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SAVANNAH RIVER LABORATORY

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DYNAMIC THREE-DIMENSIONAL PROCESS WATER DENSITY MODEL FOR ULTRASIM

INTRODUCTION

A temperature dependent D_2O density model has been developed for the 3-D hydraulics module in the near real-time plant analysis code ULTRASIM. By replacing the constant density, ULTRASIM is improved in two ways. First, all 3-D hydraulic analyses performed are more physically realistic now that the temperature dependence of the D_2O density is accounted for. Secondly, simple temperature driven process water transients can now be modeled and investigated including natural circulation tests. This report describes results in both of these areas. The new model has been shown to produce excellent results for transients beginning at full flow conditions, and limited natural circulation demonstrations have been achieved using ULTRASIM.

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*A report by the principal author of work carried out as a GEM Summer Intern.

SUMMARY

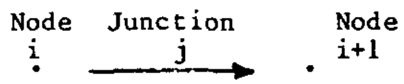
The dynamic D_2O density equation implemented in the 3-D hydraulics model of ULTRASIM is based on an equation from GRASS.[1] For steady-state and loss of pump accident (LOPA) scenarios, the new version provides excellent results when compared to the old version without increasing CPU time. Finally, natural circulation demonstrations have been achieved with ULTRASIM, although the assembly model and single-phase process water model are not ideally suited for such tests. It is recommended that, based on the conclusions in this report, the dynamic density model be permanently added to ULTRASIM. It is also recommended that further natural circulation studies for SRP reactors be considered in order to investigate the effects of temperature driven process water transients and the possibility of long-term core cooling with natural convection.

DISCUSSION

Theory

ULTRASIM Hydraulics Model

The 3-D hydraulics model in ULTRASIM includes the momentum equation applied at flow junctions, a mass balance equation applied at each pressure node, and a 3-D level tracking algorithm for the upper plenum and moderator tank. The momentum equation for a single-phase fluid can be written for the following flow junction as:



$$A_j \frac{dF_j}{dt} + P_{i+1} - P_i + B_j F_j^k = H_i \qquad (1)$$

where

$A_j \frac{dF_j}{dt}$ = inertial term for flow junction (psi),

P_{i+1} = pressure at node ahead of flow junction (psi),

P_i = pressure at node behind flow junction (psi),

$B_j F_j^k$ = friction term for flow junction (psi), and

H_i = elevation or static head term (psi).

Note that pressures are calculated at nodes, and flows are calculated at junctions.

The mass balance equation for a node is simply the sum of all junction flows entering or exiting the node:

$$\Delta F_j = \Delta F_{j+1} \quad (2)$$

In a 3-D geometry, each node can have up to six flow junctions connecting it to neighboring nodes. The level tracking algorithm calculates liquid levels in vertical stacks of nodes. For a node with a liquid level less than completely full, the result of any mass imbalance is converted to a volume of liquid either gained or lost by the node, and a change in height results. The level tracking algorithm is dynamic in the sense that nodes and junctions are added and dropped from the system as the corresponding liquid level rises and falls.

The system of equations generated for a set of nodes and junctions is linearized and solved iteratively for the junction flows and nodal pressures.[2] The effect of a dynamic D_2O density on these equations is discussed next.

3-D Dynamic Process Water Density Equation

The liquid density of the nodal volume appears in the static head term of the momentum equation (Equation 1):

$$H = \frac{\left(\rho_i \ \Delta Z_i + \rho_{i+1} \Delta Z_{i+1}\right) G}{g_i \cdot 144} \quad (3)$$

where

ρ_i = density of liquid in node i,

ρ_{i+1} = density of liquid in node i+1,

ΔZ_i = height of liquid between center of node i and the boundary of nodes i and i+1,

ΔZ_{i+1} = height of liquid between center of node i+1 and the boundary of nodes i and i+1,

G = acceleration due to gravity,

G_i = force/momentum proportionality constant

= 32.14 (ft-lb-m/lb-f-s^2), and

144 = conversion from (ft^2) to (in^2).

$$\rho_i = 68.967 + 0.013842 \cdot T_i - 0.67123E-3 \cdot T_i^2 + 0.39925E-5 \cdot T_i^3 - 0.1242E-7 \cdot T_i^4 \quad (4)$$

where

T_i = temperature of the liquid in node i (°C).

Figure 1 is a plot of liquid D_2O densities over a range of saturated temperatures. There is roughly a 4% change in D_2O density over the normal operating temperatures of SRP reactors. Therefore, a change in temperature adds another small driving force to the momentum equation.

Applications

Process Water Model Nodalization

The nodalization for the process water system is shown in Figure 2. In order to track nonuniform level effects in the upper plenum and moderator tank, each are split into axial levels. The upper plenum consists of two levels, each containing four rings (to match the core's three gangs and buckled zone) and six sectors (for the six external loops). The moderator space is composed of five axial layers with the same planar geometry. Assemblies are represented by vertical flow junctions between level 2 of the upper plenum and level 3 at the bottom of the moderator tank.

The level tracking algorithm follows two groups of node stacks. One group consists of the two upper plenum layers and level 3 of the moderator tank, representing the flow path from the top of the plenum down through the assemblies into the moderator tank bottom. The second stack groups the five levels of moderator space bounded above by the gas plenum and below by the tank bottom.

Each of the six external loops is comprised of six nodes:[3] (1) the pipe run from the reactor outlet nozzle to pump suction, (2) the pipe run from pump discharge to the heat exchanger inlet, (3) the heat exchanger inlets, (4) the heat exchanger outlets, (5) the pipe run from the heat exchanger outlet to the plenum inlet, and (6) the septifoil header. In addition, two rings of nodes representing the outer plenum annulus are present.

Implementation of the Dynamic D_2O Density Model in ULTRASIM

Revising ULTRASIM to include the new D_2O density model is relatively straightforward. Figure 3 represents a crude skeleton of the ULTRASIM code. An equally crude description of a typical ULTRASIM run is as follows:

The run begins by setting up the data base from a set of JOSHUA input records. From there, the code sequentially executes a number of models, each calculating a different set of reactor parameters. 3-D power and reactivity profiles are computed first, followed by the process water pressures and flows (using Equations 1 and 2). The cooling water and heat exchanger parameters are found next, and then the assembly temperature profiles and flows are calculated. Finally, an energy balance routine is entered which calculates the nodal D_2O temperatures and densities based on the heat added by the assemblies and removed by the heat exchangers. When this is complete, the code branches to a new steady-state iteration or tests for a scram and increments the time, depending on whether the run is a steady-state or transient case, respectively.

The dynamic density equation is inserted in two places in ULTRASIM. One is the energy balance routine which uses the nodal D_2O temperature to calculate the nodal D_2O liquid density via Equation 4. The new densities can then be used in the momentum equations in the hydraulics model. The second is a subroutine which calculates process water properties for the assembly model.

Steady-State ULTRASIM Calculation

The first test for the new version of ULTRASIM is a steady-state case. A full power, full flow condition is set up by running ULTRASIM in the steady-state mode, and this is followed by a 60 sec null transient. In the null transient, no perturbations to the system are made, and the new code with the dynamic density model is compared to the old constant density version.

Figures 4 and 5 are representative of the output resulting from the new density model. Figure 4 is a plot of tank bottom pressure for nodes 19 and 23 (from Figure 2, these are the nodes leading to Systems 1 and 5, respectively). The new version calculates a tank bottom D_2O density of 67.3 lb-m/ft^3 compared with the constant 68.48 lb m/ft^3 of the old version. The 2% drop in density is reflected in the 0.1 psi drop in tank bottom pressure due to the change in the static head term for the stack of nodes in the moderator tank. Figure 5 plots the outlet nozzle flow for the same Systems 1 and 5. Because the sum of the ΔP and static head terms across the nozzle is now greater for the dynamic density case, the flows are slightly greater, as expected. Note the 6 gpm difference is negligible for the 25,000 gpm full flow case.

LOPA Calculations Using the New D_2O Density Model

As in the case with the steady-state calculations, one would expect the differences between the new dynamic density version and previous constant density version of ULTRASIM during transient conditions to be minor. A loss of pump accident (LOPA) analysis is now described that again compares the two versions.

For the LOPA, the pumps were denied both AC and DC power at 2.0 sec. Reactor scram occurred at 3.25 sec due to a plenum pressure trip. The system was allowed to coast down until ECS flow was initiated in Systems 2 and 5 at about 47 sec. Figures 6 and 7 are plots representative of the results for this transient. Figure 6 shows moderator tank bottom pressure for nodes 19 and 23. Recall that these nodes feed external loop Systems 1 and 5, respectively. At 4.25 sec, the vacuum breakers blow in the constant density version, but the same phenomenon does not occur until two timesteps later (4.75 sec) in the new dynamic density version. The difference is due to a change in moderator height in the tank resulting from the added buoyancy effect of the new model. This trend is common throughout the test cases. Reactor response often differs by a timestep or two (Δt=250 msec) because of the slight changes in pressures, temperatures, and flows resulting from the temperature dependent density. The remainder of the LOPA in Figure 6 proceeds as expected; the differences between the new and old models are slight, and both track the LOPA admirably. Figure 7 plots plenum inlet flow for Systems 1 and 5. The results for the new and old versions of ULTRASIM yield identical results as the system coasts down, including the response after ECS flow is initiated in Systems 2 and 5 at 47 sec. In terms of computer time, the constant density and dynamic density versions require the same 156 CPU seconds to execute the 60 sec transient.

Natural Circulation Demonstrations Using ULTRASIM

With the density gradient now another driving force in the momentum equation solved by ULTRASIM's hydraulics model, natural circulation analyses become a possibility. In addressing the natural circulation demonstrations discussed in the next two sections, it is important to realize the limitations, both physical and analytical, to such analyses.

First, natural circulation experiments have been performed in the past in both the Heat Transfer Laboratory[4] with limited success and in L-Area[5] with no success. Physically, SRP reactors are not designed to capitalize fully on the effects of natural circulation since the heat source (the core) is not physically lower than the heat sink (the heat exchangers). In the Heat Transfer Laboratory experiments, single-phase natural circulation was found to be minimally successful, although two-phase natural circulation was shown to have promise for long-term cooling of the assemblies. Natural circulation was not achieved in the L-Area tests, primarily due to the draining of the plenum before a natural circulation loop could be established. The Heat Transfer Laboratory experiments maintained a full plenum (as do the ULTRASIM tests described in this report), but experiments in L-Area showed the plenum drains through the piston ring seals on the housing tubes in the permanent sleeves (see Figure 8) in approximately 20 minutes. Therefore, any possibility of setting up a long-term natural circulation loop in SRP reactors would require a design change (replacing the piston ring seals with O-rings has been suggested).[5]

Secondly, the computer code ULTRASIM is limited in its ability to effectively model the natural circulation capabilities of SRP reactors. The most limiting factor is that the 3-D hydraulics model is strictly single-phase. There are no plans to develop a two-phase hydraulics model for ULTRASIM, primarily because the mathematical complexity and computational burden of such an expansion contradict ULTRASIM's philosophy: to reduce the complexity of the models in order to achieve an accurate near real-time engineering analysis tool. In addition, TRAC (the Transient Reactor Analysis Code from Los Alamos) is being made available to SRL, and that code is capable of reliable two-phase flow modeling, albeit with very long running times.

Another limitation of ULTRASIM in natural circulation analyses is the inability to model reverse flow in the assemblies. The current model is a daughter product of the model in GRASS, which does not allow upflow through the core. Therefore, when reverse flow sets in, we lose the capability of calculating assembly flows and temperatures. Upflow through the core is calculated from the same flow - ΔP polynomial used in the hydraulics model for the normal downflow case. There is no current way of accurately estimating the temperature of the assembly fuel and housing without a reverse flow assembly model because of the geometric complexity of SRP assemblies.

Finally, the friction and inertia constants used in Equation 1 are geared for full flow, turbulent conditions. Since the flows resulting from the natural circulation tests are significantly lower than full flow (as we shall see in the following sections), the presented responses may not accurately reflect the magnitude and time response of the actual flow phenomena. The general flow behavior, however, is believed to be qualitatively correct within the limits of the model.

With these physical and analytical restrictions in mind, we can now turn our attention to ULTRASIM's natural circulation demonstrations.

Natural Circulation From Static Steady-State Conditions

The first natural circulation demonstration involves a simple perturbation from a no flow, static state. To achieve a steady-state condition, all D_2O temperatures are set at an arbitrary 30°C, the pumps remain off, cold assemblies are used, and the heat exchangers do not service the primary side. In effect, the process water system is simply a large unperturbed volume of D_2O at 30°C. The natural circulation transient is initiated by placing an artificial heat source at the inlet to the assemblies (level 2 of the plenum in Figure 2). Approximately 4 MW of power is distributed equally among the 24 planar nodes, and the heat source remains on for the first 100 sec and then is turned off. The system is allowed to approach equilibrium again during the remainder of the 500 sec transient. Figures 9 through 11 plot results from this test.

Figure 9 shows total core flow for this demonstration (labeled NC2.1 on the graphs). Since ULTRASIM's assembly model does not allow reverse flow, that model is removed from the calculation and registers zero flow. The flow represented by the curve marked HYDR is that calculated from the flow - ΔP polynomial in the hydraulics model. When the heat source is turned on, the density gradient is sufficient to "draw" D_2O up the assemblies into the plenum. It is this flow that forces flow out through the external loops to set up the natural circulation loop. At 100 sec, the heat source is turned off, and the density gradient ceases to drive the transient. As the system again approaches static equilibrium, small oscillations between positive and negative flow results. These oscillations represent the "sloshing around" of the immense volume of process water as it seeks a new equilibrium. The magnitude and frequency of these oscillations are governed by the friction and inertia constants of Equation 1 and, as previously mentioned, may not truly reflect the time response of the system. It is important to note that the flow rate is very small when compared to the normal 145,500 gpm core full flow value, but this may also be affected by the flow constants. Natural circulation, however, is successfully achieved.

Figure 10 is a graph of the flow into the plenum from the external loops. Negative flow represents reverse flow. The small initial flows are a result of the compounding roundoff error in setting up the initial steady-state data base. When the heat source is turned on, the warmer D_2O rises to the top of the plenum, and process water is drawn up through the assemblies. By 20 sec, the density gradient between the plenum inlet and the external loop, along with the upflow from the assemblies, is sufficient to overcome the difference in static pressure, and reverse flow begins. As the system rises in temperature, flow increases until the flow resistance in the piping retards the progress at the 75 sec mark. At 100 sec the heat source is turned off, and the system returns to static equilibrium, as discussed above. Again we see the flow oscillations that are present in the core flow graph. Also evident in Figure 10 are the physical differences in the external loops. Oppositely positioned systems have similar pipe lengths, and the dimensions differ between the resulting three groups. Systems 3 and 6 have 25 ft^3 less volume than Systems 2 and 5, and 34 ft^3 less volume than Systems 1 and 4.[3] This results in the different flow patterns exhibited in Figure 10.

Figure 11 plots plenum inlet temperature for the same transient. By 50 sec, the reverse flow has carried the hotter D_2O into the external loops. This continues until after the source is turned off and the last of the warmer process water reaches the plenum inlet. The system then begins to cool and the temperatures approach a new equilibrium value of about 35.5°C.

With limited natural circulation successfully achieved for the simple case starting from static equilibrium and constant temperature, a more physically realistic approach to natural circulation is now described.

Natural Circulation From Full Flow, Full Power Steady-State

A more useful demonstration would be to find out if natural circulation can be set up in the reactors should an extended LOPA occur. This section describes the attempts to model this situation.

A full power, full flow condition is first achieved by running ULTRASIM in the steady-state mode. For the transient, the reactor is scrammed at 1 sec and the power allowed to decay according to the specified scram table in the JOSHUA input records. Pumps are maintained at full AC output for 200 sec, by which time the reactor power has reached a decay power of 56 MW and the temperatures have reached steady values. At 200 sec, the pumps are denied both AC and DC power. Since the ULTRASIM assembly model does not allow reverse flow, an artificial heat source representing the 56 MW of decay heat is inserted to emulate core power. The heat imparted to the primary coolant as well as direct housing-to-moderator heat are included in this heat source. From 200 sec to 1250 sec, no further changes occur. The important results are shown in Figures 12 through 14.

Figure 12 plots total core flow as calculated by ULTRASIM's hydraulics model. Data starting at 300 sec is graphed to show the detail of the low flow conditions since during the first 200 sec, total core flow remains a constant 145,500 gpm. At about 450 sec, flow reversal occurs in the core, and a natural circulation loop is established. A maximum core upflow value of 3000 gpm occurs at approximately 525 sec. If we turn to Figure 13, we can see that the 525 sec point is the time at which the single-phase hydraulics model ceases to be valid as the plenum D_2O temperature exceeds 100°C. Therefore, whether or not reverse flow reaches a maximum at 525 sec is still an unanswered question, and one that can only be answered by a two-phase hydraulics model.

Figure 14 plots tank effluent temperature during the transient. When the pumps are tripped at 200 sec, the D_2O entering the external loops from the core bottom is at 24°C. During pump coast-down and flow reversal, the temperature at the tank outlet nozzle remains below 50°C. This suggests that, even under low flow conditions, the heat exchangers are capable of removing enough heat to keep the heat exchanger discharge process water single-phase. Once again it must be stressed that the temperatures within the assemblies can not be found with the current code under reverse flow conditions. Other test cases were run to see if a decay heat value could be found which did not boil the process water as it travelled up through the core. This value would put an upper limit on the applicability of ULTRASIM in its present form in modeling natural circulation transients. The maximum heat that can be successfully removed from the core while still maintaining single-phase heat transfer is 5 MW, with a corresponding core upflow value of 1000 gpm.

Applications Conclusions

The new 3-D dynamic density model implemented in ULTRASIM provides realistic results for a variety of steady-state and normal transient analyses without increasing the computational time necessary to run the code. Additional tests involving large break LOCA's with the new version (not documented in this report) also show the dynamic density behaves as expected.

It is clear that ULTRASIM is only capable of demonstrating single-phase natural circulation in SRP reactors. These tests are dependent on the plenum remaining full, a situation not physically possible with the present reactor design due to drainage through the piston ring seals on the housing tubes in the permanent sleeves. However, the new dynamic density model has opened the door for temperature driven process water transient analyses, and results indicate that natural circulation is indeed possible for SRP reactors, starting from both static and full flow conditions.

Recommendations

Based on the results outlined in this report, it is recommended that the dynamic density model be integrated in the permanent version of ULTRASIM. It is also recommended that further consideration be given to developing a two-phase 3-D hydraulics model and a reverse flow assembly model in order to further explore the possibility of significant cooling via natural circulation for SRP reactors. The TRAC code may be one vehicle for such an analysis.

References

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2. B. N. Aviles and M. V. Gregory. Improved Hydraulics Model for SIMULATE, DPST-85-681, August 1985.

3. J. P. Morin. Process Water System Hydraulics and Heat Transfer Data Base for Savannah River Simulator (SARIS), DPST-83-282-TL, January 1983.

4. J. L. Butler. Natural Convection and Boiling for Cooling SRP Reactors During Loss of Circulation Conditions, DPST-83-1055, December 1983.

5. J. L. Butler. L-Area Natural Convection Cooling Tests, DPST-84-354, April 1984.

FIG 1. D2O DENSITY CURVE

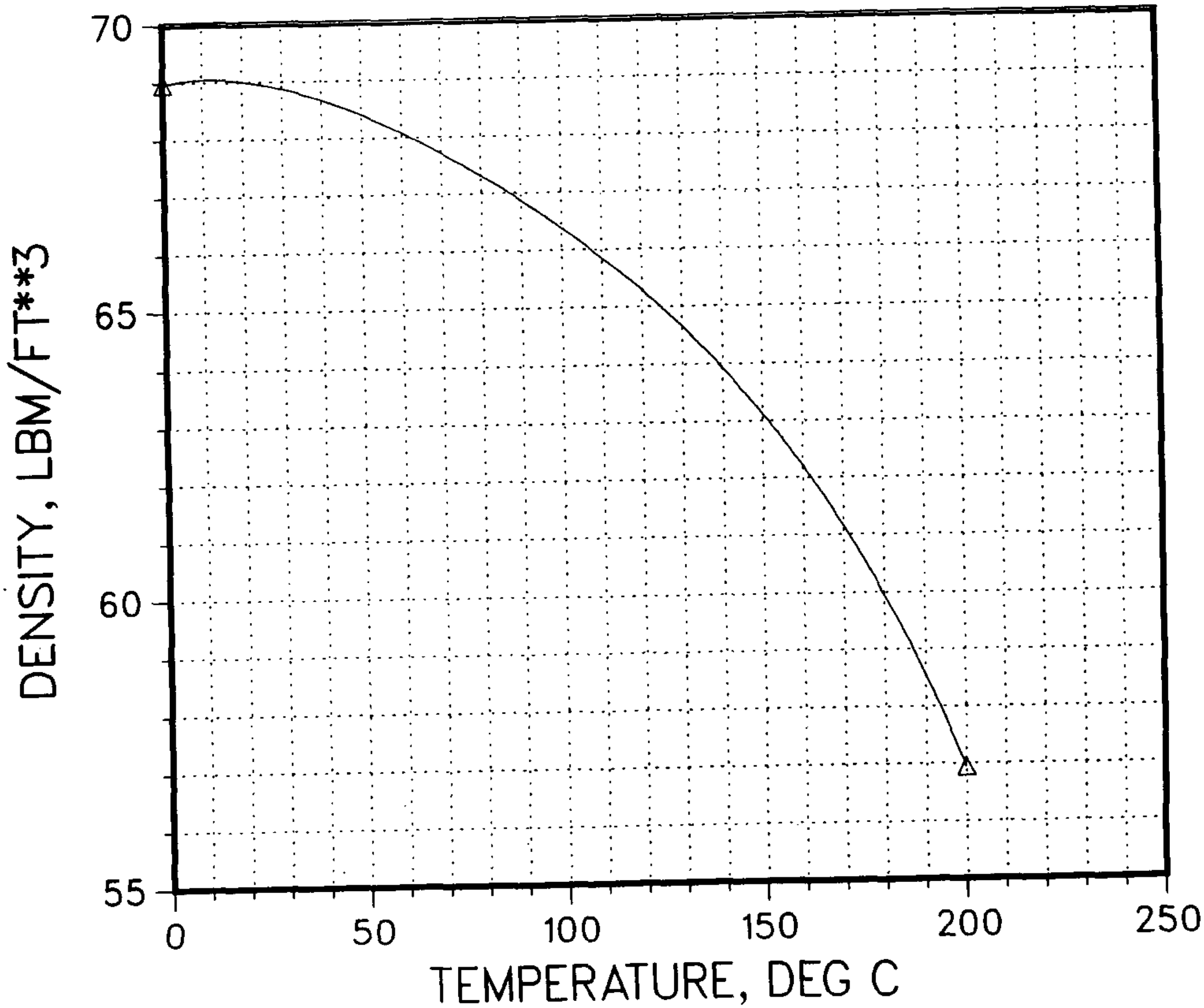
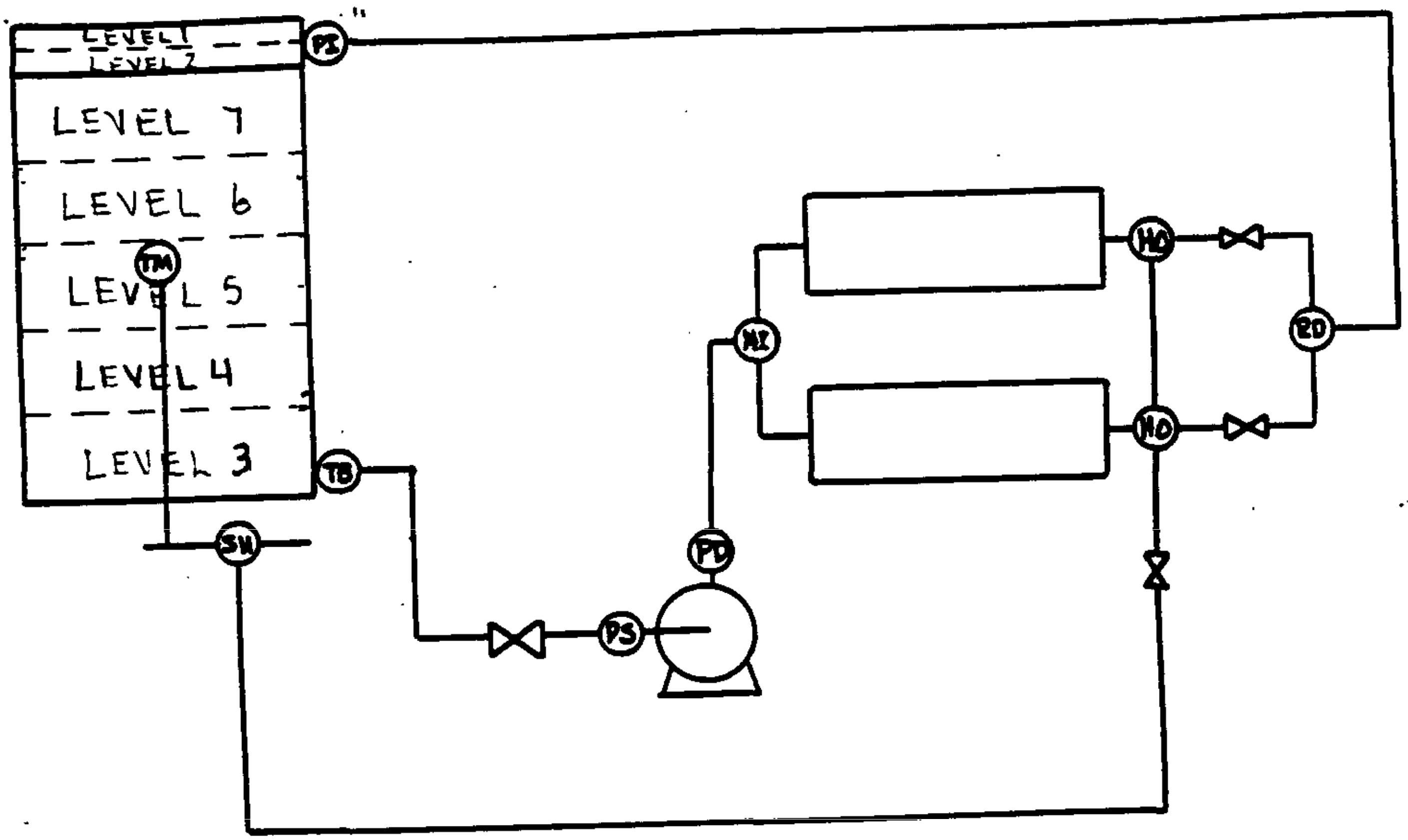


FIG 2. PROCESS WATER NODALIZATION



UPPER PLENUM AND MODERATOR TANK LEVELS

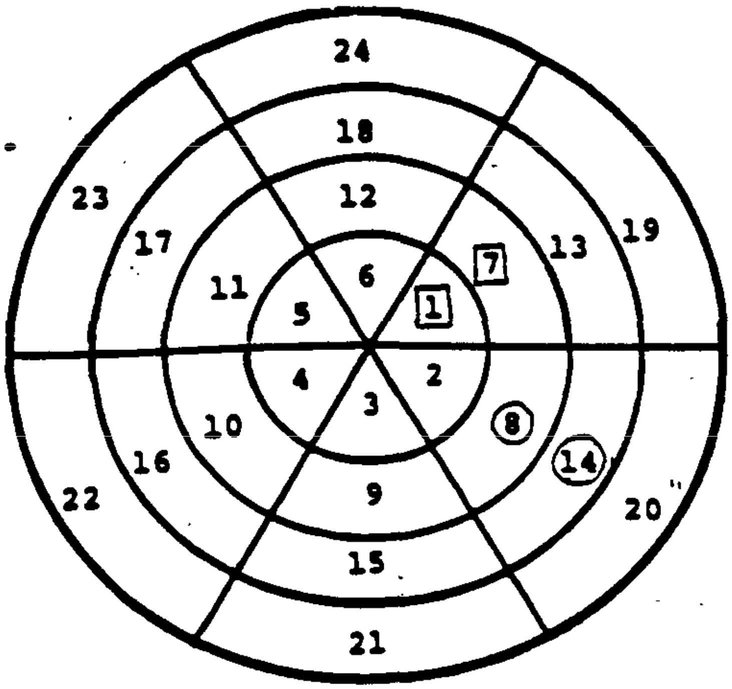


FIG 3. ULTRASIM SKELETON

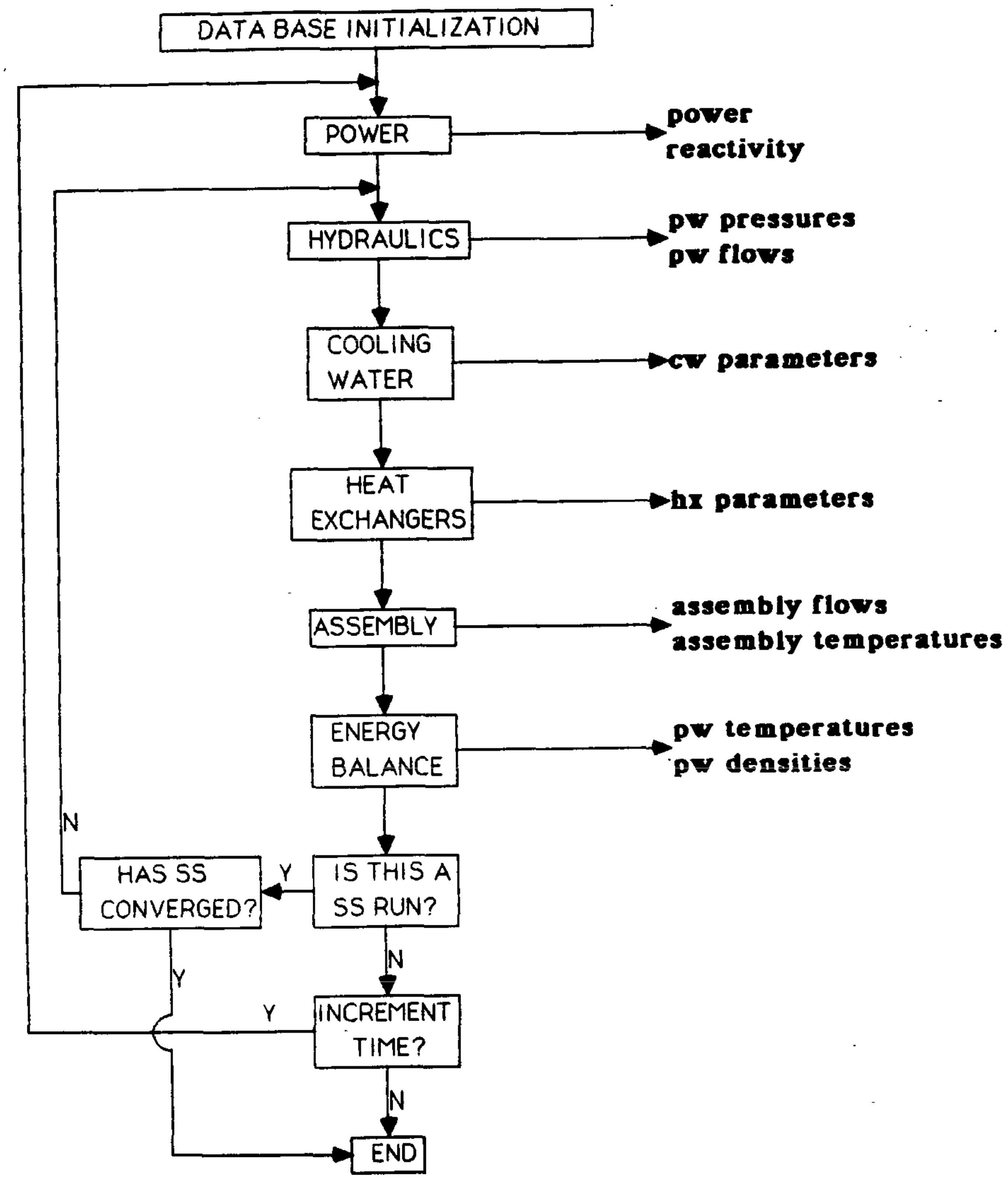


FIG 4. TANK BOTTOM PRESSURE, NULL

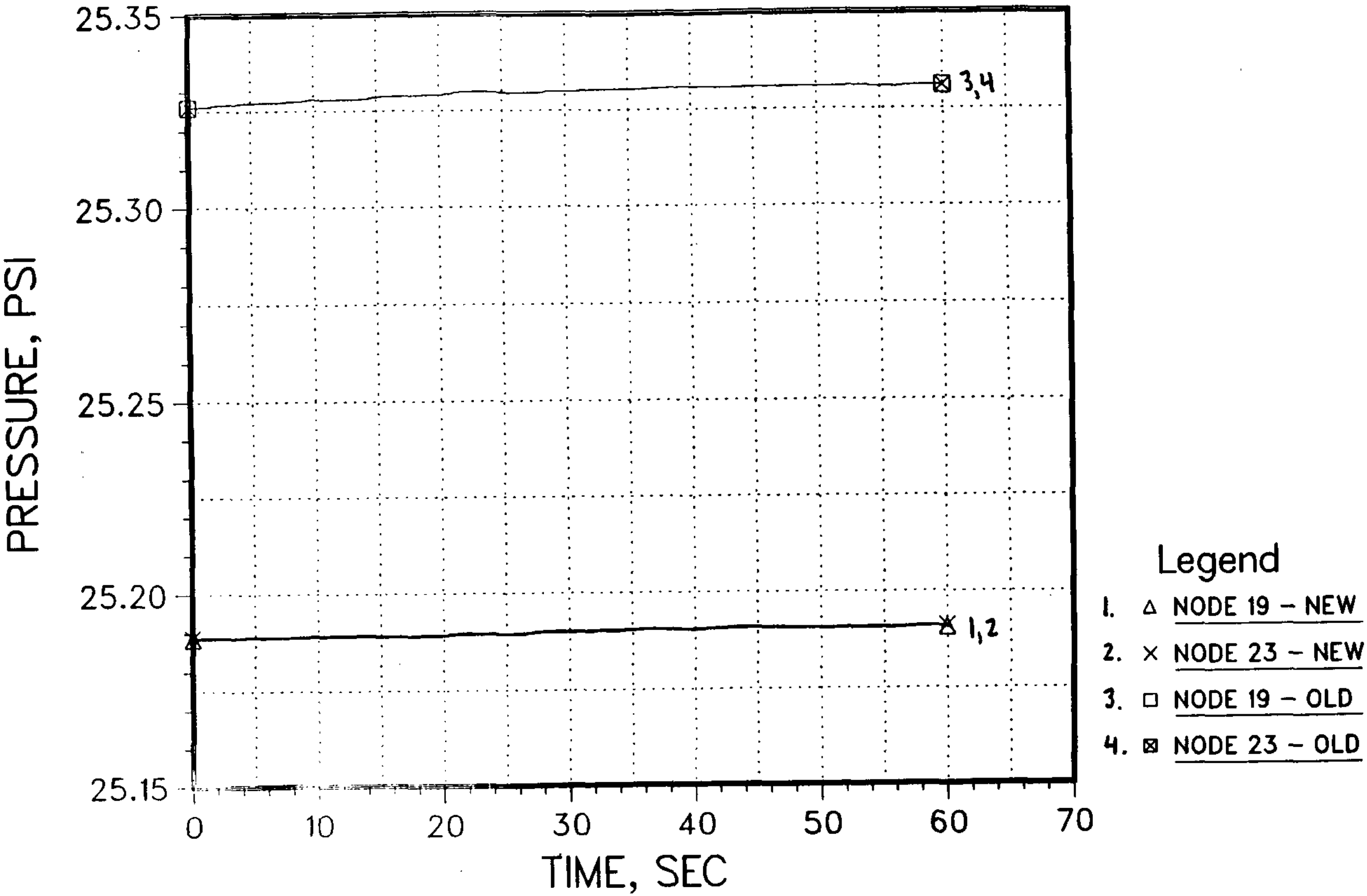


FIG 5. OUTLET NOZZLE FLOW, NULL

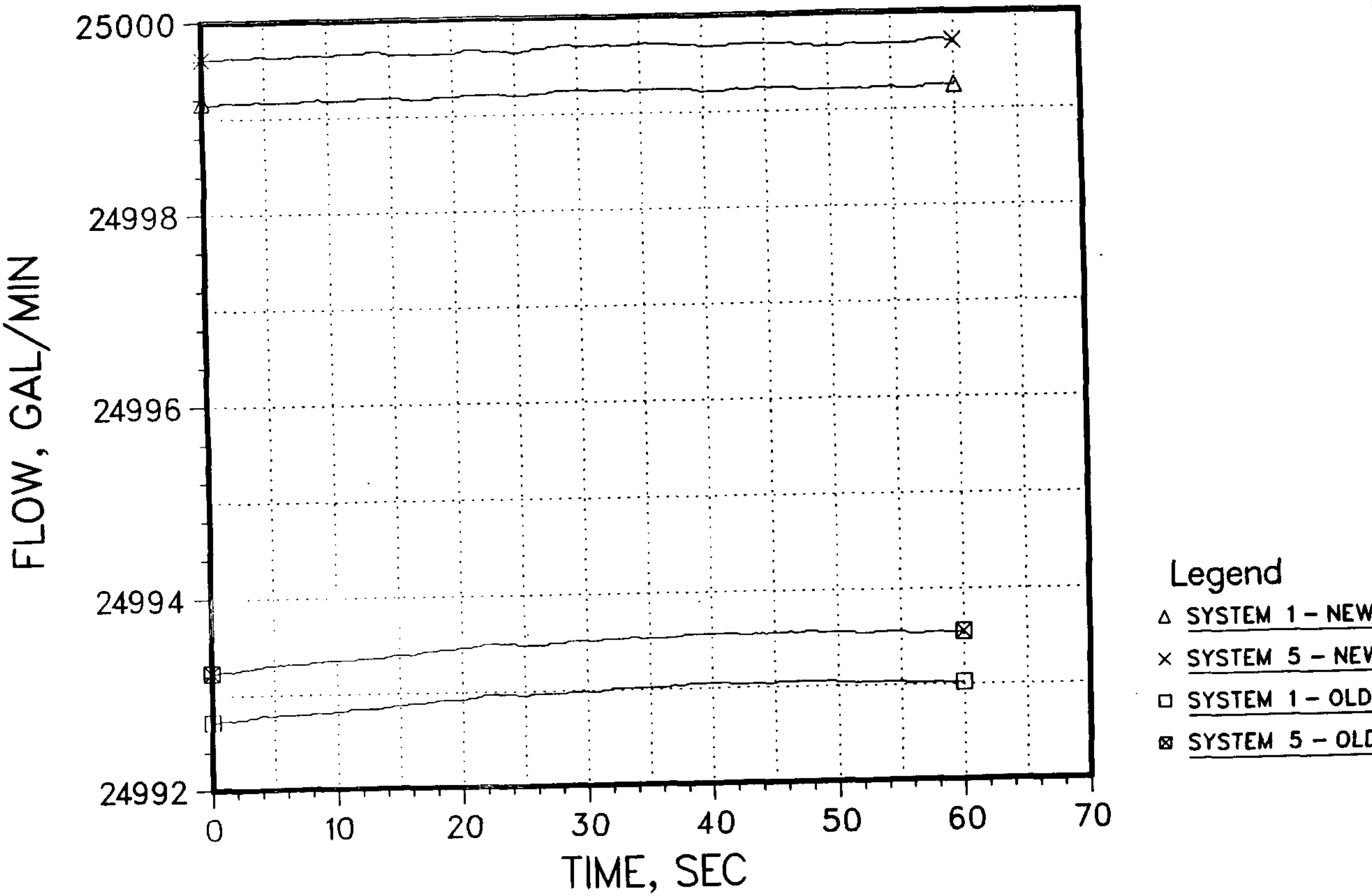


FIG 6. MODERATOR BOTTOM PRESS, LOPA

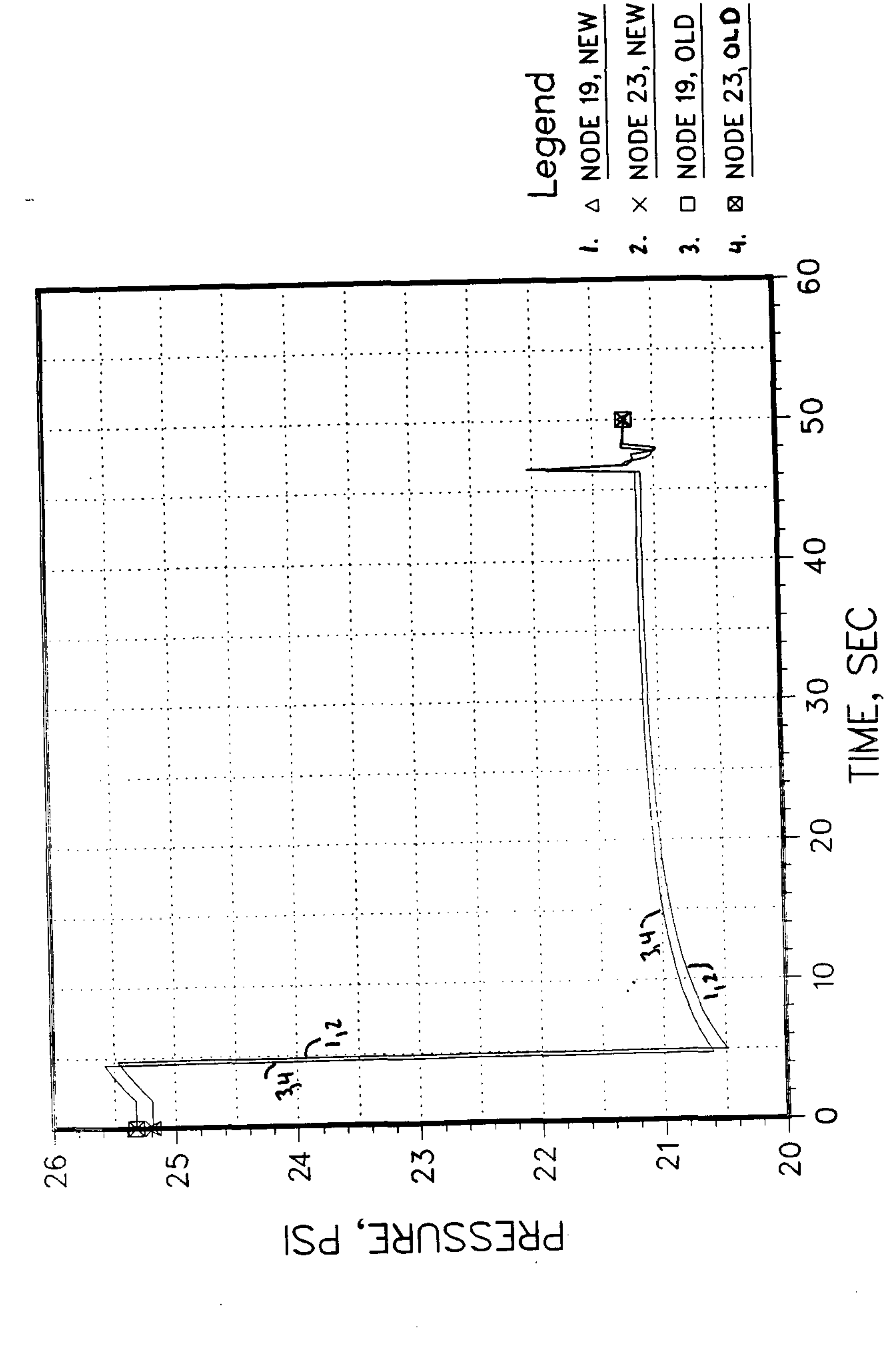


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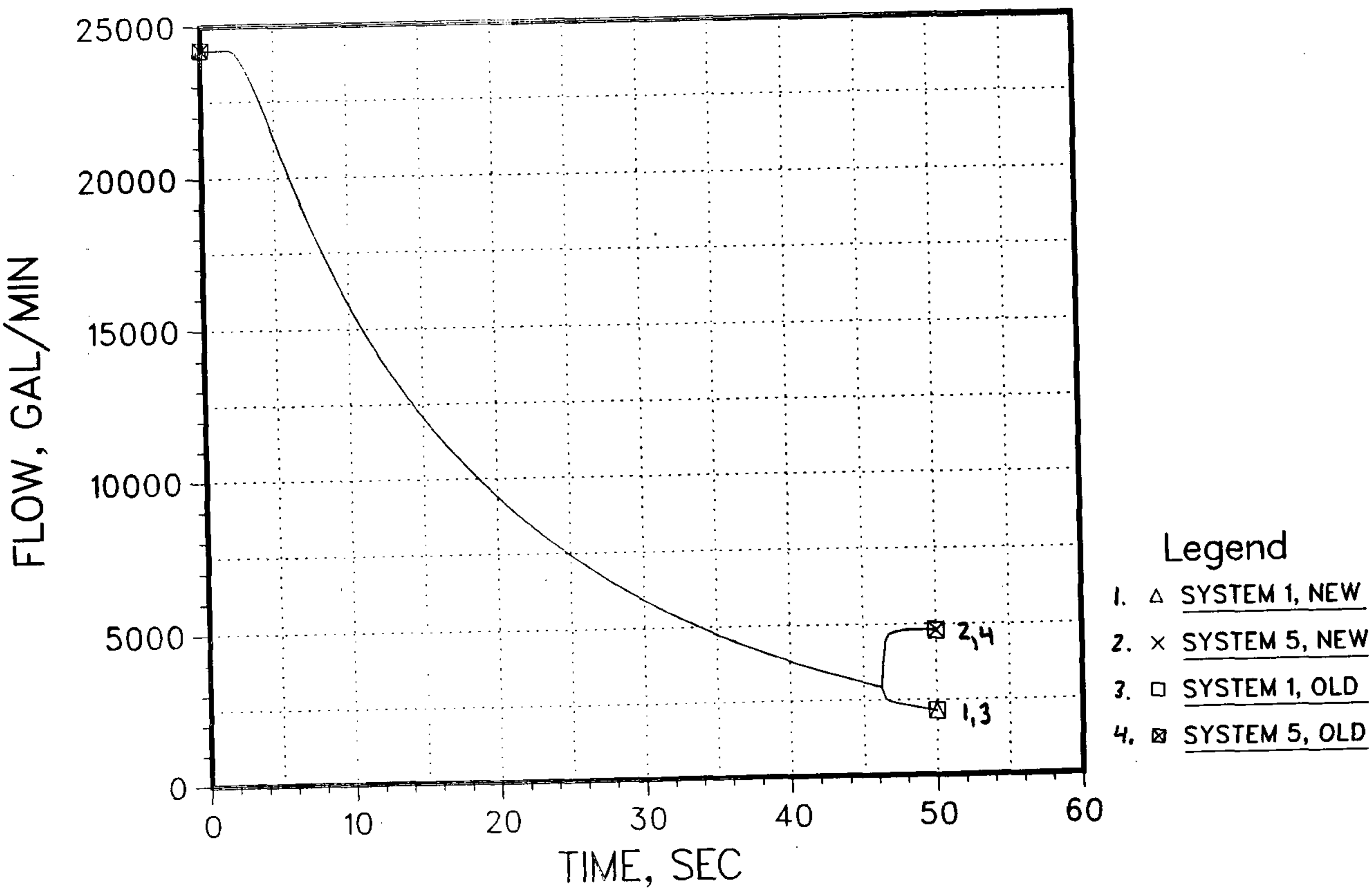
FIG 7. FLOW INTO PLENUM, LOPA



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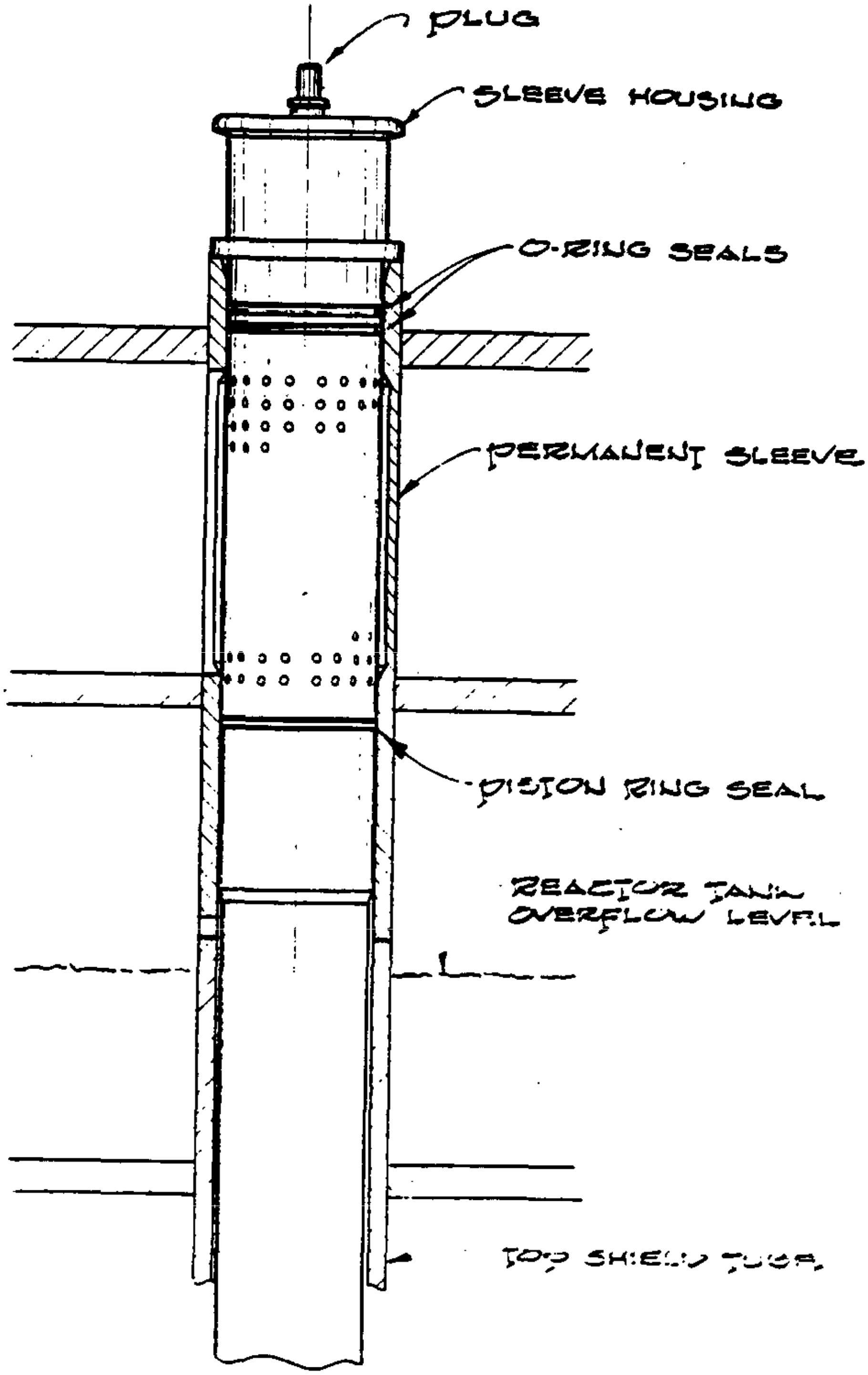

Figure 8. Sleeve Housing Connecting Water Plenum to Reactor Tank.

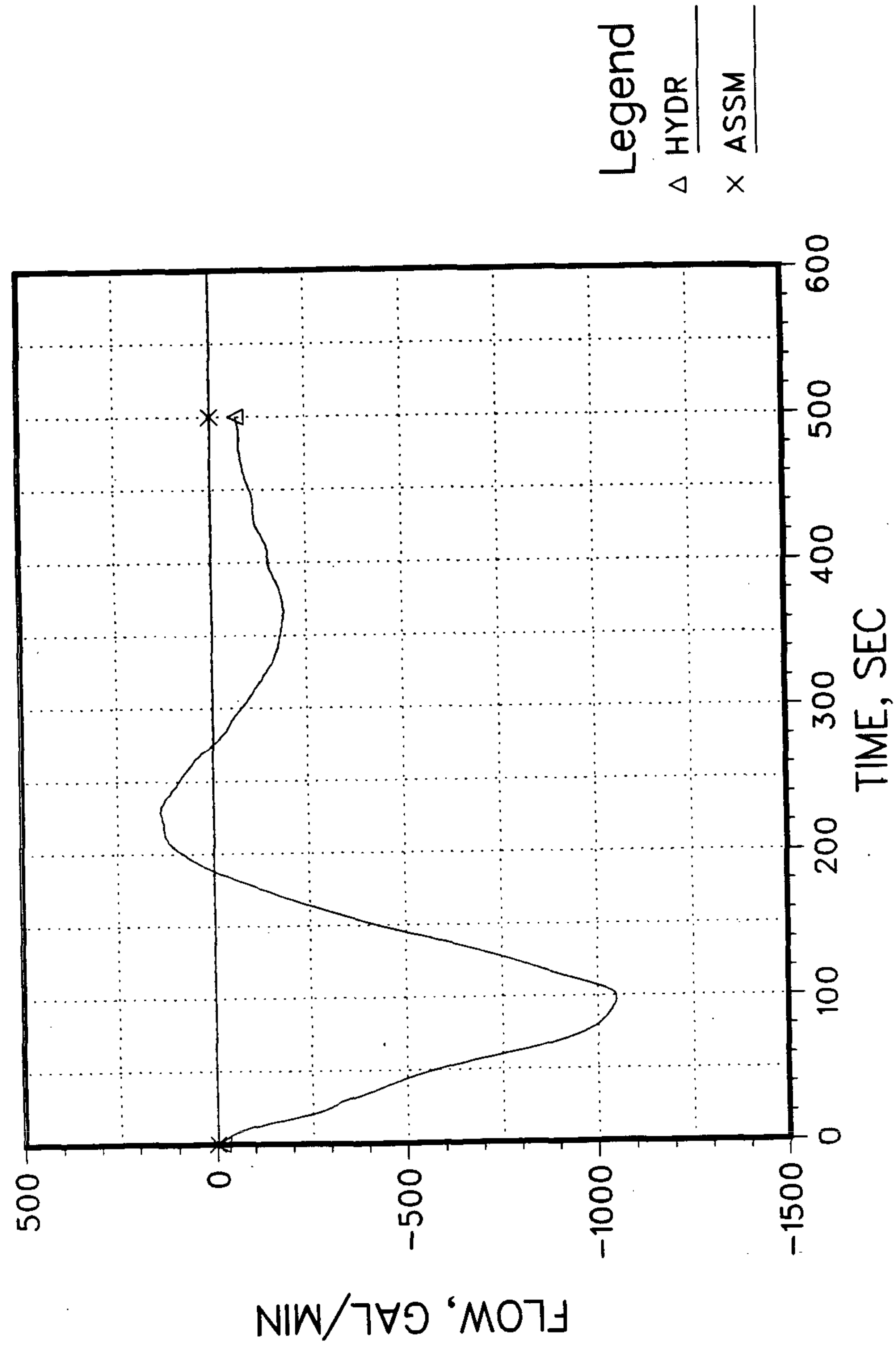

FIG 9. TOTAL CORE FLOW, NC2.1

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FIG 10. FLOW INTO PLENUM, NC2.1

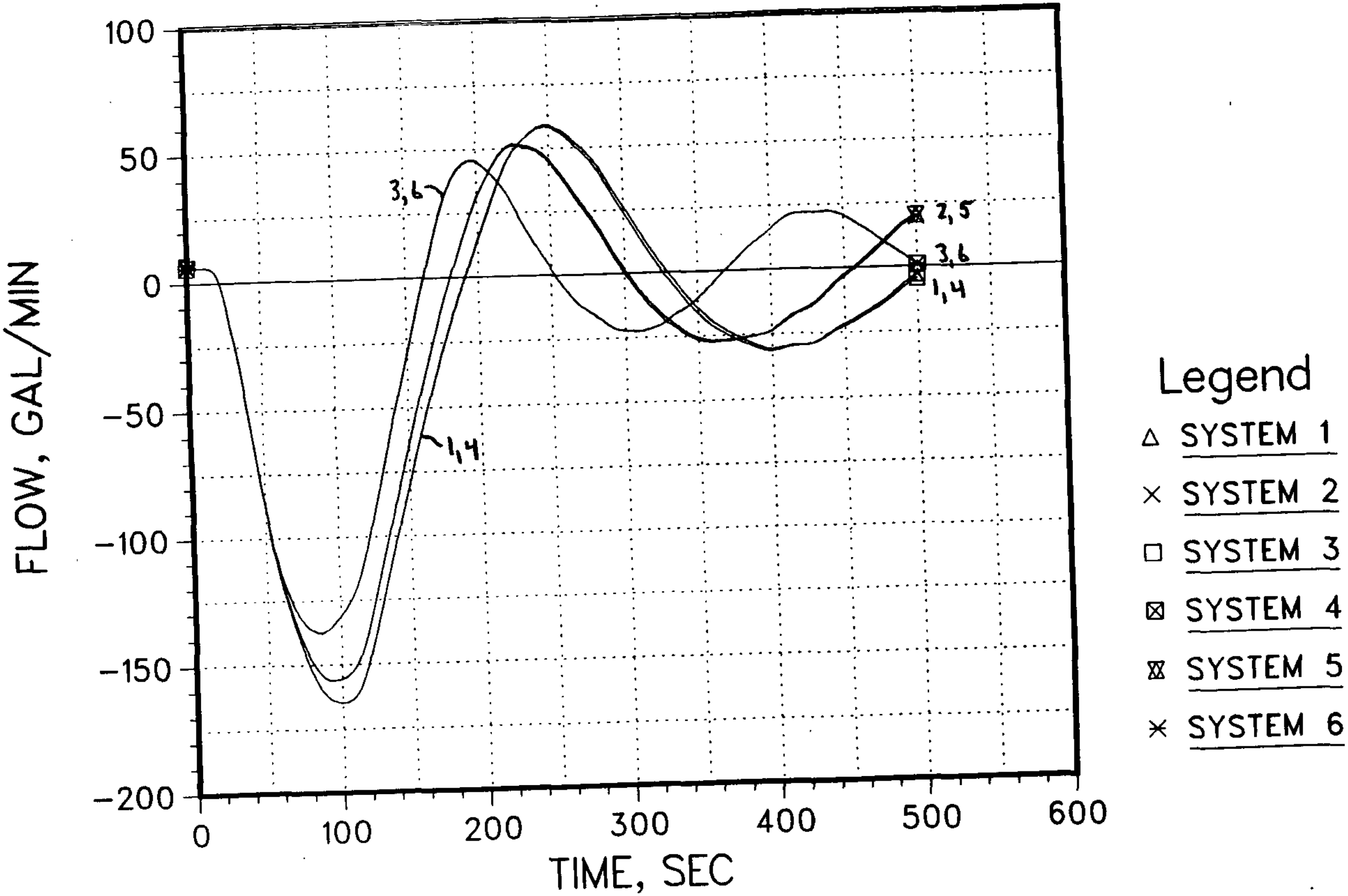

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FIG 11. PLENUM INLET TEMP, NC2.1

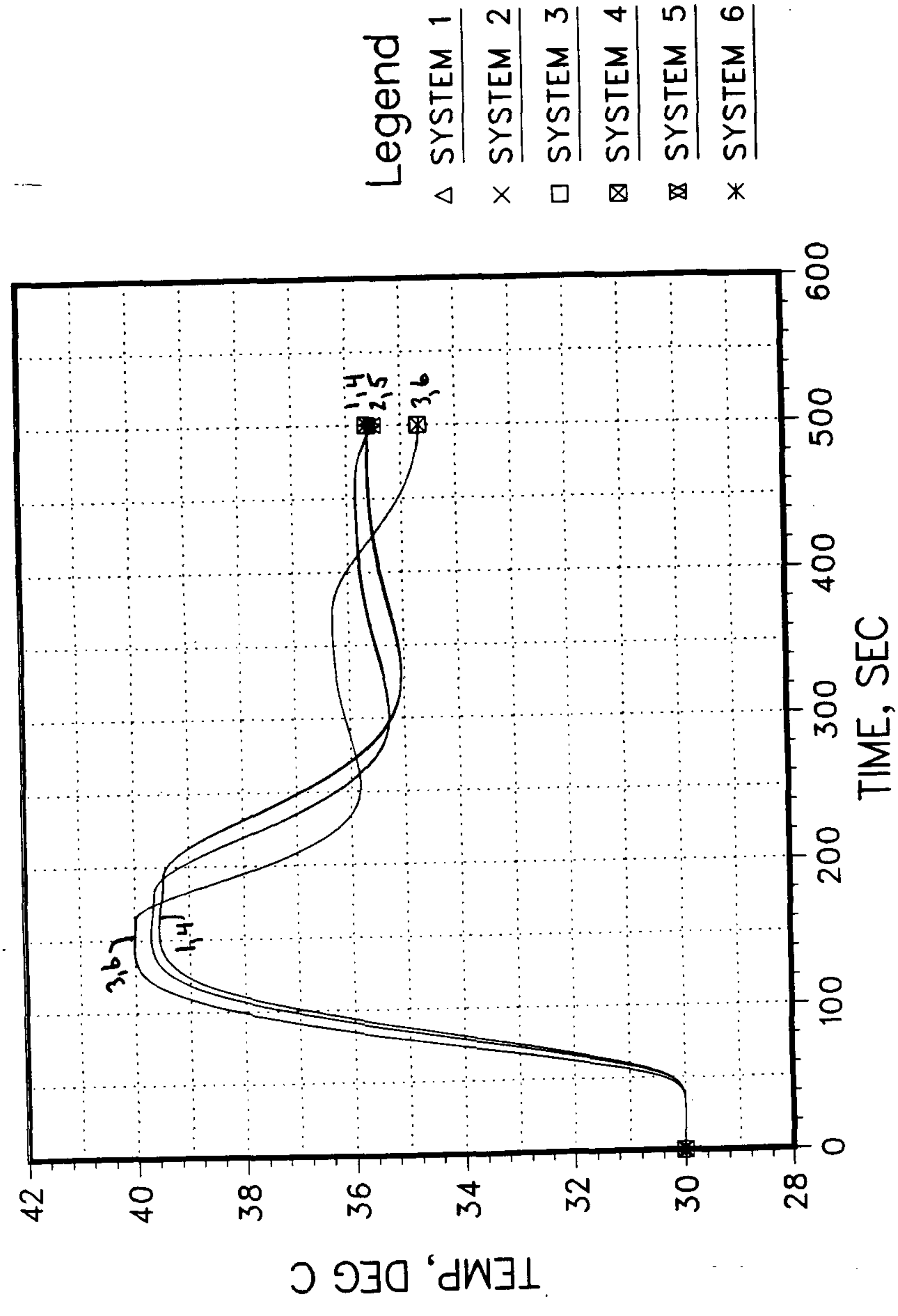

FIG 12. TOTAL CORE FLOW, NC5

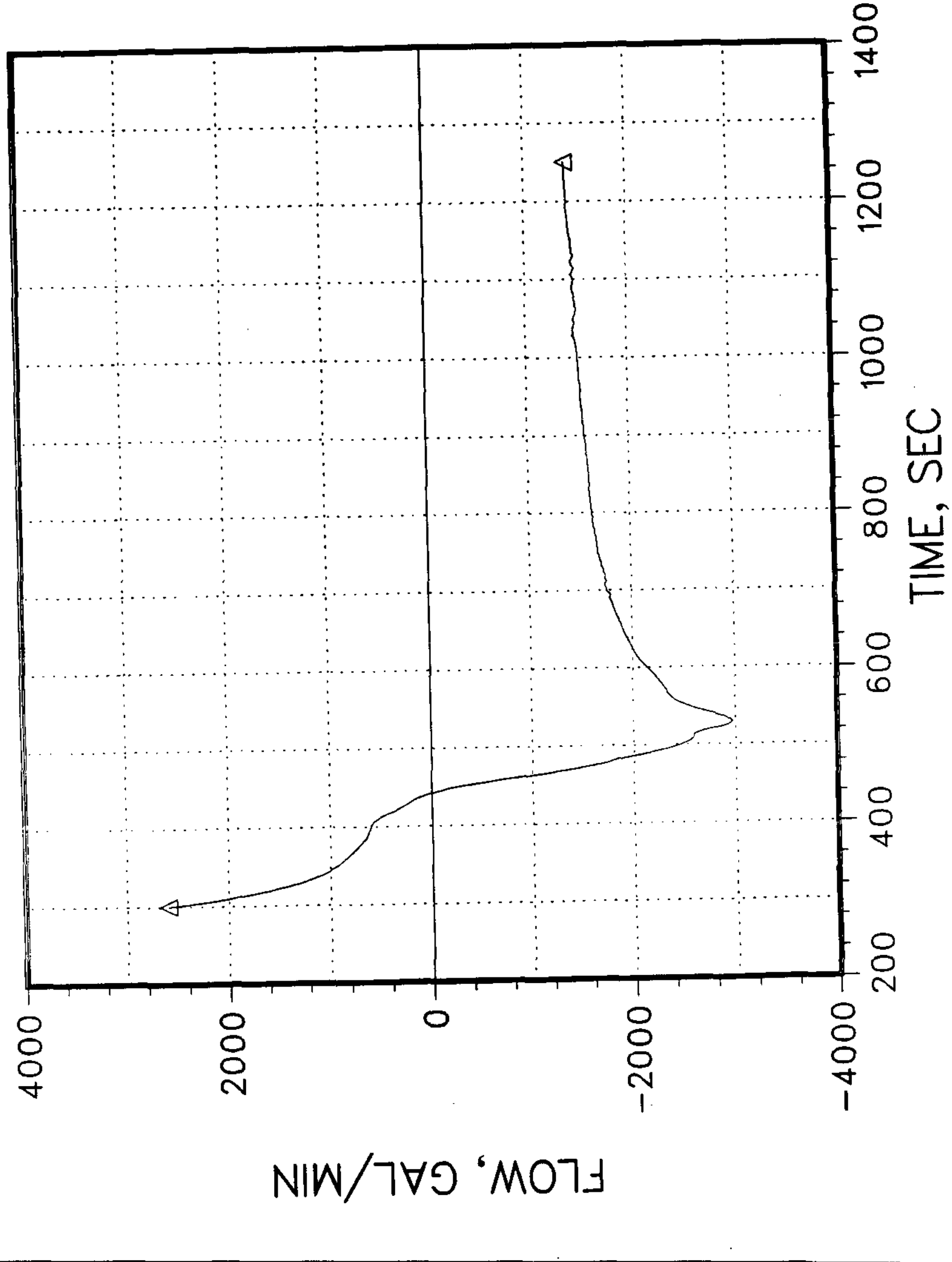

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FIG 13. PLENUM INLET TEMP, NC5

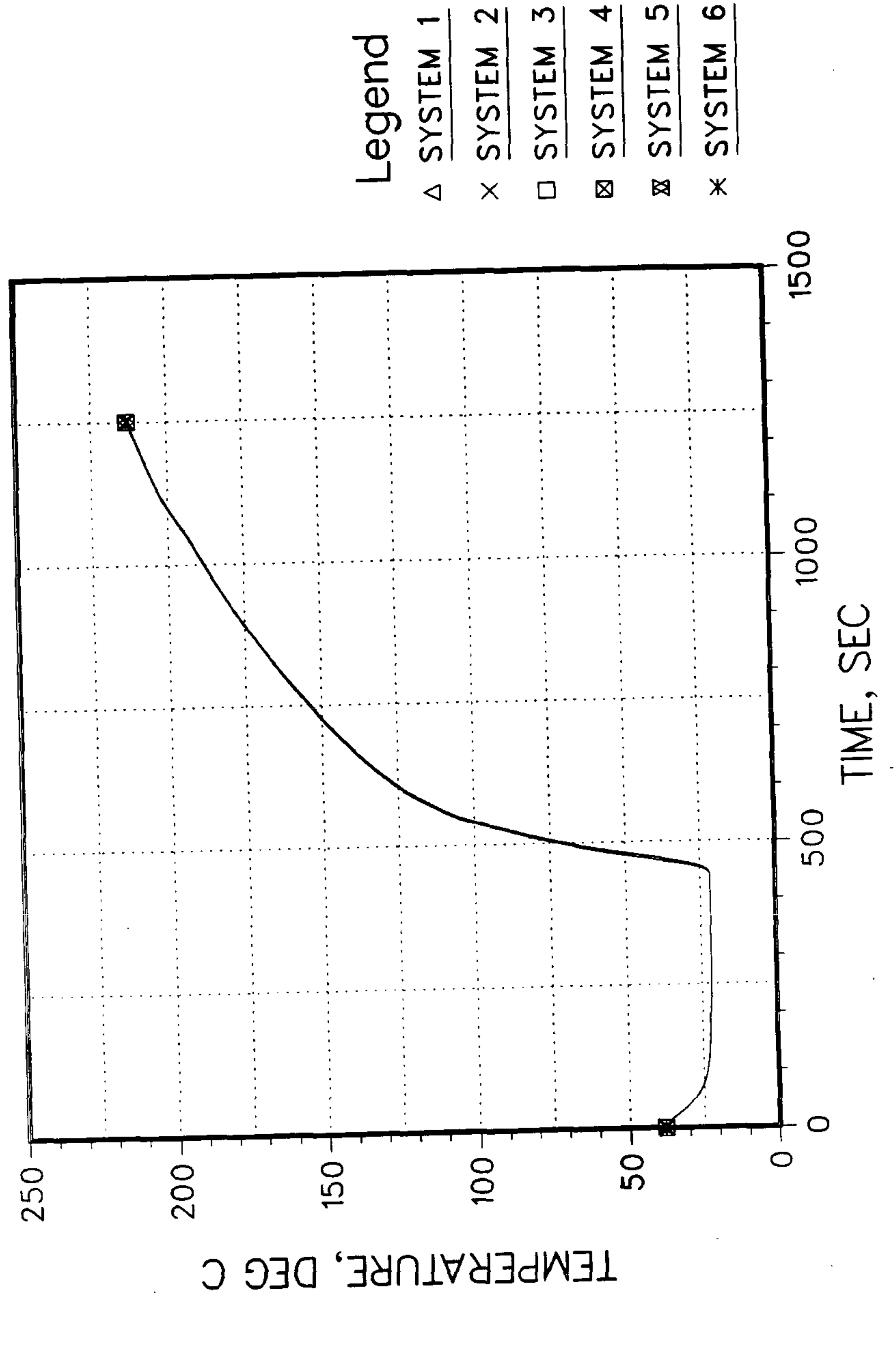
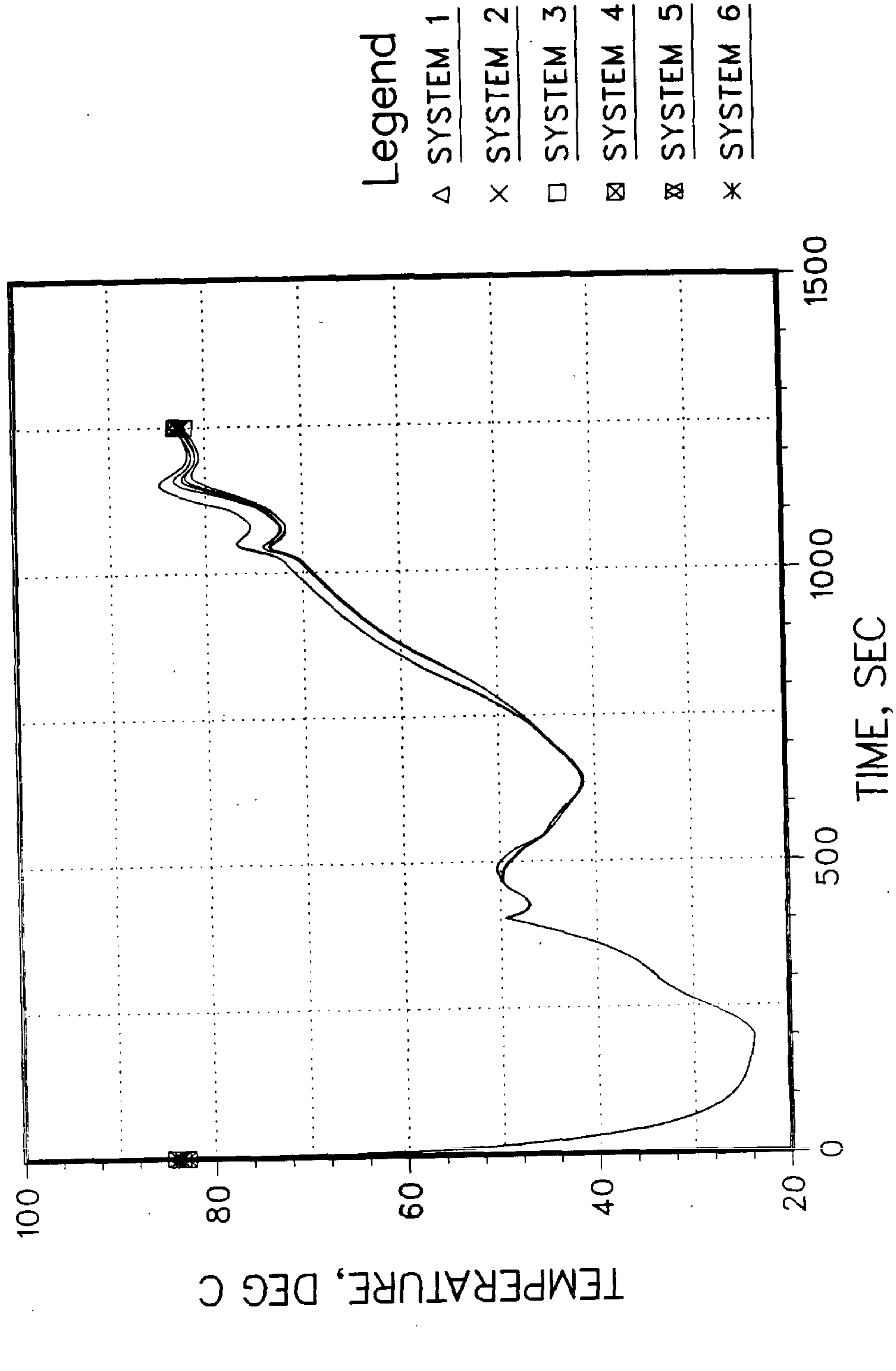


FIG 14. TANK EFFLUENT TEMP, NC5



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