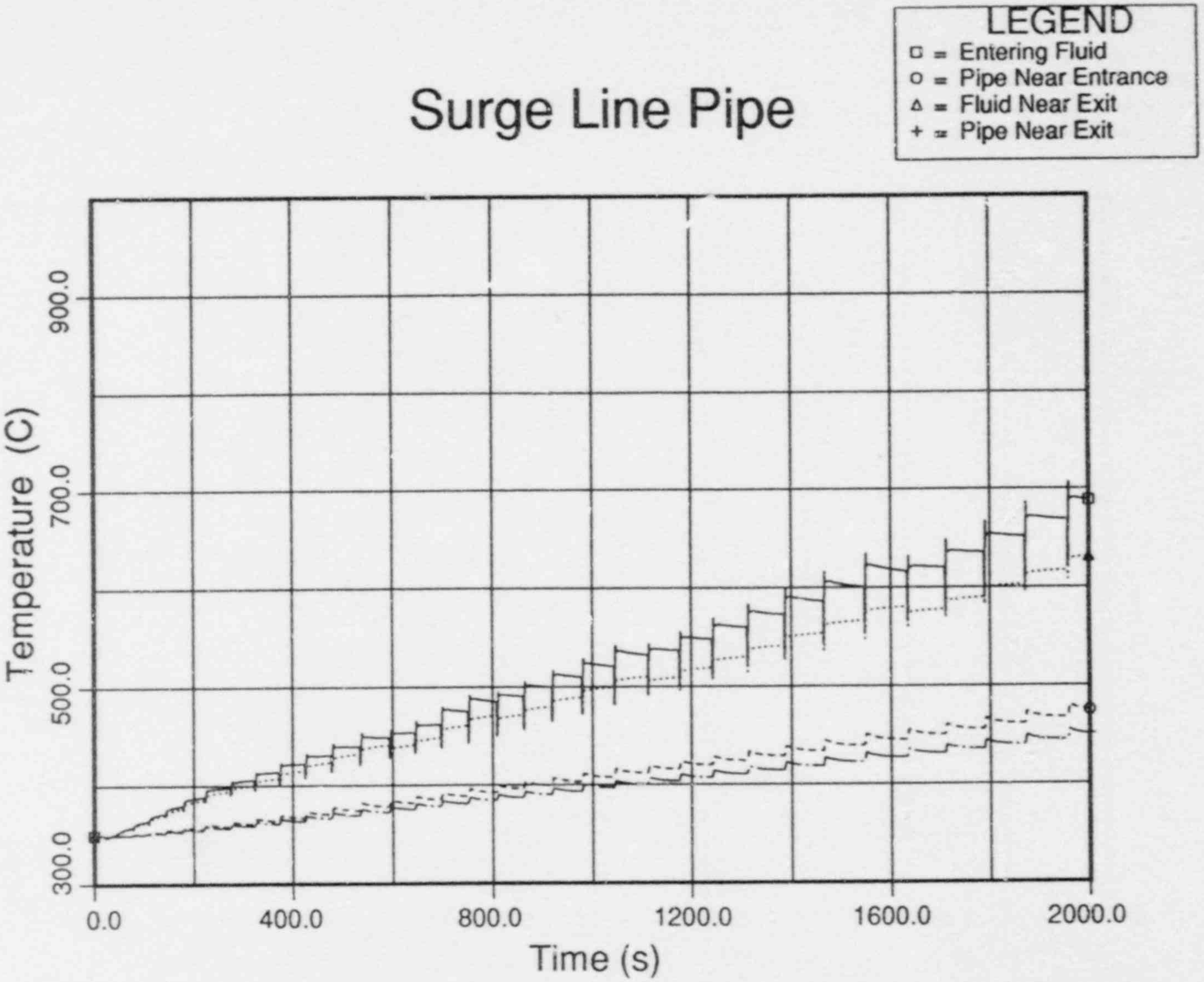

Fig. 24. Temperature in Surge Line

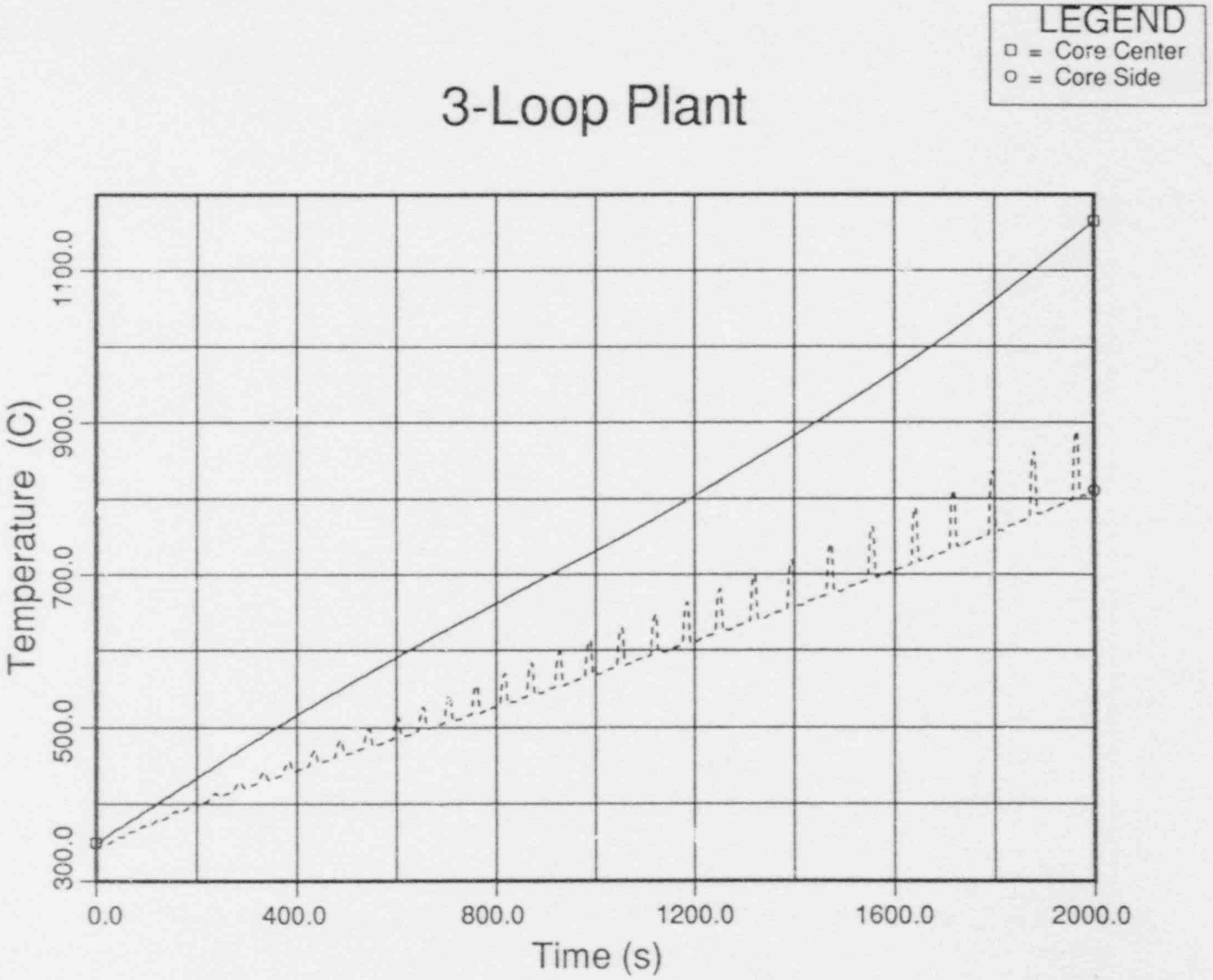

Fig. 25. Steam Temperature in Core

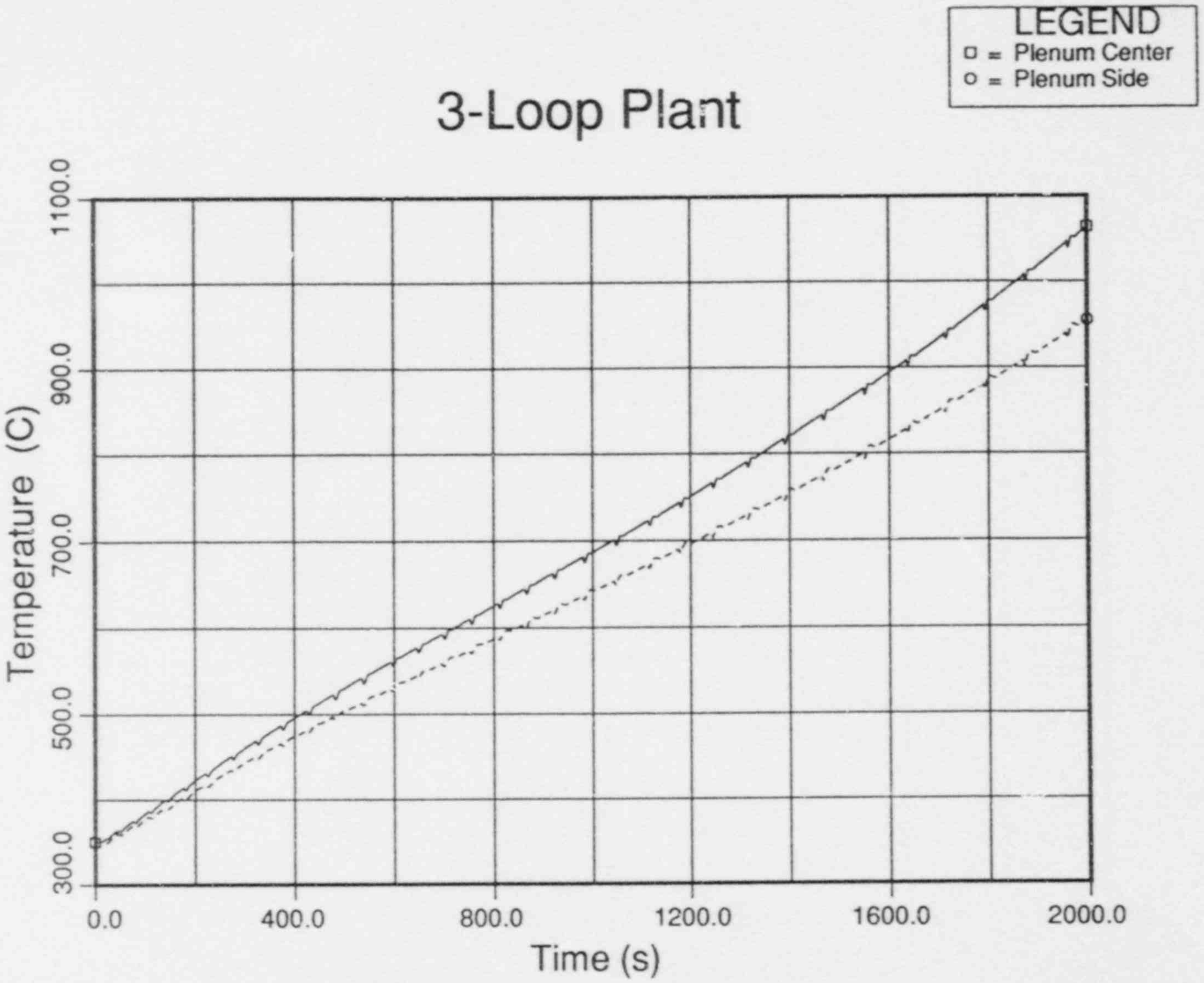

Fig. 26. Steam Temperature in Plenum

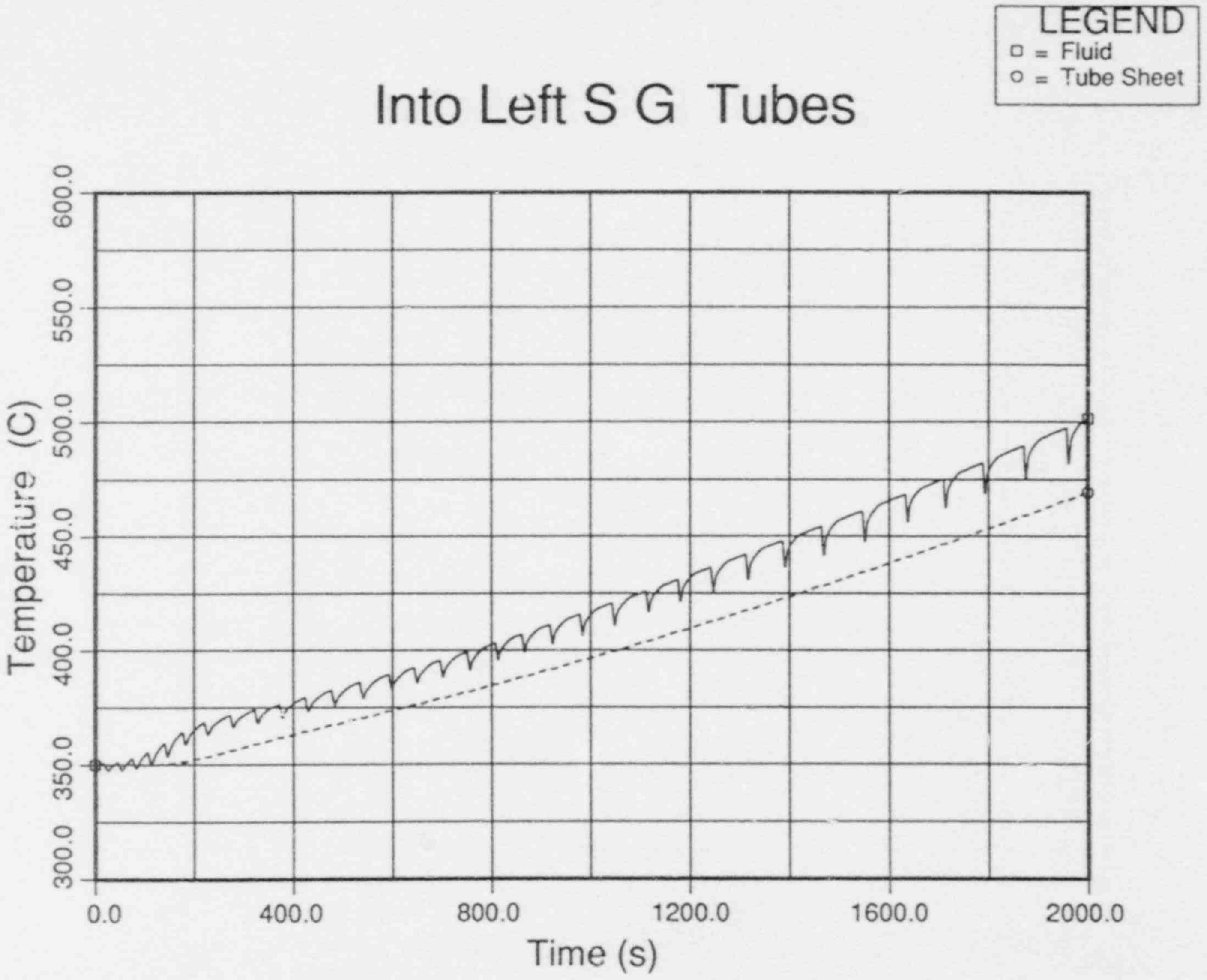

Fig. 27a. Temperature of Flow Into Left Steam Generator Tubes

Fig. 27b. Temperature of Flow Into Left Steam Generator Dead Plenum

Fig. 27c. Temperature of Flow From Left Steam Generator Dead Plenum

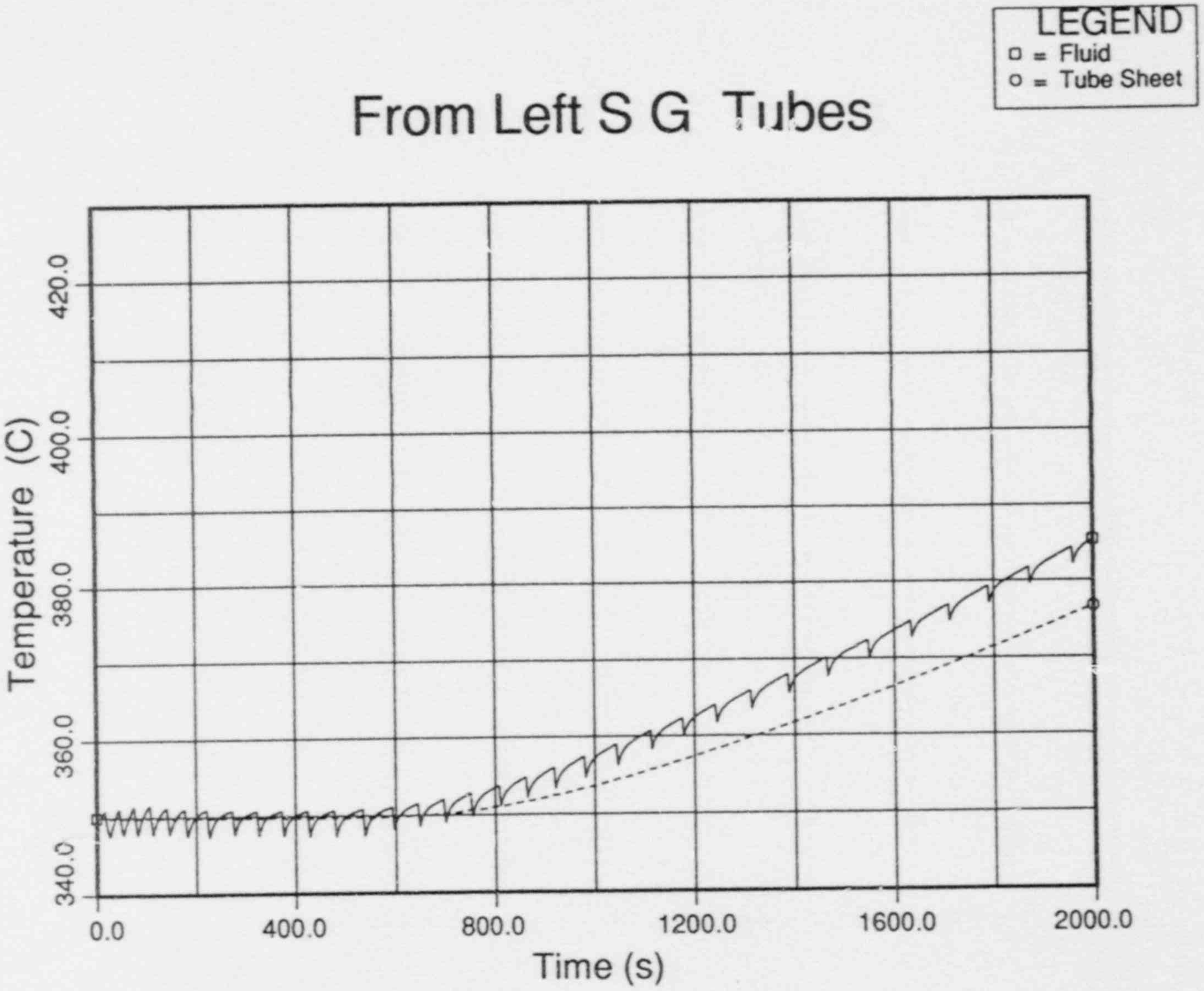

Fig. 27d. Temperature of Flow From Left Steam Generator Tubes

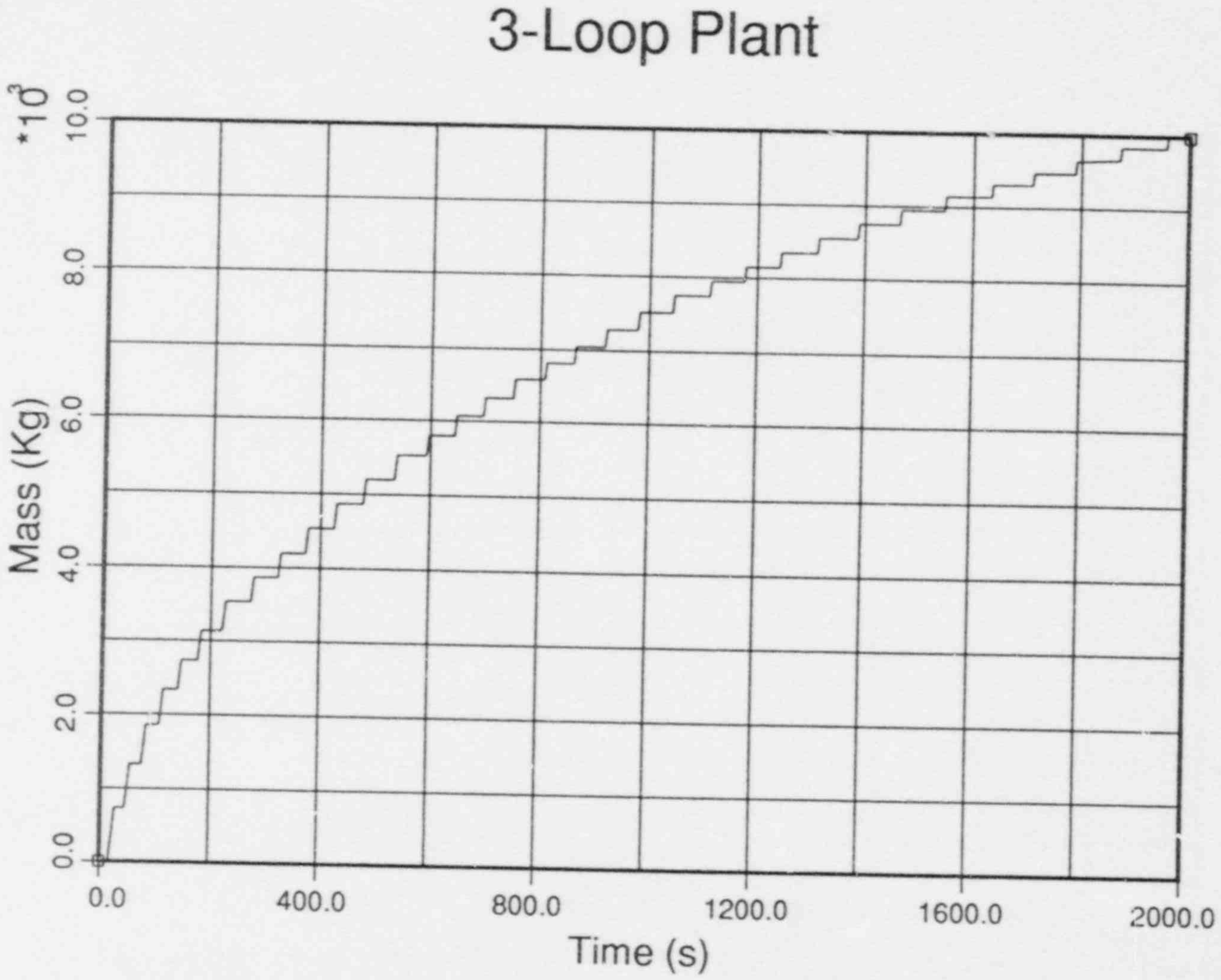

Fig. 28. Steam Mass Leaving System

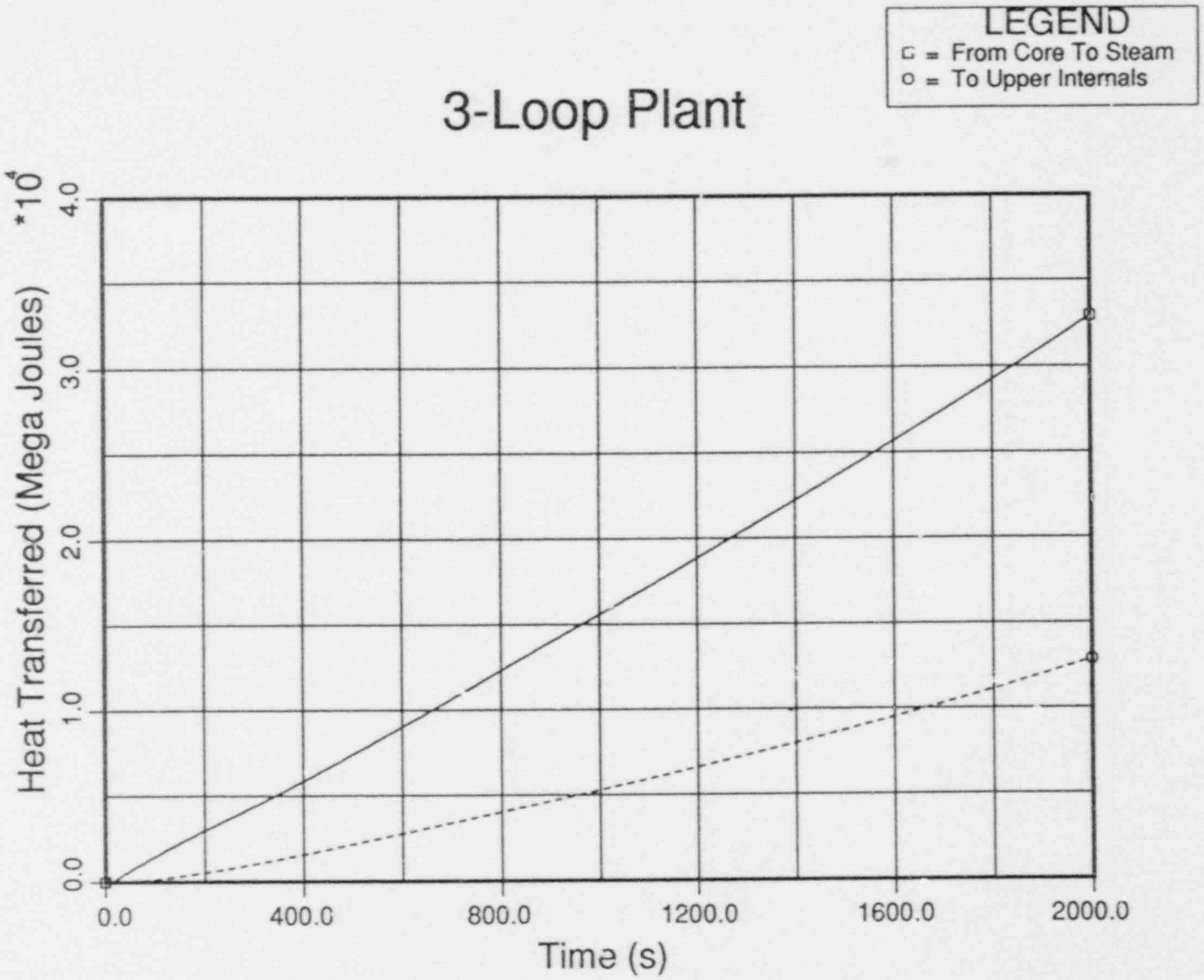

Fig. 29. In-Vessel Heat Transferred

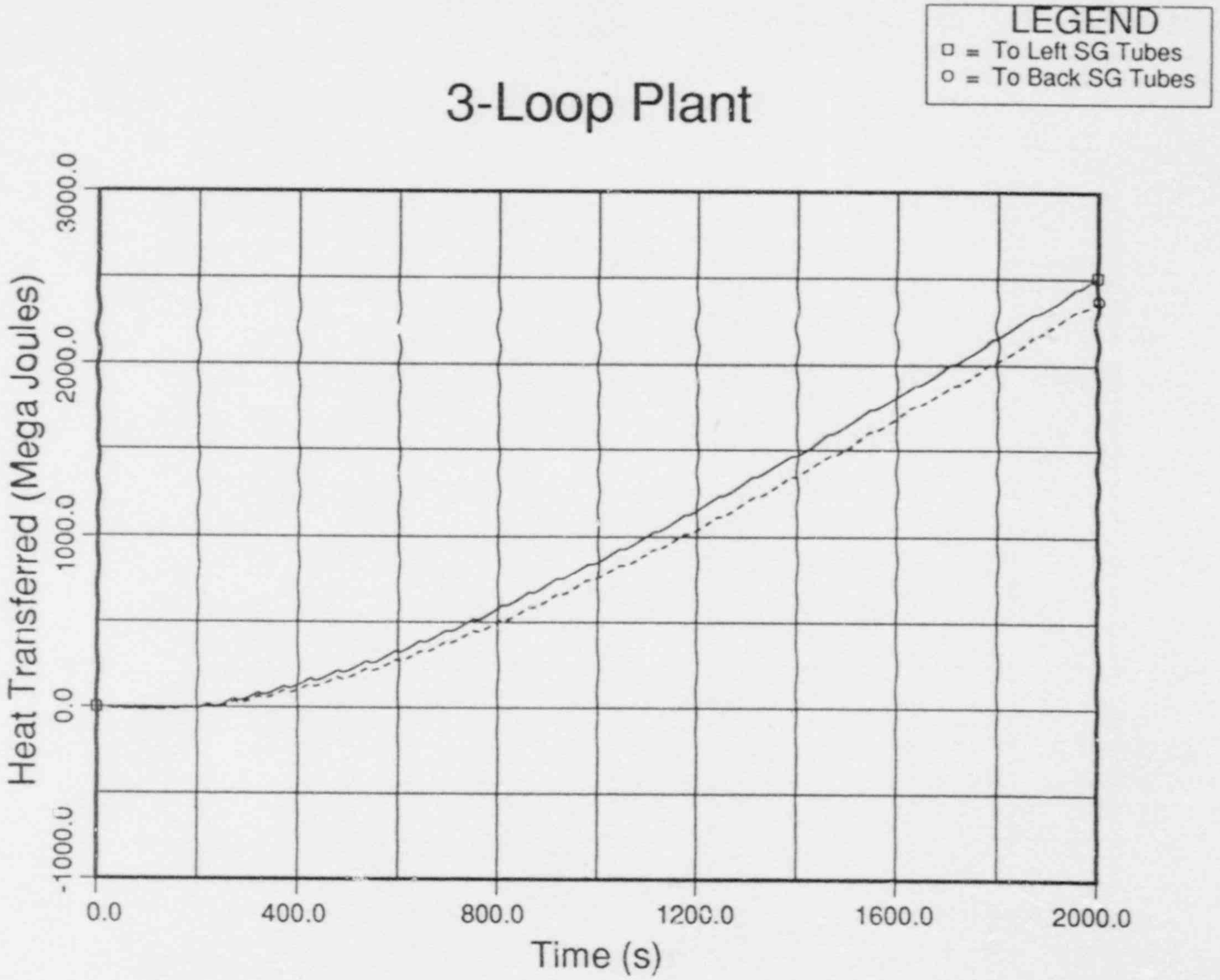

Fig. 30. Total Heat Deposited Onto Steam Generator Tubes

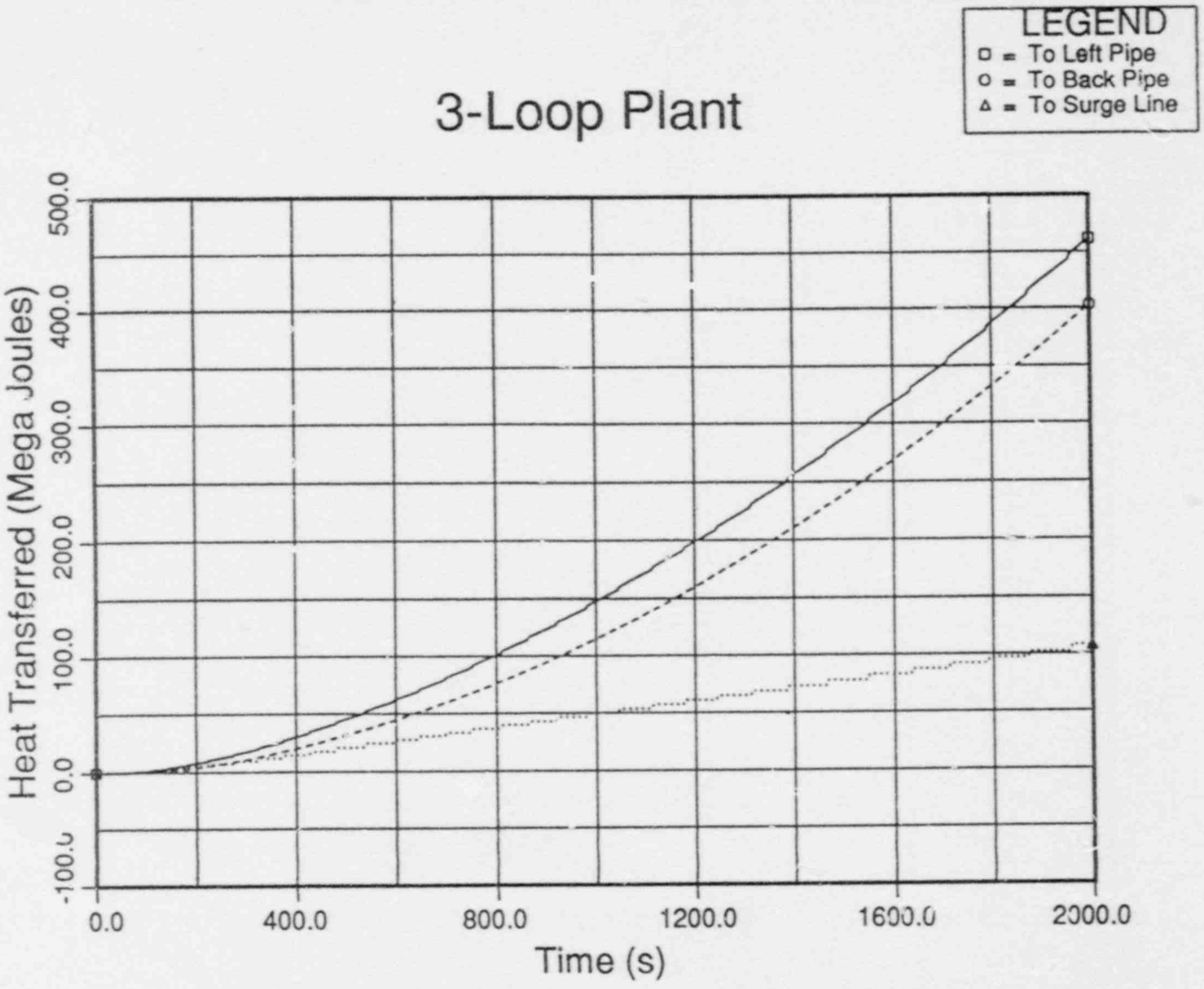

Fig. 31. Total Heat Deposited Onto Pipe Walls

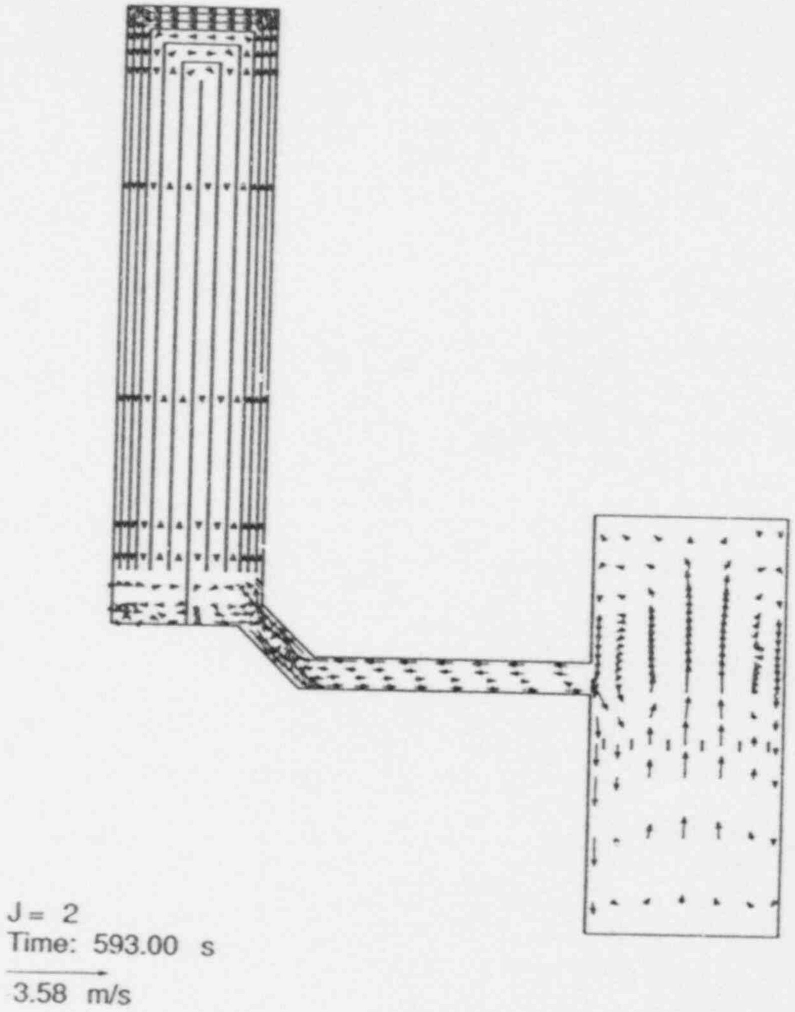

Fig. 32a. Vessel and Left Hot-Leg Flow Before Valve Opened at t = 593 s

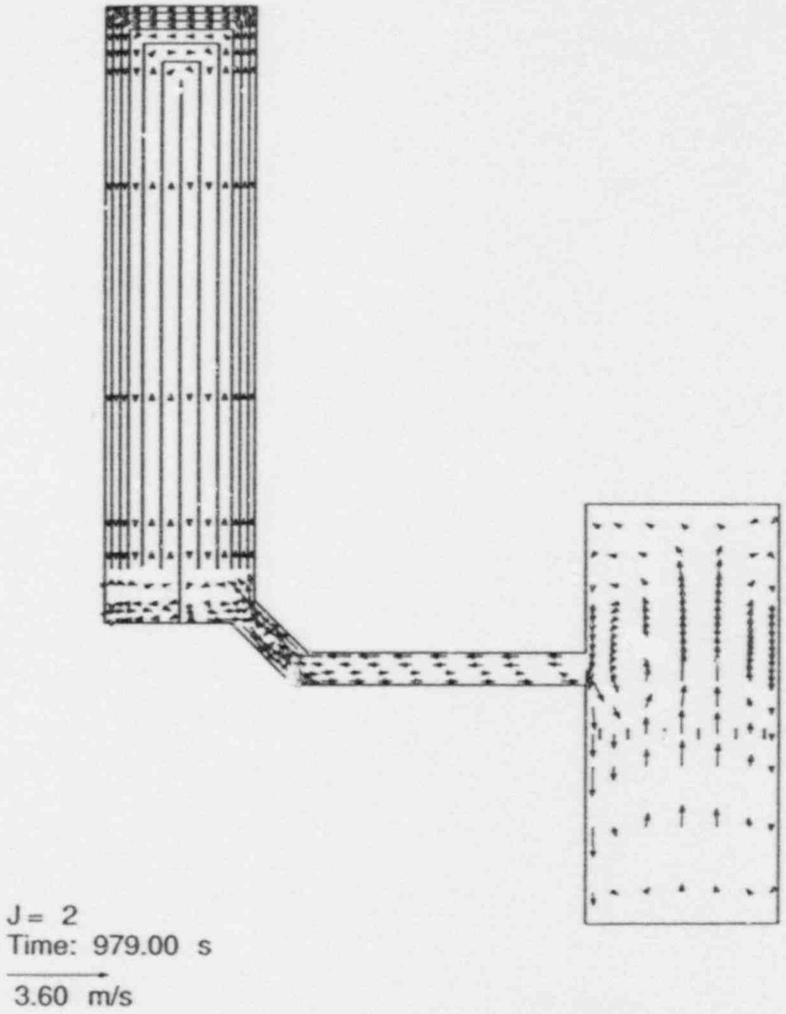

Fig. 32b. Vessel and Left Hot-Leg Flow Before Valve Opened at t = 979 s

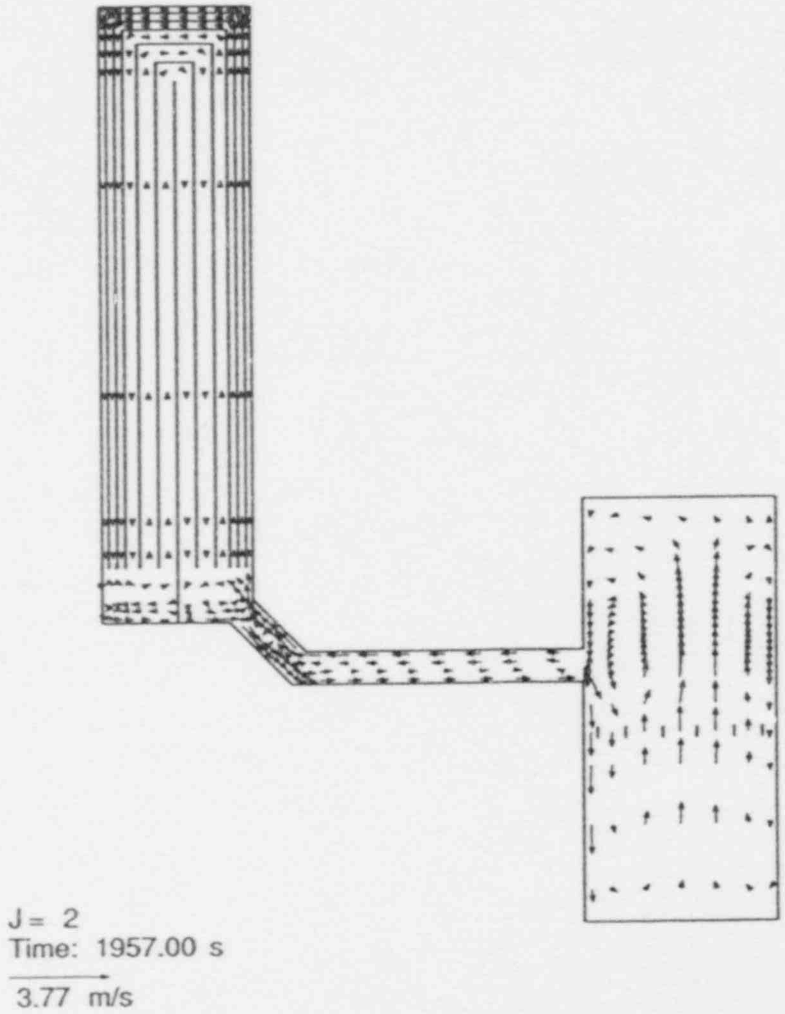

Fig. 32c. Vessel and Left Hot-Leg Flow
Before Valve Opened at t - 2957 s

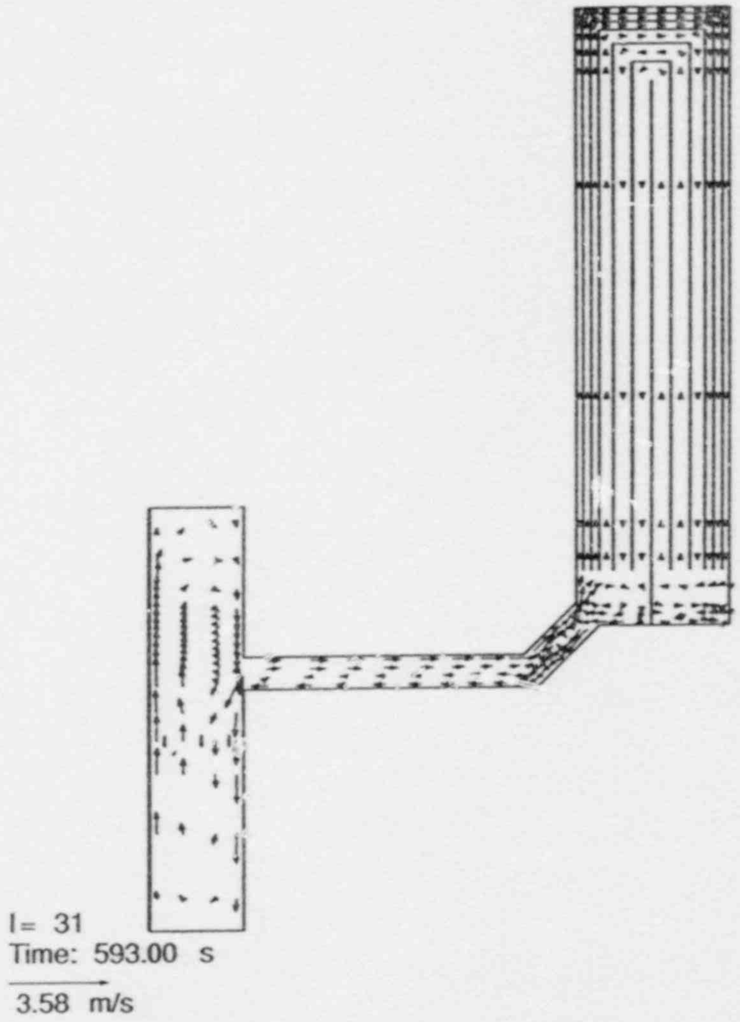

Fig. 33a. Vessel and Back Hot-Leg Flow
Before Valve Opened at t = 593 s

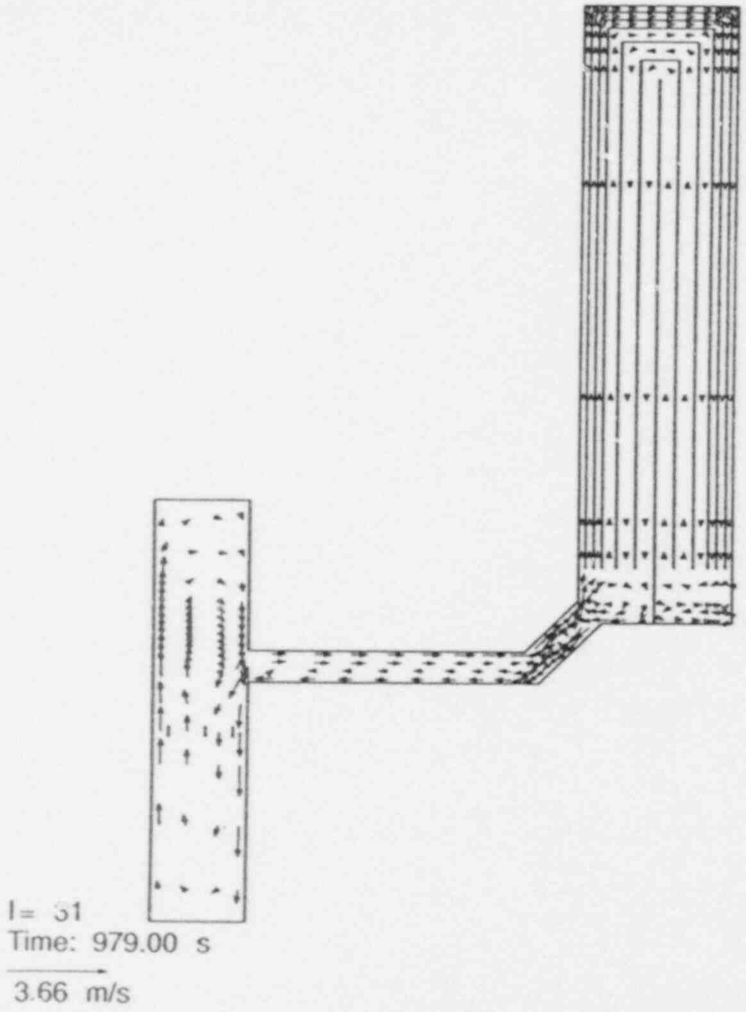

Fig. 33b. Vessel and Back Hot-Leg Flow Before Valve Opened at t = 979 s

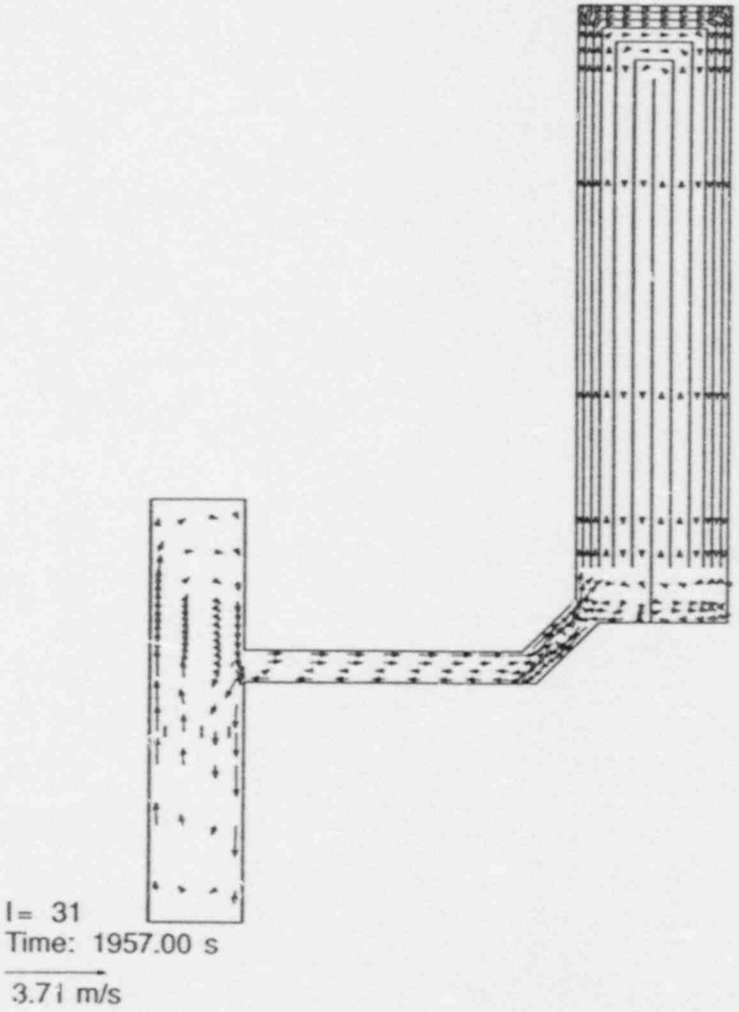

Fig. 33c. Vessel and Back Hot-Leg Flow Before Valve Opened at t = 1957 s

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A numerical simulation of the multidimensional thermal-hydraulic characteristics in a 3-loop PWR during a hypothetical TMLB' accident scenario has been performed by means of the COMMIX computer code. The operating conditions, as well as the modeling approaches used in the simulation, are discussed. Selected results, which show the natural-circulation phenomena and compare the thermal-hydraulic behavior in the different loops, are presented.

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