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DPST-83-1055

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NATURAL CONVECTION AND BOILING FOR COOLING SRP REACTORS DURING LOSS OF CIRCULATION CONDITIONS

INTRODUCTION

Commercial nuclear power plants are designed to take advantage of natural convection cooling in the event of loss of circulation to the reactors. SRP reactors were not designed to take full advantage of this cooling mechanism under shutdown conditions. Natural convection flow is density driven with the density gradient being established by localized heating and cooling. Studies were conducted in the Heat Transfer Laboratory to determine if any potential exists for natural convection to occur in SRP reactors in the event of loss of circulation. Boiling as a means of cooling was also investigated. These cooling mechanisms, when combined, result in a two-phase natural convection cooling mode that yields benefits from both boiling and

---

*Introduction & Summary only

natural convection. Results of studies are preliminary but show adequate promise to warrant further evaluation.

SUMMARY

This study investigated natural convection and boiling as a means of cooling SRP reactors in the event of a loss of circulation accident. If these mechanisms can be shown to provide adequate cooling, it may be possible to avoid initiation of the Emergency Cooling System (ECS) in this situation. A cost of $40 million due to degraded and lost moderator would result directly from initiation of the ECS*. In addition, the potential exists for a large release of tritium to the environment. Although the bench scale reactor model used in these tests could not completely model a full scale SRP reactor, studies show that single phase (liquid) natural convection is limited, at best, in SRP reactors without some modifications.

Vented plenum boiling proved to be a relatively effective cooling method. The single channel test assembly with a heating power of 200 KW was effectively cooled. This cooling mechanism, however, is limited by the amount of moderator available for vaporization. It also requires adequate venting to avoid steam pressurization of the plenum. At present the only vents available are through the top of the sleeve housing tubes with the plenum plugs removed. As venting of generated steam continued, moderator loss and tritium release would approach that of ECS initiation. A combination of natural convection with boiling, however, was found to be significant in providing cooling for the single channel test assembly while still maintaining a closed loop system. A power level of 75 KW in the test assembly was cooled effectively during a 5 hour run with two-phase natural convection. A follow-up study of both vented plenum boiling and two-phase natural convection is planned. It will include multi-channel, multiple assembly, and long term flow tests. The key parameter of void fraction will also be determined. This information is necessary for modeling these passive cooling systems.

RESULTS AND DISCUSSION

The results of each phase of this study[1] are presented, including single phase natural convection, vented plenum boiling, and two-phase natural convection.

Single Phase Natural Convection

A bench scale model, shown in Figure 1, was constructed to model one of the cooling loops of the reactors. The critical dimension for this model was the elevation of the heat exchanger relative to the centerline of the reactor core. Although care

*Estimated cost to replace moderator

was taken to model the loop dimensionally correct, uneven heating characteristics of the steam heater were discovered during testing. The extent of the effect is unknown, but would tend to reduce the driving force for flow. The model was constructed to allow fluid visualization in the loop. Thermocouples located in the vent tank and at the inlet and outlet of the heater and heat exchanger provided temperature data used to construct profiles of the fluid temperature around the loop. The piping from the heater to the heat exchanger was insulated to reduce the heat loss through the pipe wall. Fluid velocity was measured by injecting dye into the fluid and timing the observed plume over a known distance.

Six runs were made with the bench scale model varying the heater outlet temperatures without allowing boiling. Typical results from these runs are shown graphically in Figures 2 and 3. Additional results are presented in Appendix A. The water in the loop was heated while the pump was operating. No flow existed in the cooling water side of the heat exchanger. When the water temperature reached 90 - 95°C the pump was shut off and the heat exchanger cooling water was turned on. Figure 2 shows the results without a continued heat source when the heat exchanger was turned on and the pump was stopped. Figure 3 shows the results where the heater was adjusted to maintain heater effluent temperature above 95°C without boiling. The fluid in the loop rapidly reversed in flow direction in both cases with an initial surge of 0.20 to 0.40 feet per second. The flow then decreased rather quickly to less than 0.04 feet per second. Steady state conditions may not have been achieved even after the two-hour test runs. An average flow for more long term tests was less than 0.02 feet per second. These low flow rates were judged to be inadequate for any significant cooling in the reactors. These bench scale tests were short term tests. It is expected that in the long term tests flow would decrease even further. However, this has not been demonstrated.

In order to determine the effect of heat exchanger height on the natural convection flow in the bench scale model, the heat exchanger was elevated 13 inches above its original position. Two runs were made with this arrangement. The results are shown in Figures 4 and 5. No significant change in flow behavior or temperature profile around the loop was observed. It appears that in order to maintain significant and continuous natural convection cooling, the heat exchanger would have to be elevated much higher above the heater to provide the necessary driving force. Apparently the steam heater in the model did not provide even heating from the top of the tube to the bottom. It is likely that the steam entering the top of the tube was condensed in the top portion, and provided little heating in the bottom of the heater. Increasing steam pressure to provide more even heating resulted in boiling at the top of the heater. This uneven heating condition would have also existed in the other test runs. An electric resistance heater would provide a better heat source for this model. The residual heat in the pump provided a source of heat at a low elevation during the initial part of the test. As the pump cooled the flow rate began to decrease.

The SRP reactor cooling loop contains a thermal trap or loop seal which restricts the onset of thermosyphon flow. No reason exists for the thermal trap other than convenience in pipe and equipment location. The thermal trap is of little consequence in forced flow cooling. The driving force for the natural convection flow is the density gradient between the hot water and the cold water on the two sides of the loop. The piping around the heat exchanger has a local minimum in the fluid path where the cold water in the heat exchangers will not contribute initially to the driving force. This thermal trap is shown in Figure 6. The thermal trap acts as an energy barrier to inhibit the initiation of natural convection flow. However, once flow has been established the thermal trap is of little consequence. Tests were made with the bench scale model with the loop seal removed to see what effects it had on flow initiation. Surprisingly, no significant difference in flow was observed with or without the loop seal. These results with the loop seal removed are shown in Figures 7 and 8. It may be that the difference in driving force with and without the thermal trap is not significant compared to the frictional resistance in the test loop.

Boiling

The second cooling mechanism investigated was boiling from a non-circulating tank. These studies were conducted with a full length, single channel assembly. The assembly is shown in Figure 9. This assembly was installed in A-tank in the Heat Transfer Laboratory. A sketch of the test system is shown in Figure 10. No circulation around the cooling loop was allowed. The plenum was vented to release steam so no pressurization would occur. The tank was also vented to the atmosphere. After the first test at 100 KW the plenum was provided with a drain to let condensate drain to the tank. This drain did not allow steam to pass through it to the tank. The 100 KW run had the heat exchanger side of the loop open, providing a larger reservoir than just the tank. This side of the loop was valved off for subsequent runs. The power level was increased from the 100 KW level in 25 KW increments until burnout of the silver solder joint (682°C) in the bus connection occurred at 225 KW. The 200 KW run appeared to be near steady state conditions with sufficient cooling taking place to prevent burnout. The results of the 200 KW run are shown in Figure 11. Other results are shown in Appendix A. At 225 KW the assembly failed in the first 10 minutes of the run, with temperatures rising in a fast ramp.

The rate of fluid loss in A-tank with power level is shown in Figure 12. A conservative calculation was made for the present reactor moderator inventories. These results are shown in Figure 13. The calculations do not take into account heating of the water to saturation, but do account for heat removal by vaporization of the water. They also do not include a factor for decreasing power levels due to the radioactive decay that would occur in actual fuel and target assemblies.

This cooling mechanism is very effective for short periods. With this steam generation, the mass transfer of steam out of the plenum is the limiting step, rather than the cooling rate of the assemblies. Preliminary calculations for steam transport limitations are given in Appendix B. The boiling cooling mechanism has the major drawback of being an open system. Moderator is continually lost - this costs money to replenish the moderator and releases tritium to the atmosphere.

Two-Phase Natural Convection

The third cooling mechanism, that of two-phase natural convection, was not originally considered in these studies. However, the concept developed as a natural combination of the other two cooling mechanisms. The first two-phase natural convection runs were thought to be single phase natural convection in the A-tank loop. A schematic of the test loop is shown in Figure 14. The system had no sight glass for flow visualization. Flow was measured by injecting a salt solution into the fluid and timing the difference between signals from two conductivity probes downstream of the injection port. Temperatures at various points around the loop were measured. The power levels during these runs ranged from 15 KW to 35 KW. These results are shown in Appendix A. Little or no flow was expected because the center of the heat exchanger was much too low for traditional natural convection to occur. The level of the heat exchanger in reference to the center of the heater would provide little or no density gradient to drive the flow. Surprisingly, the convection loop came to equilibrium at fairly high flow rates. Figure 15 shows the results of the 35 KW run. There were some unexplained spikes in the measured flow rate of the 25 KW run. The plenum and channel top temperatures were reading slightly above 100°C in both the 30 and 35 KW runs. These results indicated that something more than single phase natural convection was occurring.

In an effort to better understand natural convection with boiling, test runs were made with the bench scale model in order to visualize the flow patterns. Figures 16 and 17 show the results of these tests. The water in the heater was allowed to boil. The air separator tank served as a reservoir to keep the loop filled and maintain continuity. It also served to vent the system and maintain atmosphere pressure (see Figure 1). This vented tank essentially accomplished the same results as a condenser would have. Steam was removed and a single phase fluid was maintained on the outlet side of the tank. An interesting phenomena of flow oscillation occurred with the boiling. Vigorous boiling would begin in the top of the heater. This would promote a high flow rate around the loop. This surge would bring cold water into the heater and boiling would cease. The flow would then actually reverse slightly until boiling began again and another surge would occur. The net effect was an average flow rate about ten times greater than for single phase natural convection. Fluid velocity during the surges was about 50 times greater than for the single phase natural convection. These oscillations appeared to have a constant period in a quasi-steady state condition. A review of the literature[2-7] shows that this oscillatory behavior is typical in simple thermosyphons at specific heat flux input.

The oscillations could possibly explain the spikes in flow rate observed in the A-tank tests. It is possible that if oscillations did occur, salt injection may have occasionally happened just at the right time in a fluid surge to flow past both conductivity probes in a short time period. Under normal conditions, however, the signals from the probes would only show the average flow. This would appear to be constant flow masking the real flow oscillations.

It was necessary to determine the extent of cooling possible for this two-phase natural convection with the test assembly is the A-tank loop. The limitation of steam pressurization existed with the closed loop system where boiling occurred. It was speculated that at powers $\leq$ 35 KW, enough steam condensation on the pipe walls occurred to maintain a relatively low pressure. However, in order to extend the test range to higher powers, a simple water jacket was installed around the inlet line to the plenum (outlet for these natural convection tests) to further enhance condensation. Figure 18 shows the location of the condenser in the convection loop. This condenser was not designed to remove a large amount of energy, but simply to provide enough capacity to condense the steam generated in the assembly. The convection flow would then carry the hot water in the loop through the heat exchangers where the majority of cooling would occur.

Two-phase natural convection runs at power levels of 40 to 90 KW were performed with the test assembly in A-tank. The results are shown in Appendix A. The condenser capacity was exceeded at 90 KW after six hours of run time as shown in Figure 19. The actual heat balance shows the condenser removing a constant 16 KW of power throughout the run. The heat exchanger removed about 85 KW of power initially. Heat transfer out of the system with the heat exchangers gradually dropped as the flow around the loop decreased with time. Failure, as defined in this test, was not overheating of the test assembly, but overpressurizing the plenum. No burnout of the test assembly occurred. It is expected that higher assembly powers could have been effectively cooled with a condenser of larger capacity.

CONCLUSIONS

These preliminary studies show that single phase natural convection cooling of SRP reactors in shutdown conditions with the present piping geometry is probably not feasible. Tests planned in L-area prior to reactor start-up may provide additional information. A large amount of cooling can be provided by simply allowing boiling to occur in the assemblies and venting the steam to the atmosphere. Although these tests were preliminary and more work needs to be done, cooling of up to 200 KW per assembly was achieved without assembly failure for a short time period (approximately 5 hours). This cooling mechanism is limited to the time it takes to boil away the moderator in the reactor tank. It has the drawback of being an open system. The costly moderator is continually lost and tritium is vented to the atmosphere. As boiling continues with time, the monetary and radiation exposure costs approach those of ECS initiation. This cooling mechanism would be effective for short term loss of circulation. It could delay the initiation of the ECS when short term repairs could restore forced circulation.

Very effective cooling can be achieved by combining these two cooling mechanisms to result in two-phase natural convection cooling. This mechanism has the advantage of the closed loop system with no lost moderator and therefore no lost money or tritium. It also provides a high degree of cooling for an indefinite amount of time. These conclusions are based on preliminary studies conducted in the Heat Transfer Laboratory.

A more comprehensive study to obtain the correct scaling factors for modeling is underway. This study will include both vented plenum boiling and two-phase natural convection. Multi-channel, multiple assembly, and long term test runs will be performed. Flow visualization will be used to monitor boiling inception and two-phase flow patterns. Better flow measurement is planned to better characterize flow oscillations. Void fraction will also be determined as a key factor in modeling and scaling to the full size reactor system.

FIGURE 1

BENCH SCALE NATURAL CIRCULATION LOOP

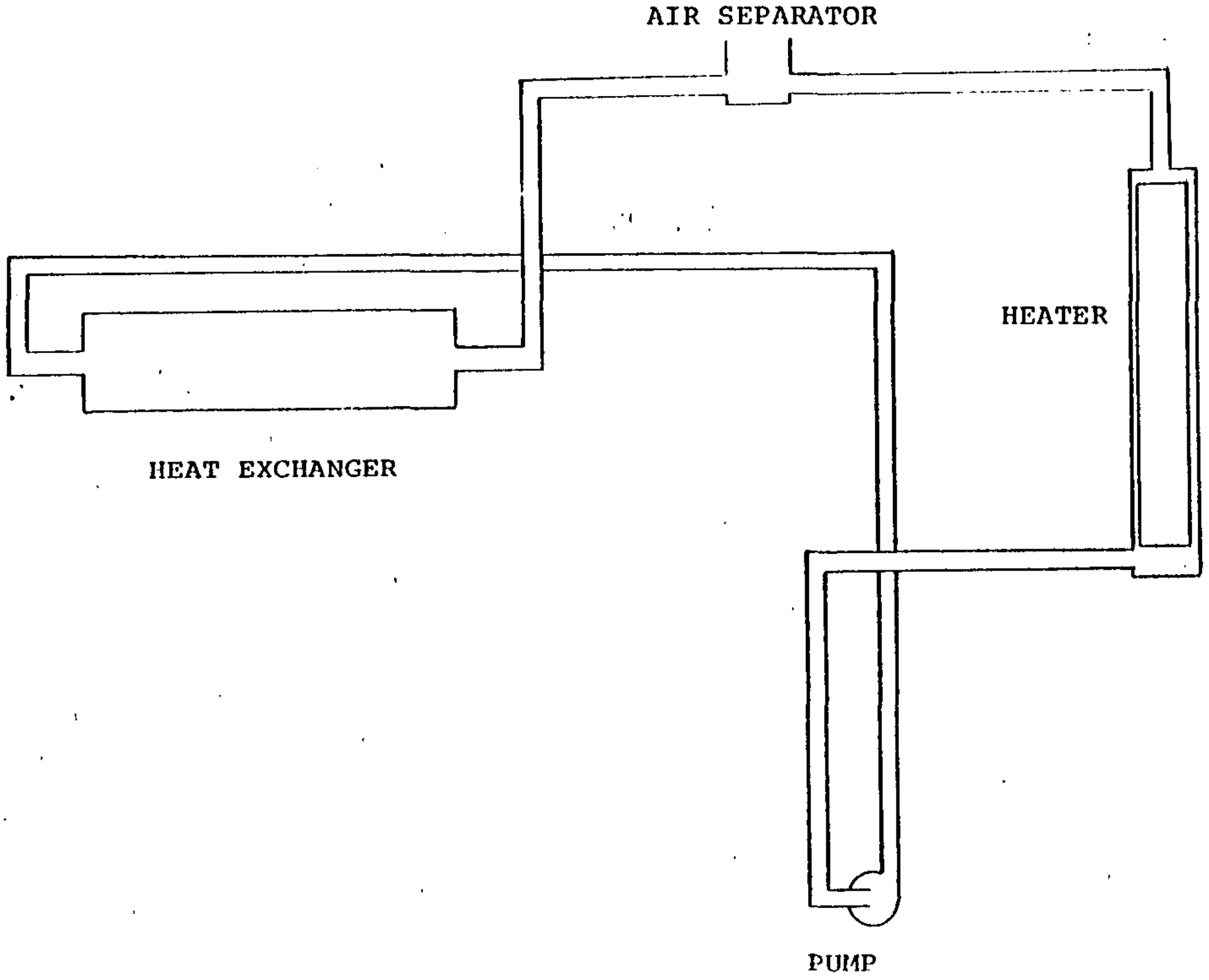


FIGURE 2

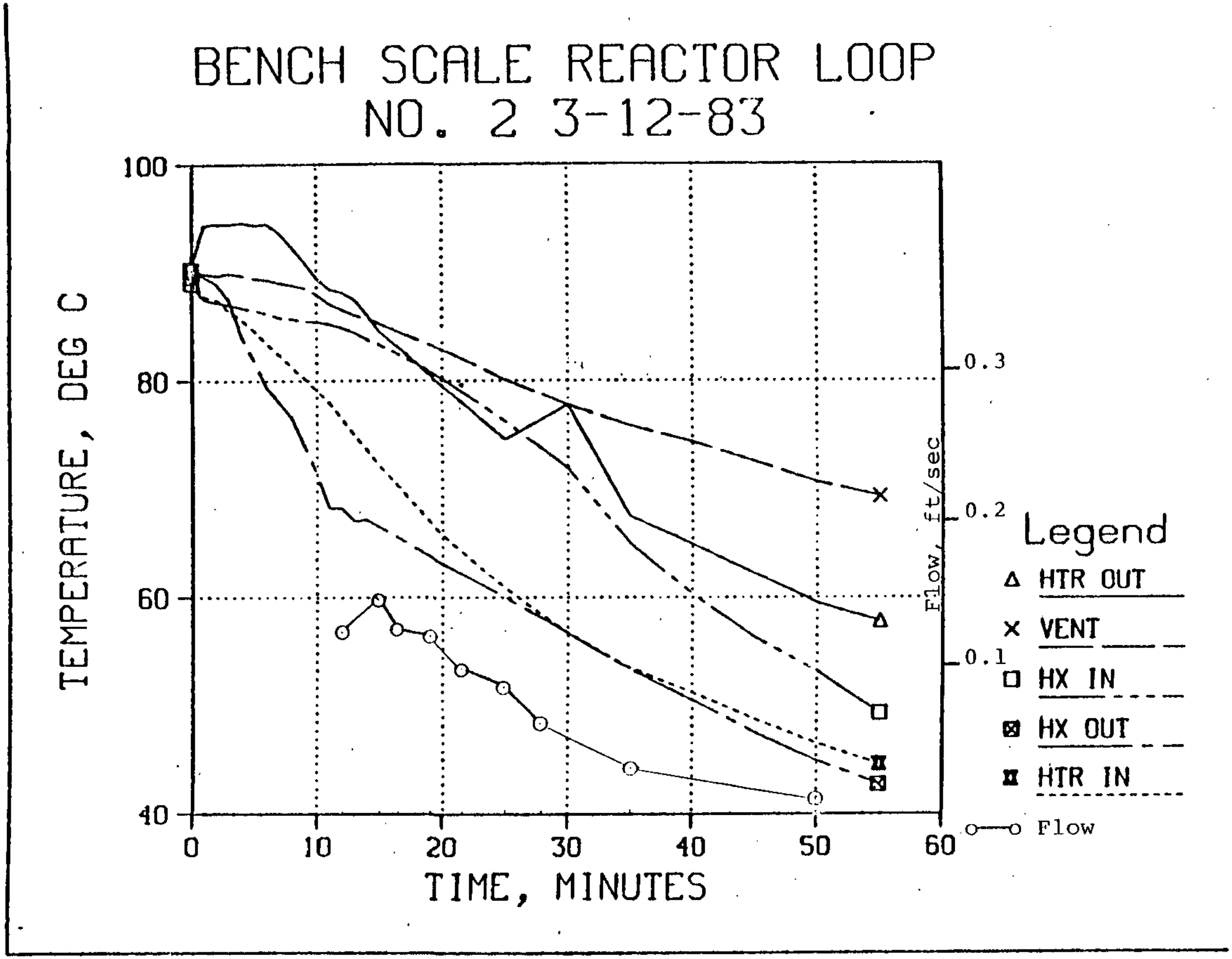

BENCH SCALE REACTOR LOOP
NO. 2 3-12-83
TEMPERATURE, DEG C
100
80
60
40
TIME, MINUTES
0
10
20
30
40
50
60
Flow, ft/sec
0.3
0.2
0.1
Legend
Δ HTR OUT
× VENT
□ HX IN
⊠ HX OUT
⧗ HTR IN
o—o Flow

FIGURE 3

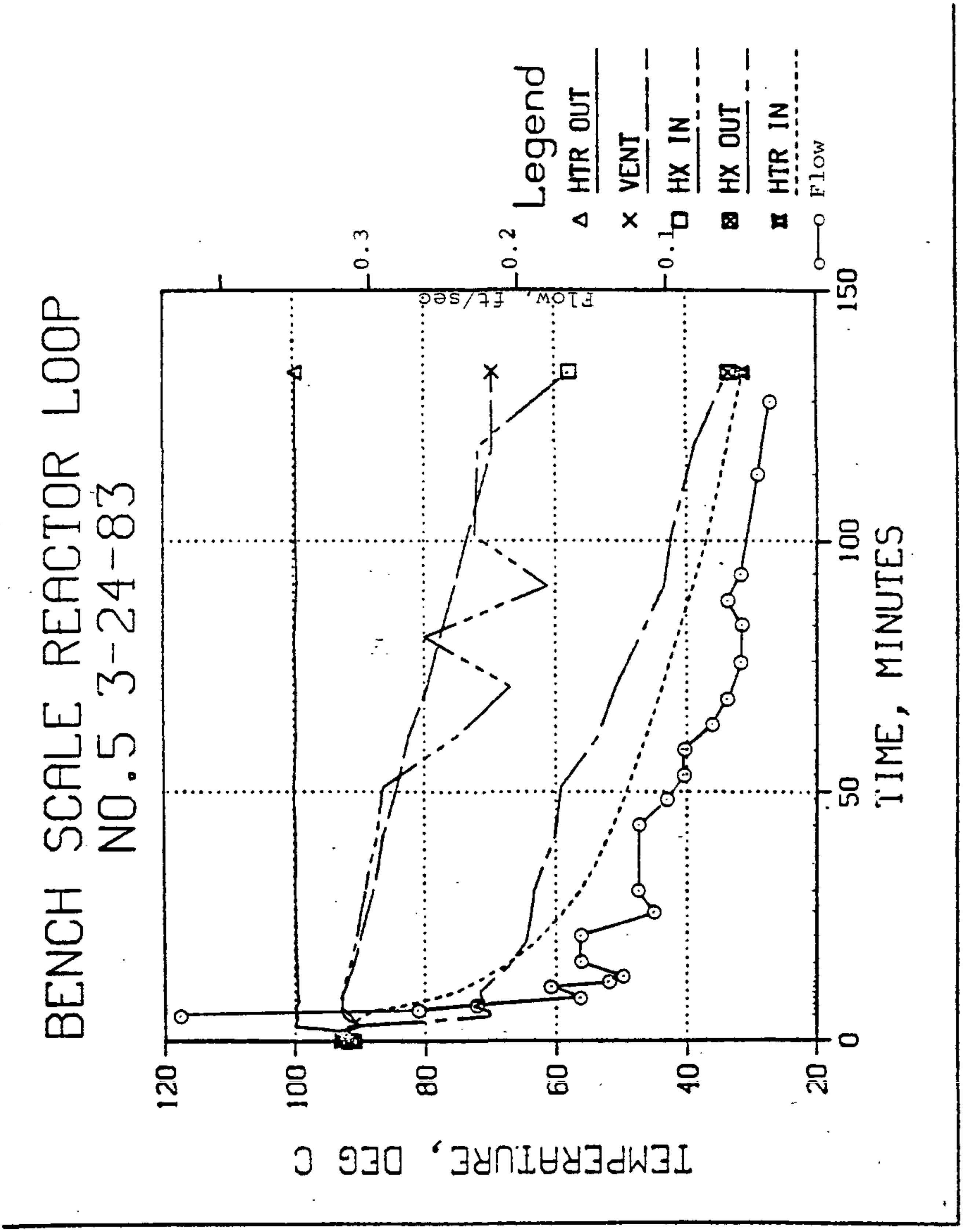

BENCH SCALE REACTOR LOOP
NO.5 3-24-83
TEMPERATURE, DEG C
120
100
80
60
40
20
TIME, MINUTES
0
50
100
150
Flow, ft/sec
0.1
0.2
0.3
Legend
△ HTR OUT
× VENT
□ HX IN
⊠ HX OUT
⌘ HTR IN
○—○ Flow

FIGURE 4

RAISED HEAT EXCHANGER

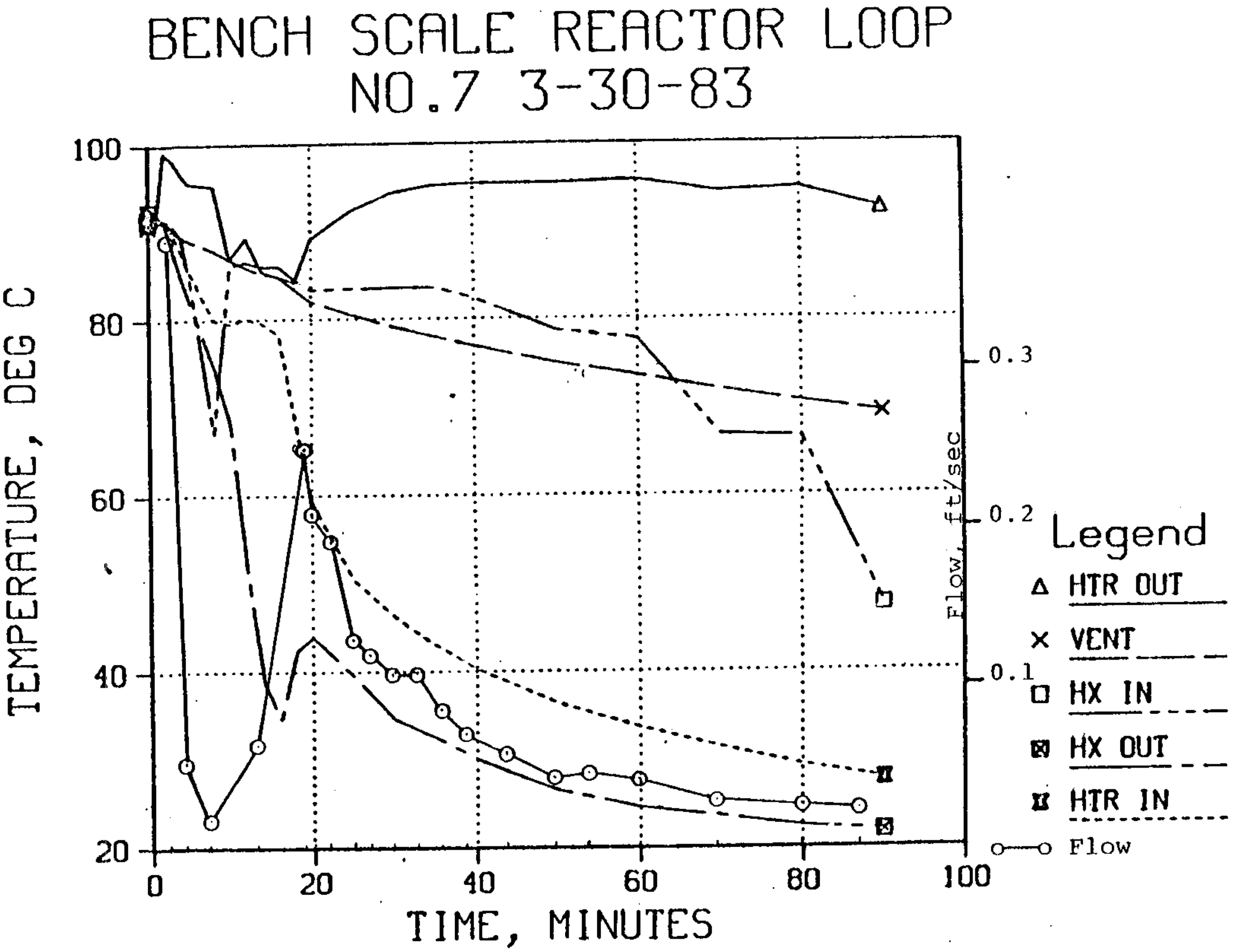


FIGURE 5

RAISED HEAT EXCHANGER

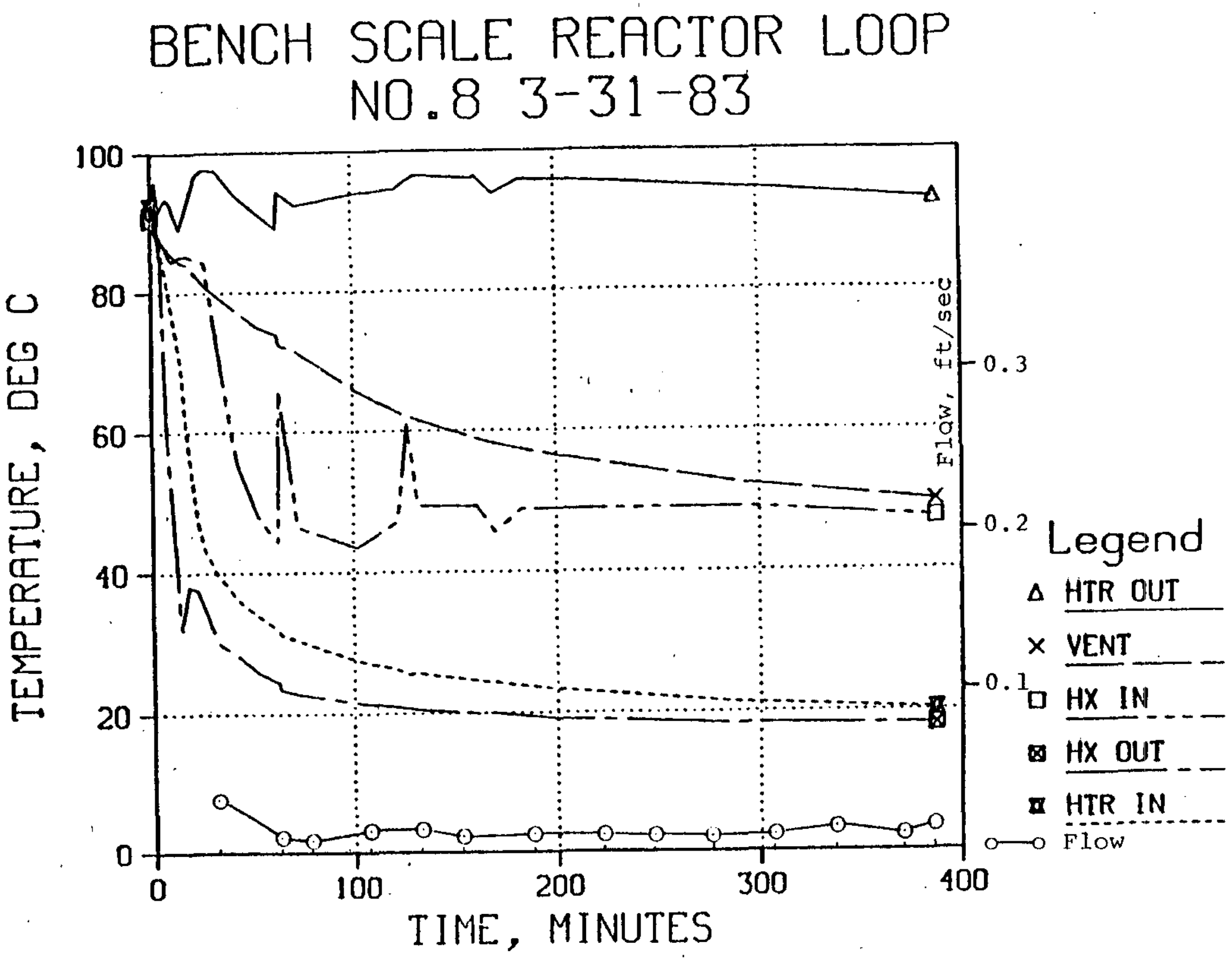


FIGURE 6

PROCESS FLOW LOOP WITH THERMAL TRAP

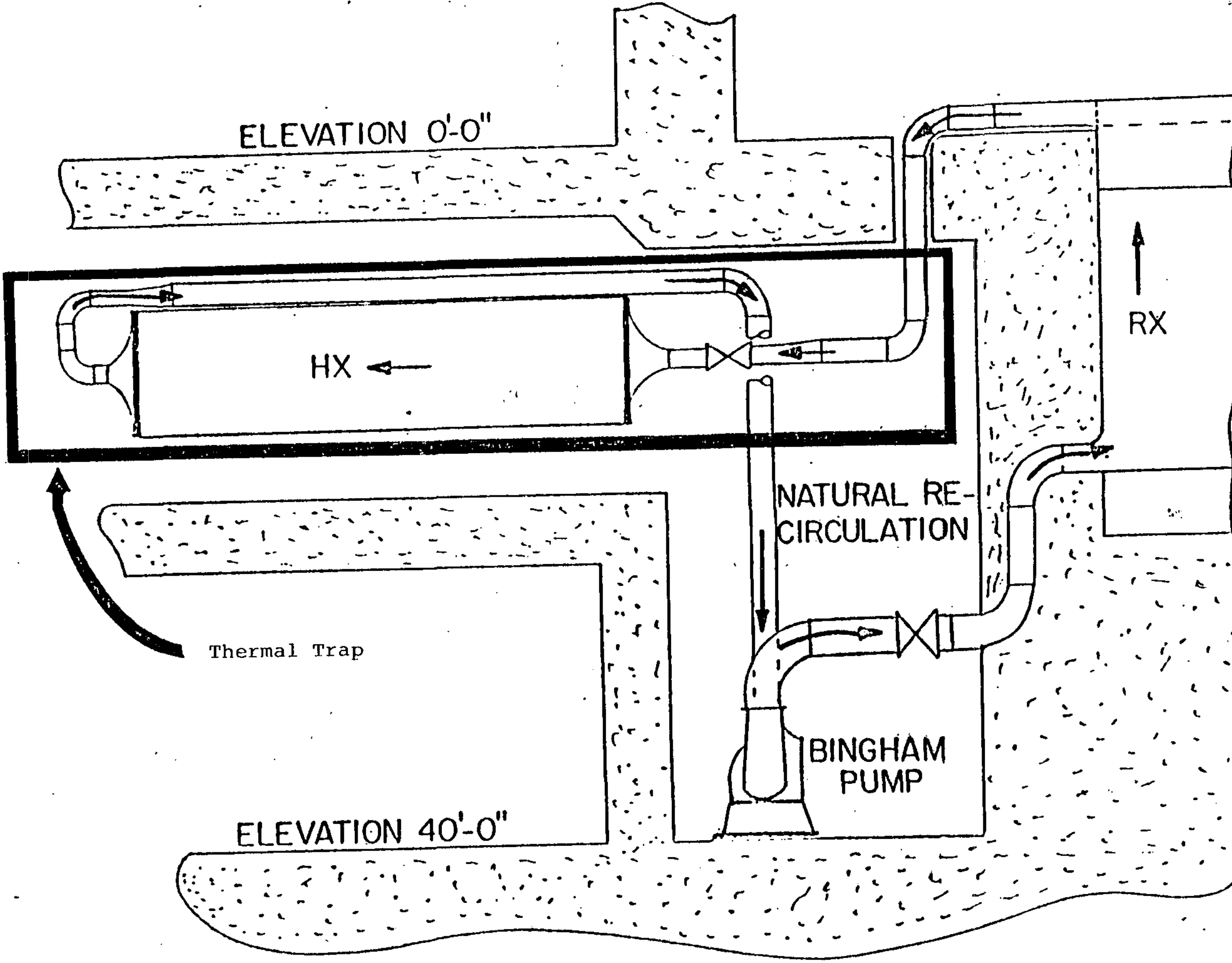


FIGURE 7

RAISED HEAT EXCHANGER WITHOUT THERMAL TRAP

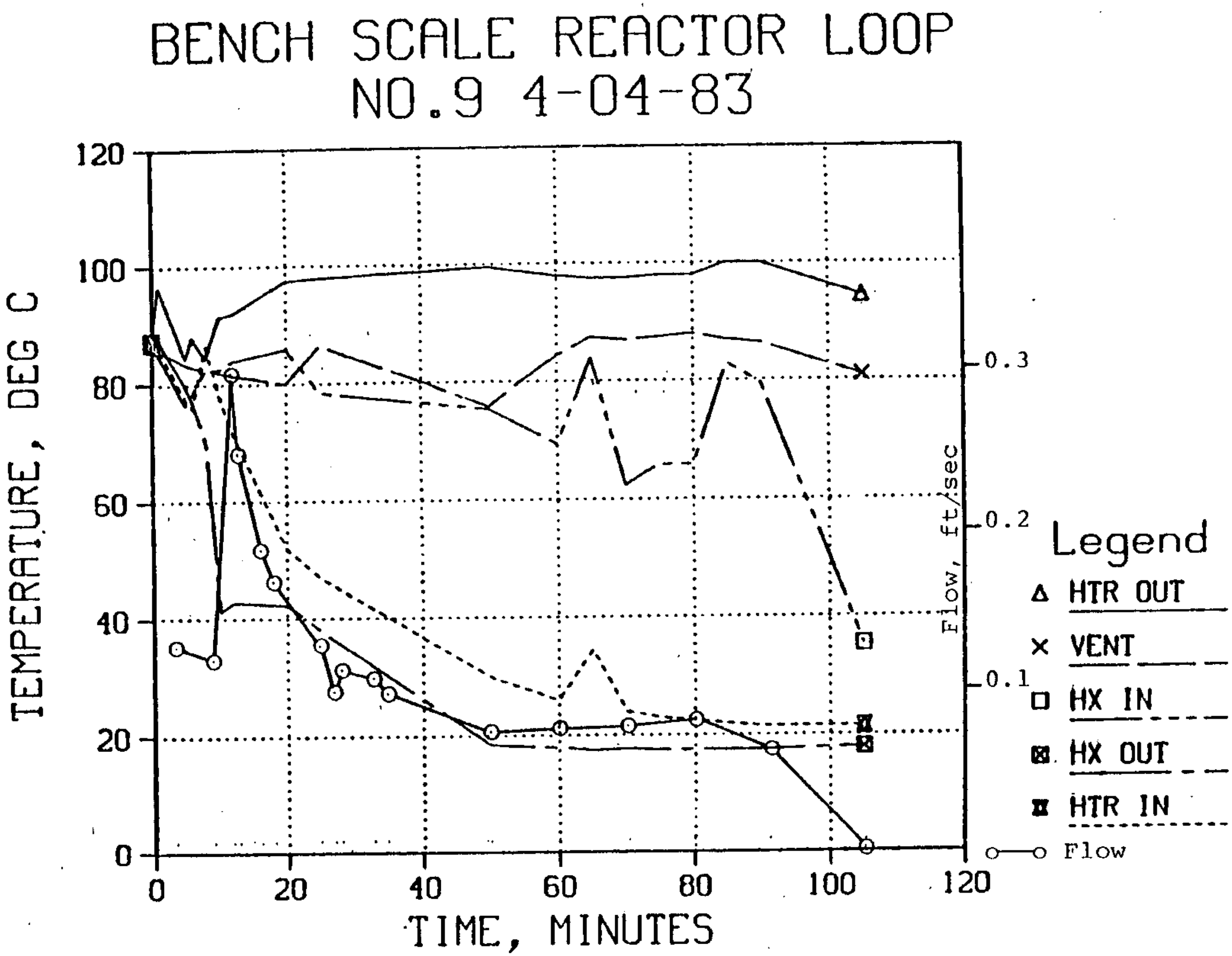


FIGURE 8

RAISED HEAT EXCHANGER WITHOUT THERMAL TRAP

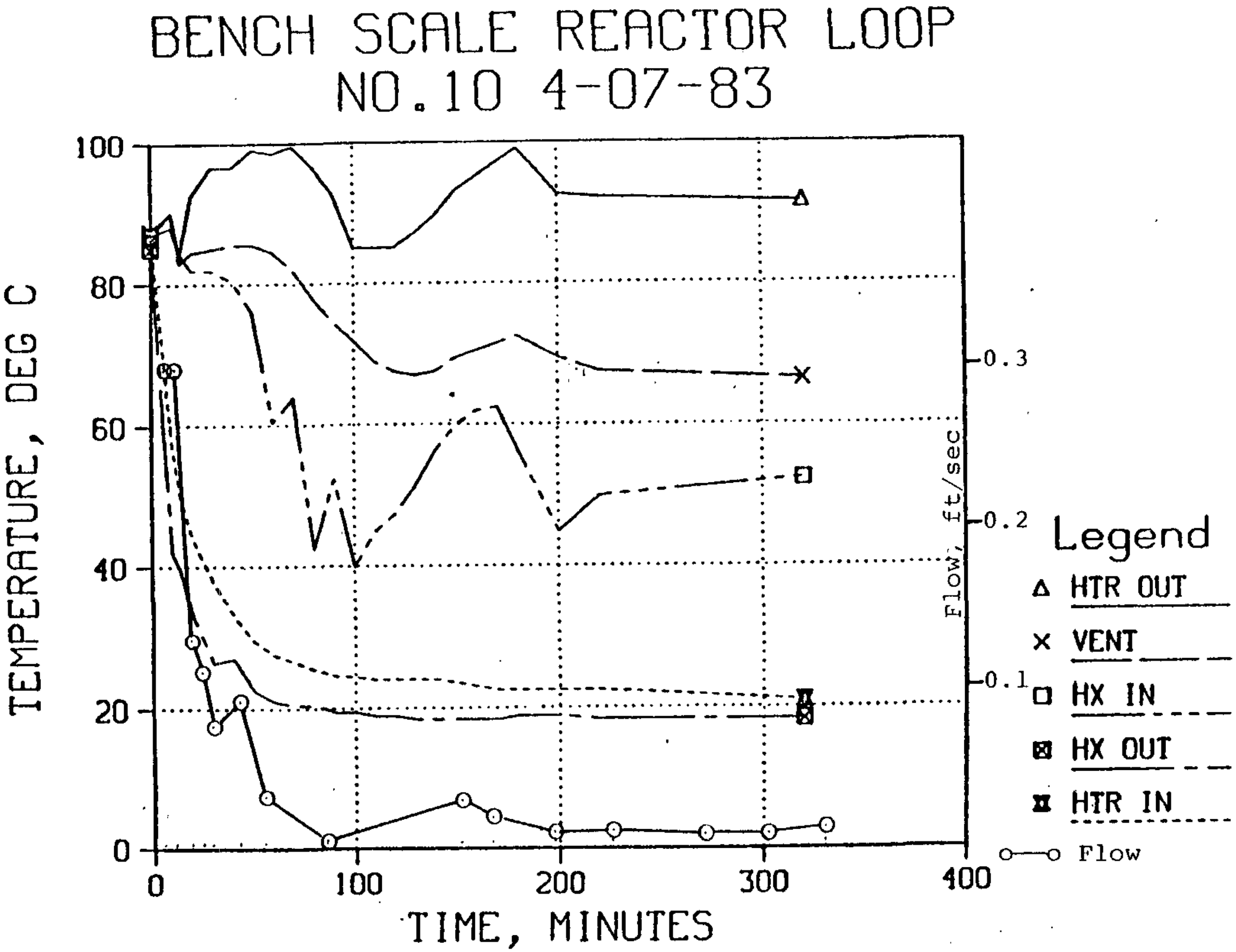


FIGURE 9

HEATER ASSEMBLY FOR BOILING AND NATURAL CONVECTION TESTS IN A-TANK

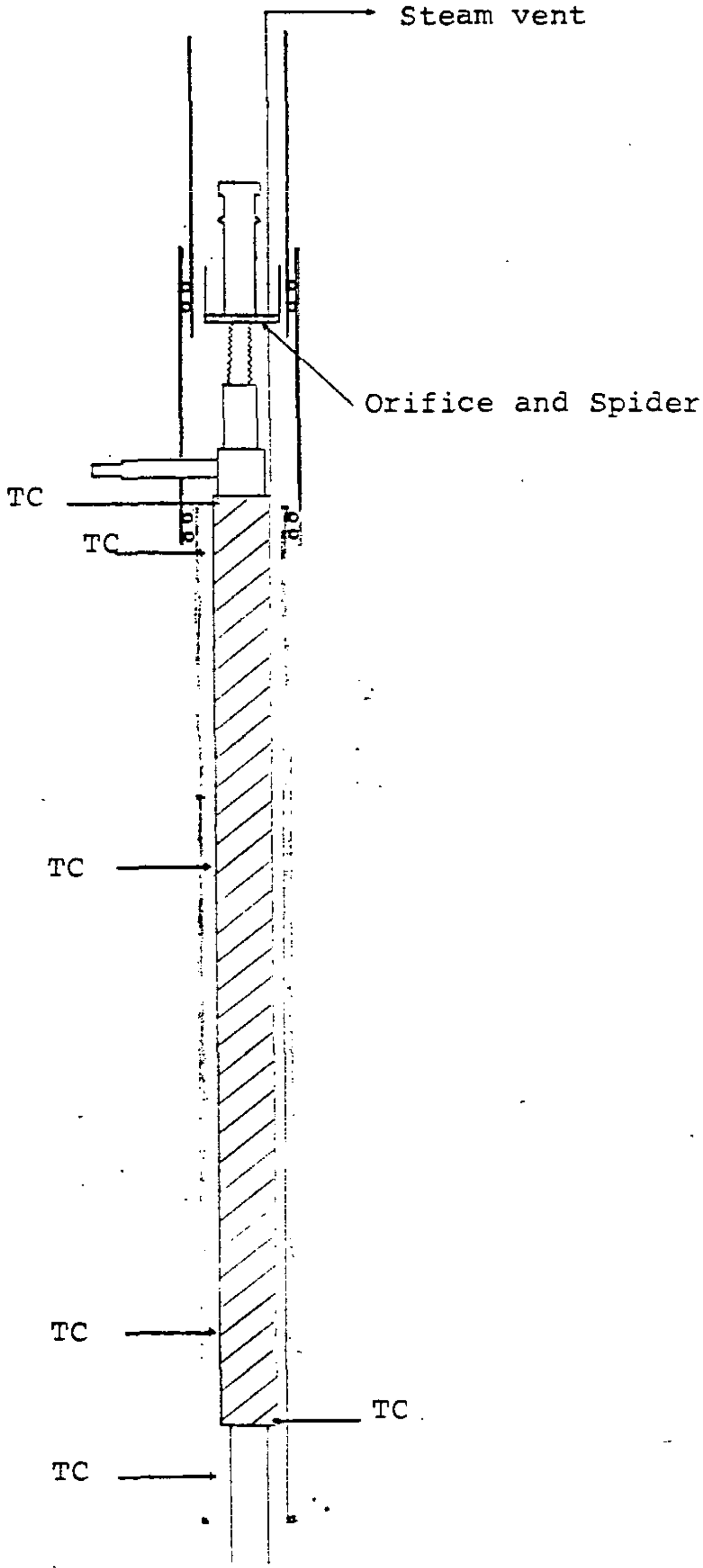


FIGURE 10

A-TANK BOILING TEST APPARATUS

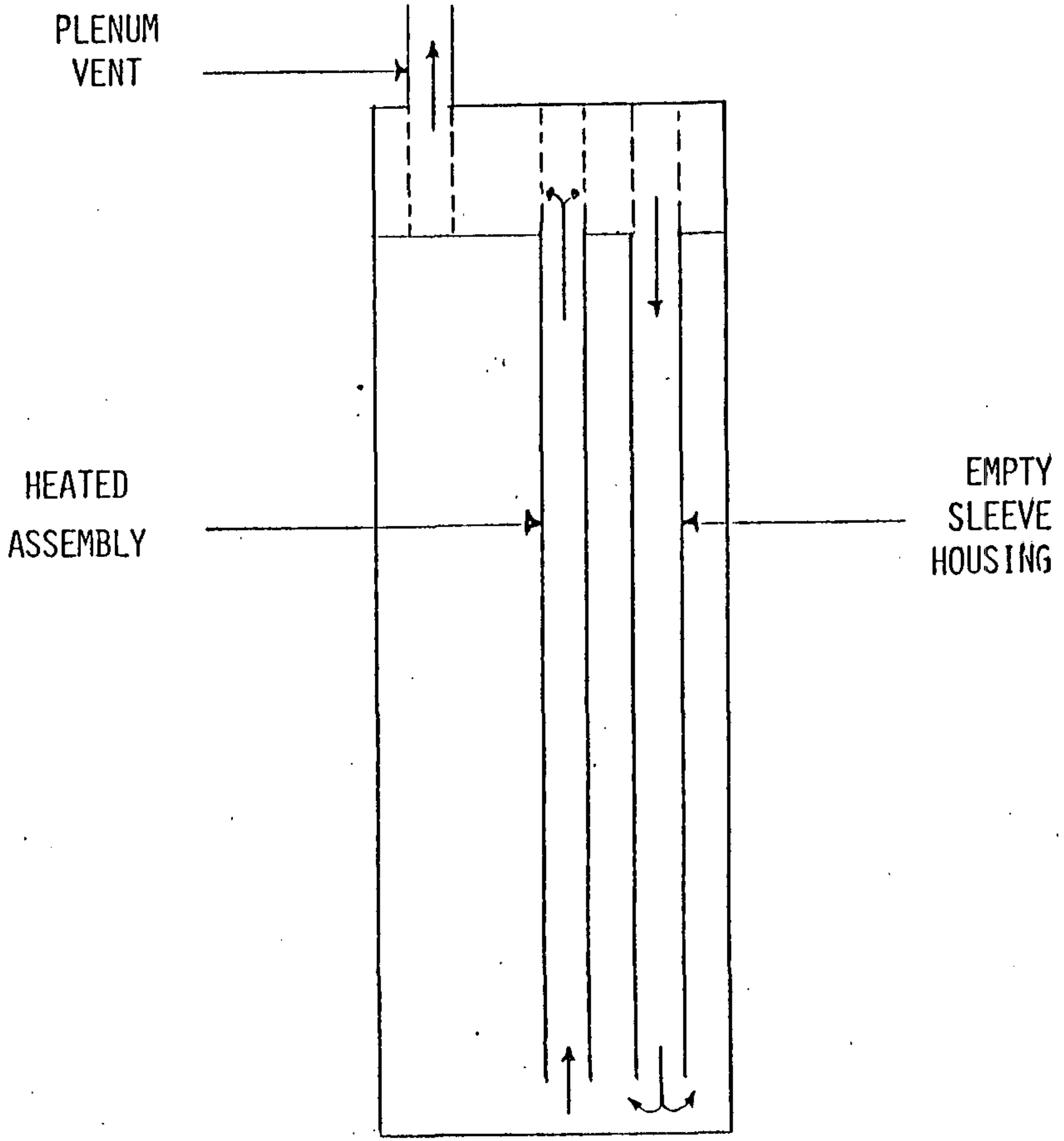


FIGURE 11

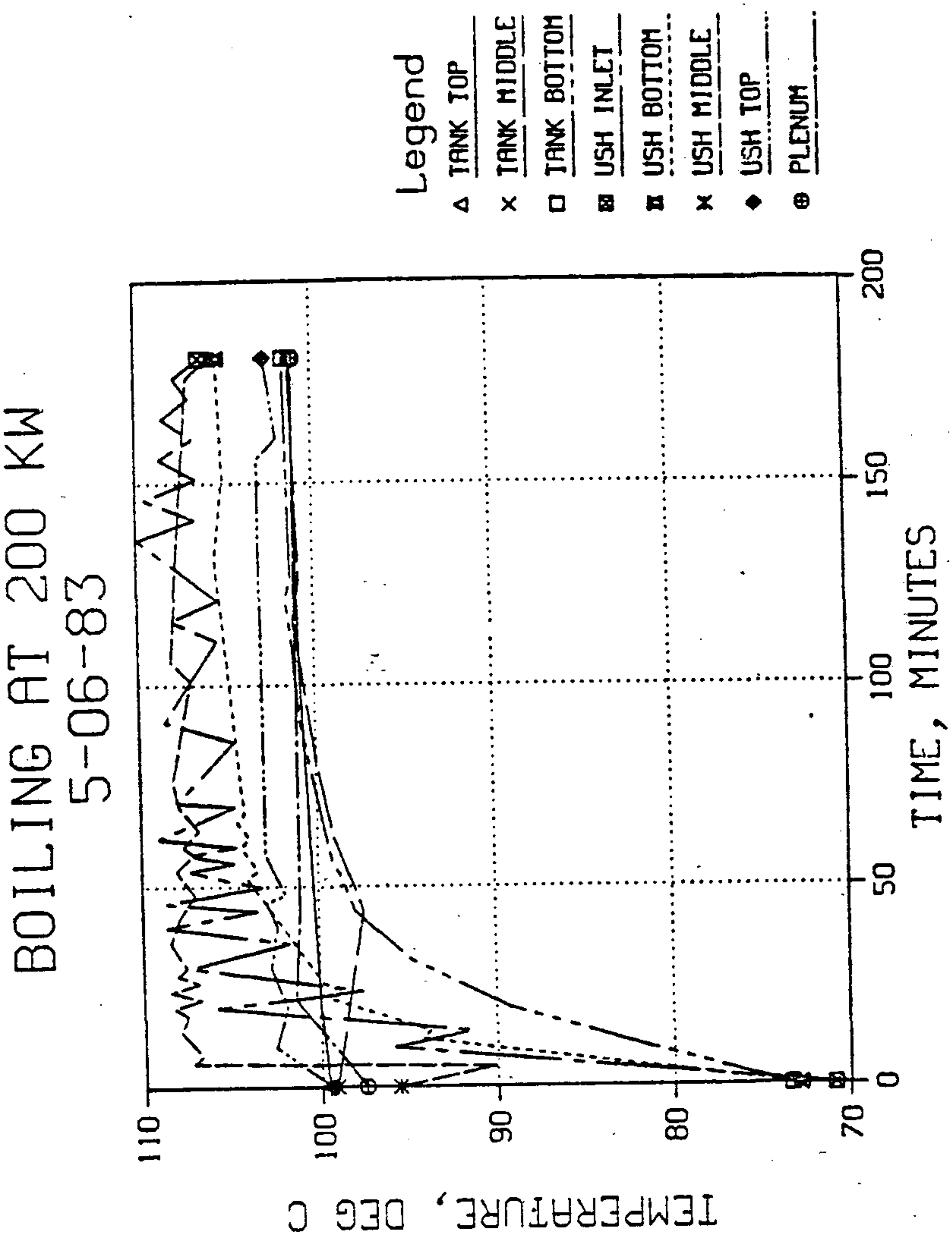

BOILING AT 200 KW
5-06-83
TEMPERATURE, DEG C
110
100
90
80
70
TIME, MINUTES
0
50
100
150
200
Legend
△ TANK TOP
× TANK MIDDLE
□ TANK BOTTOM
⊠ USH INLET
⌛ USH BOTTOM
✱ USH MIDDLE
◆ USH TOP
⊕ PLENUM

FIGURE 12

A-TANK LEVEL DROP DURING BOILING TESTS AT VARIOUS POWERS

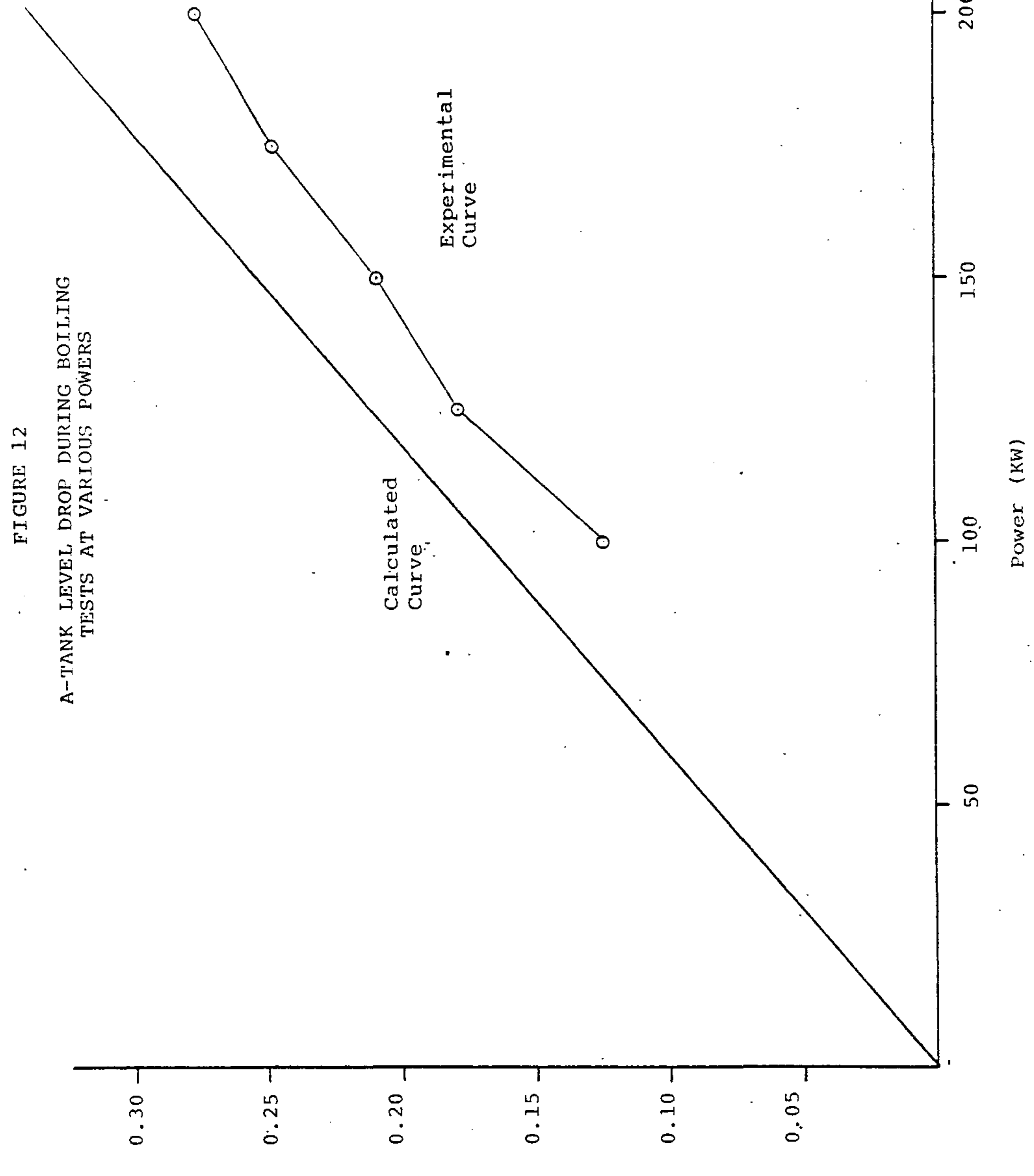
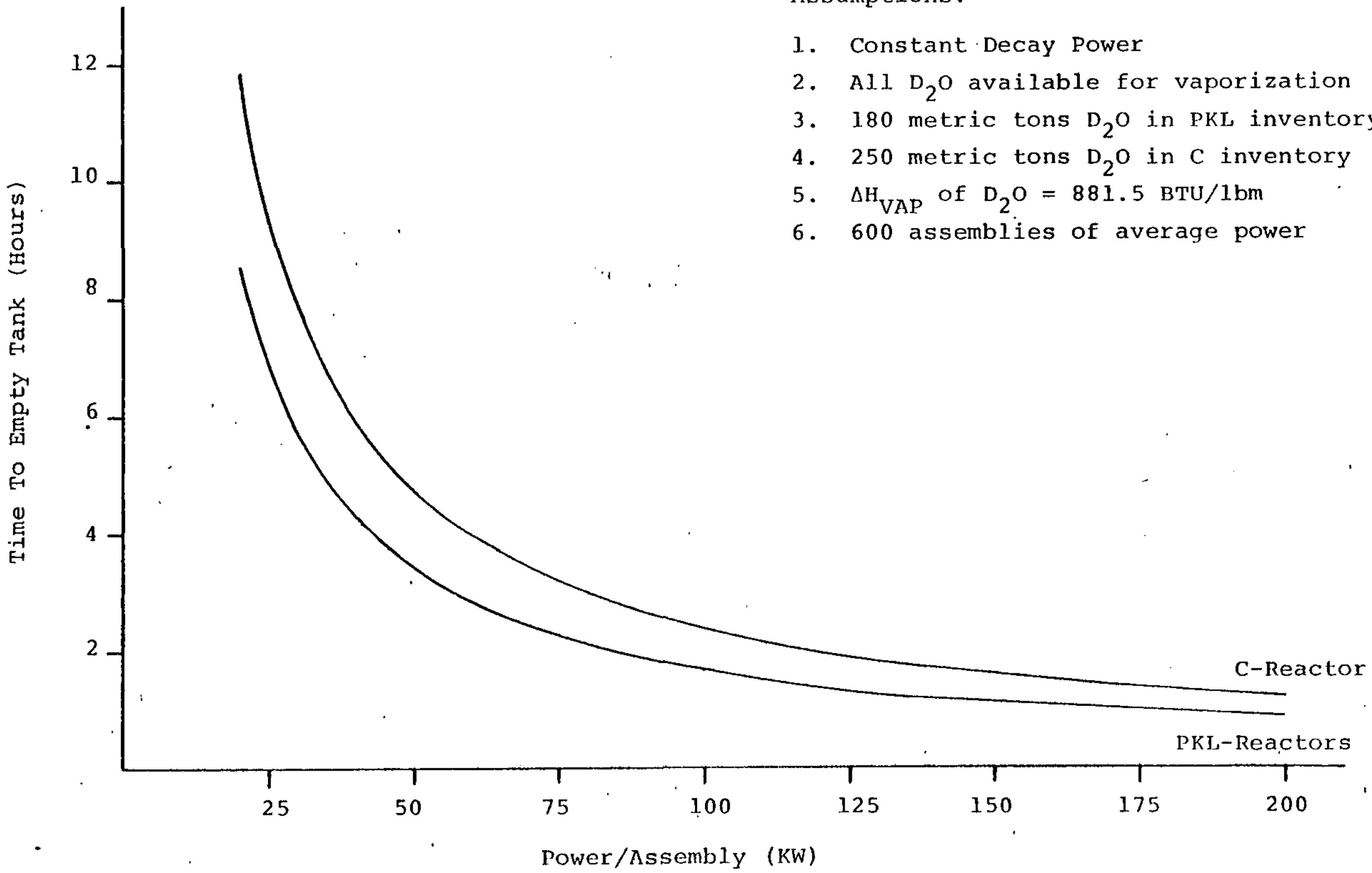


FIGURE 13

MODERATOR VAPORIZATION TIME TO EMPTY REACTOR TANK WITH CONTINUOUS BOILING



Assumptions:

1. Constant Decay Power
2. All D_2O available for vaporization
3. 180 metric tons D_2O in PKL inventory
4. 250 metric tons D_2O in C inventory
5. ΔH_{VAP} of D_2O = 881.5 BTU/lbm
6. 600 assemblies of average power

FIGURE 14

A-TANK
NATURAL CONVECTION
TEST LOOP

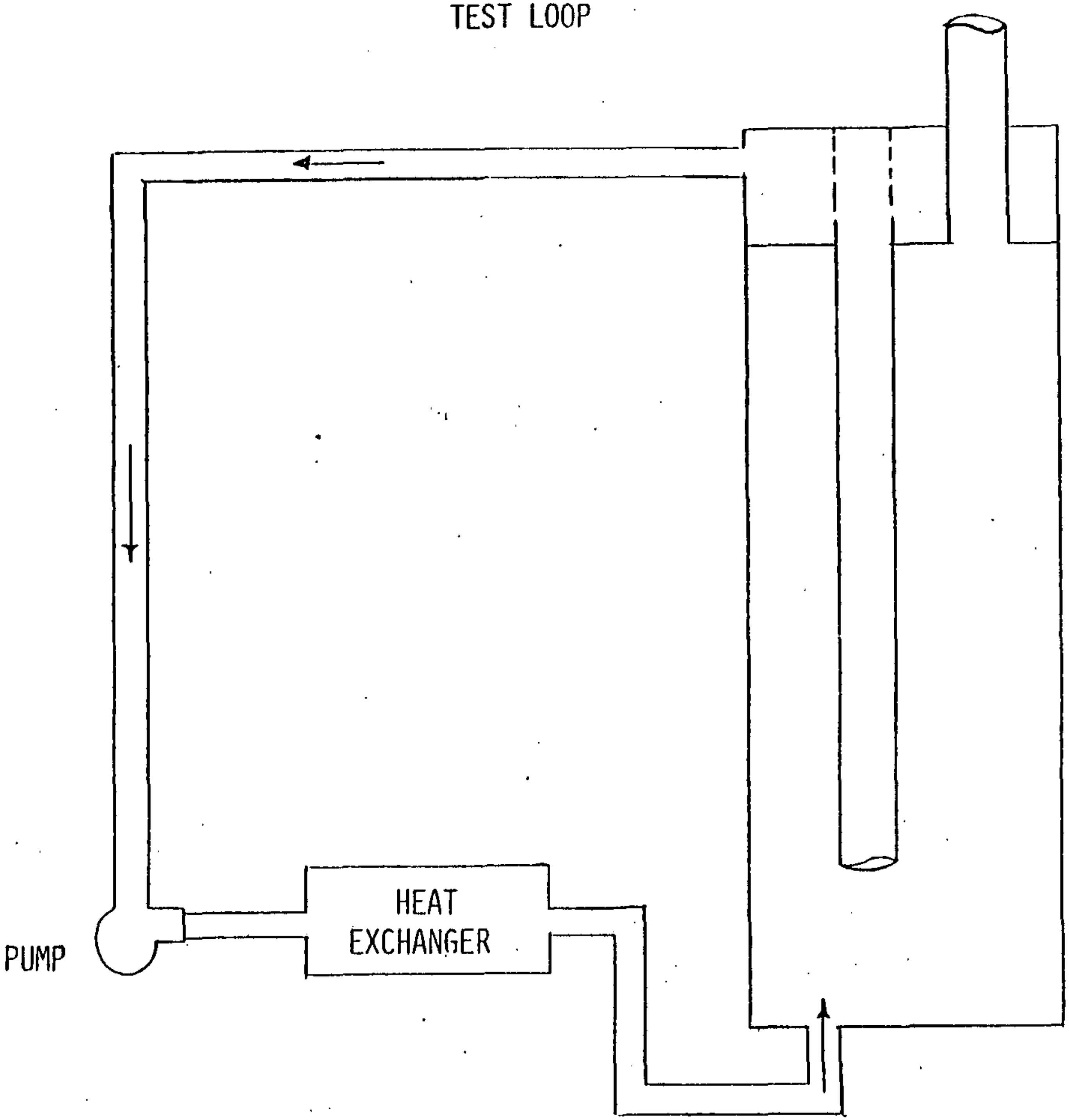


FIGURE 15

A-TANK NATURAL CONVECTION TEST AT 35 KW

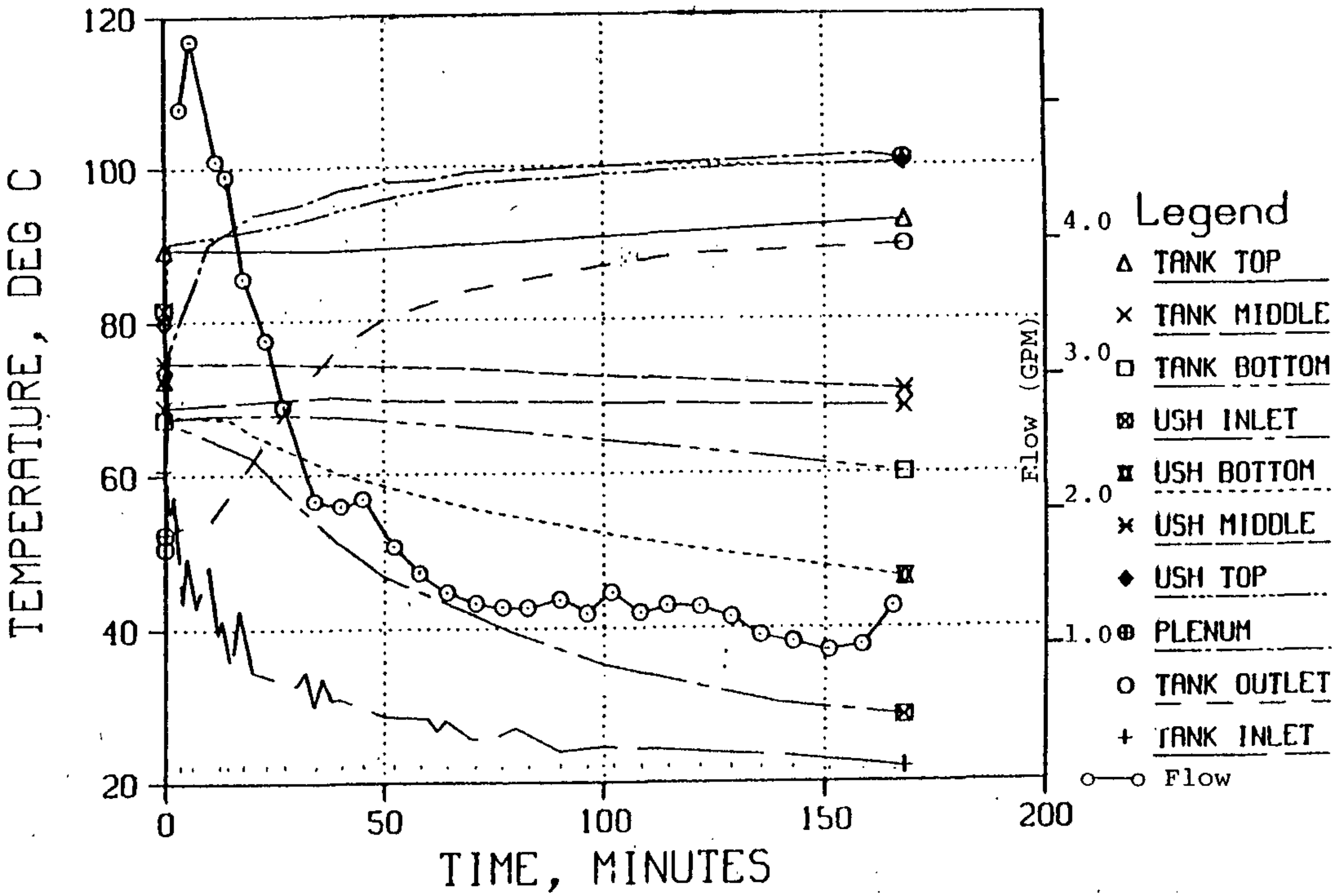


FIGURE 16

TWO PHASE NATURAL CONVECTION

BENCH SCALE REACTOR LOOP

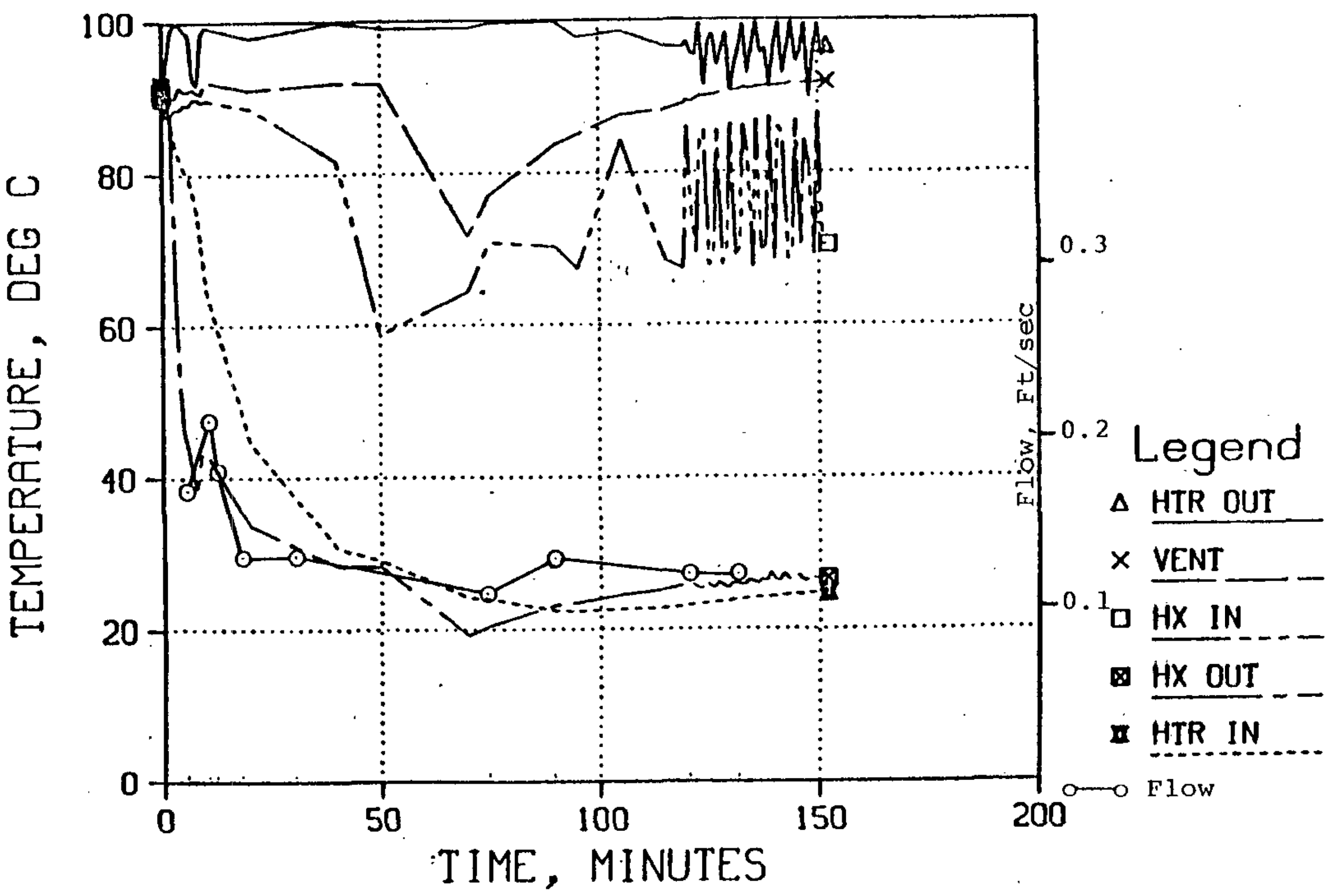


FIGURE 17

TWO PHASE NATURAL CONVECTION

BENCH SCALE REACTOR LOOP

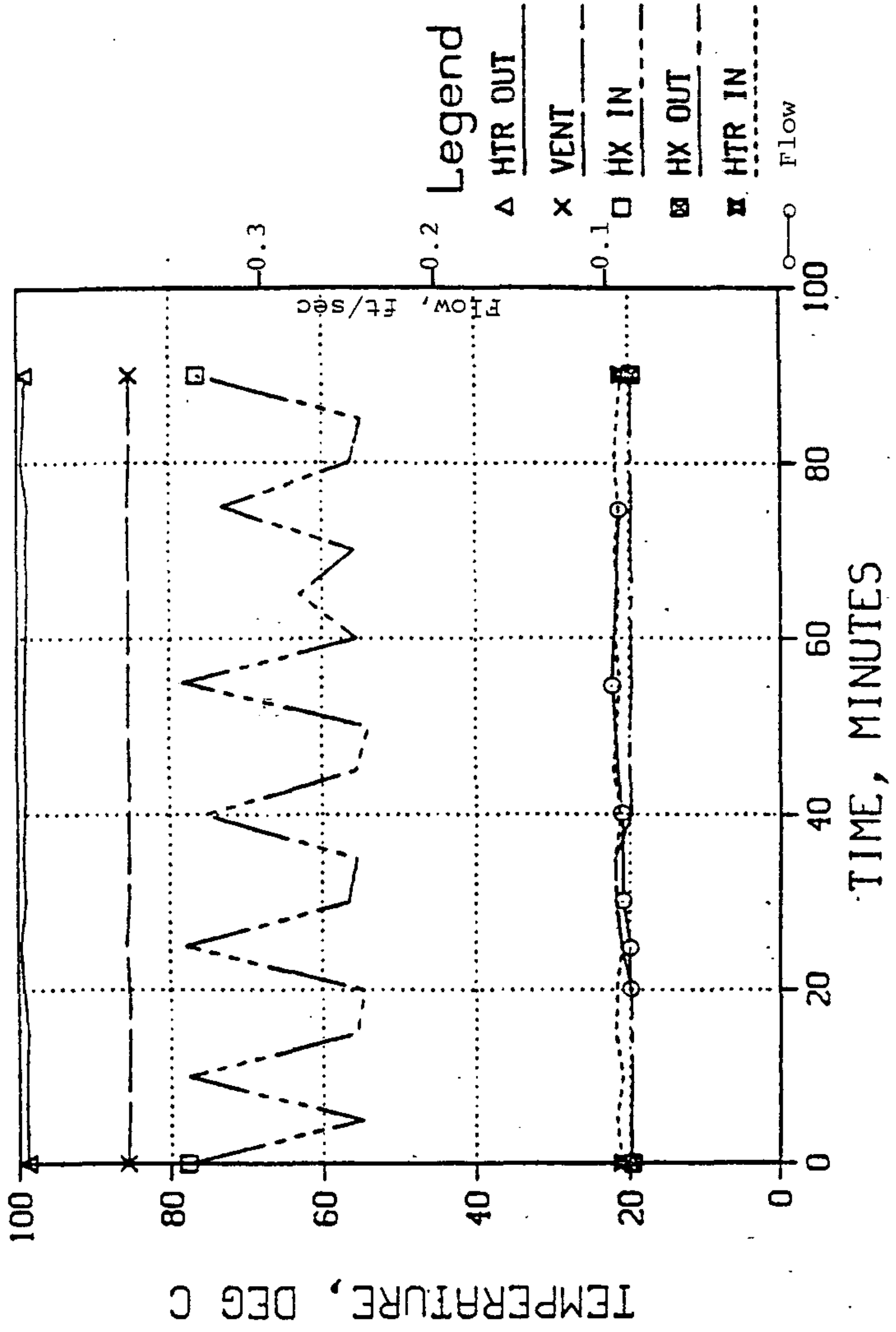


FIGURE 18

A-TANK NATURAL CONVECTION TEST
LOOP WITH CONDENSER

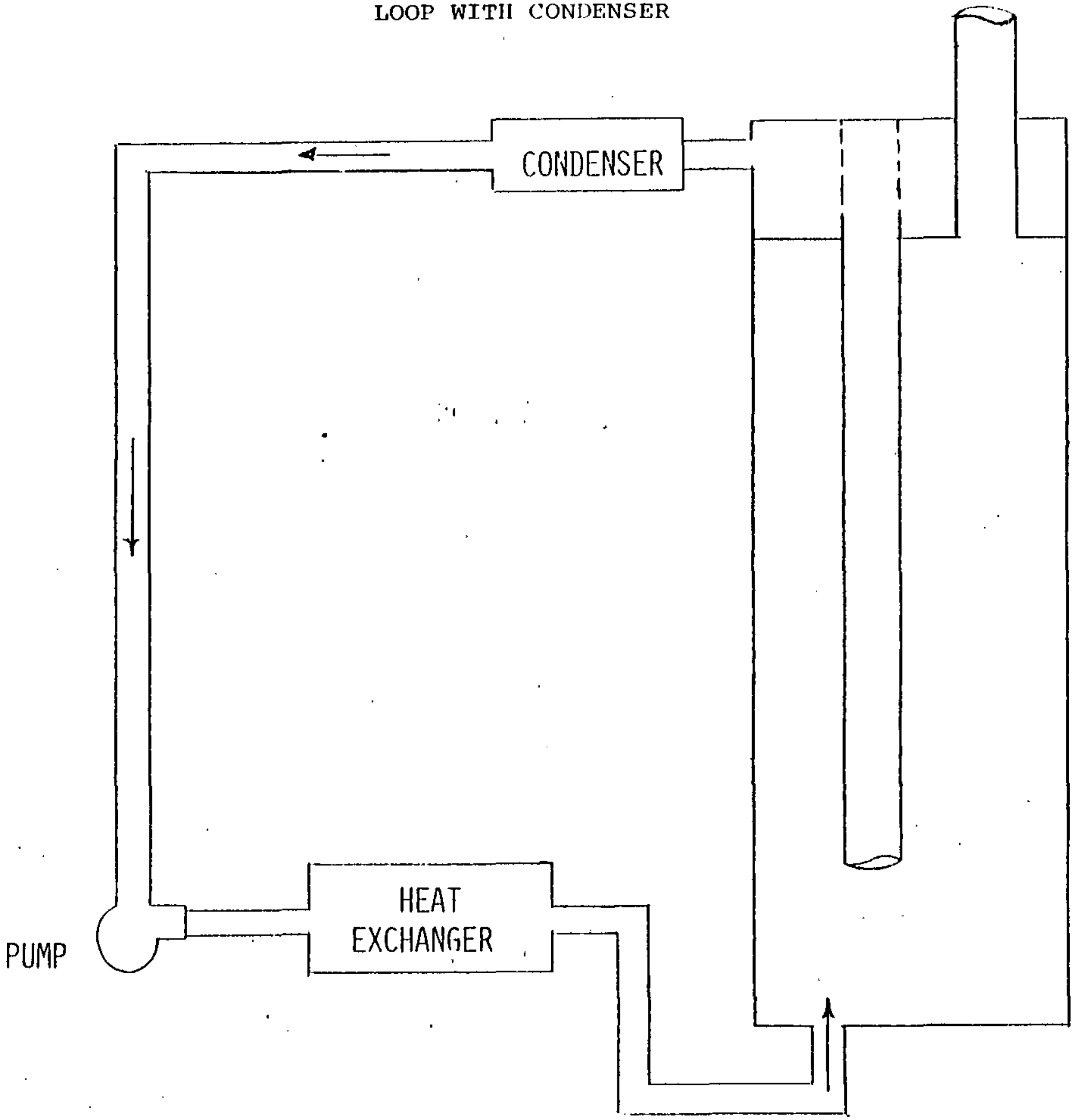
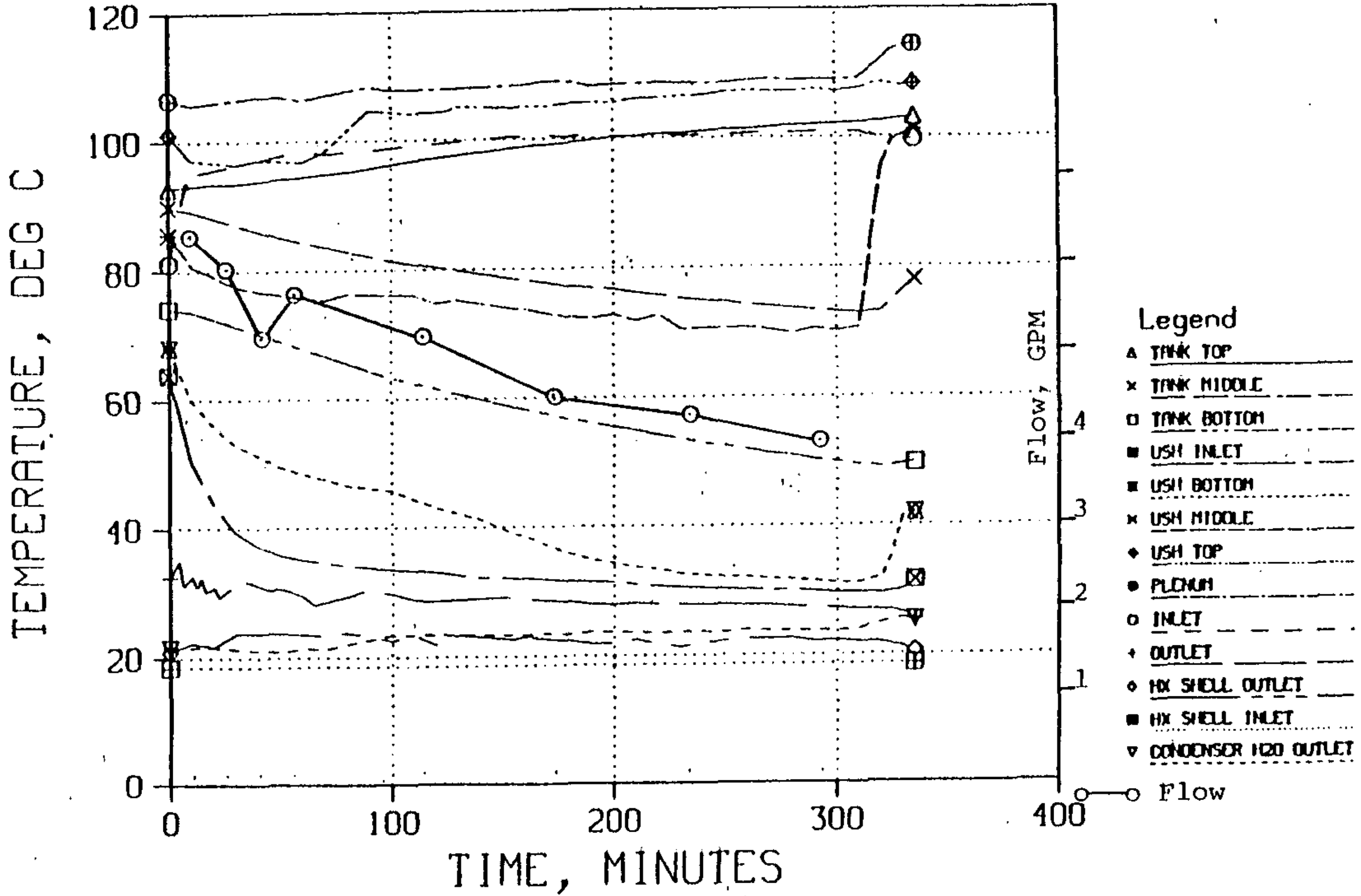


FIGURE 19

A-TANK NATURAL CONVECTION LOOP WITH CONDENSER AT 90 KW



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APPENDIX A

FIGURE 1n

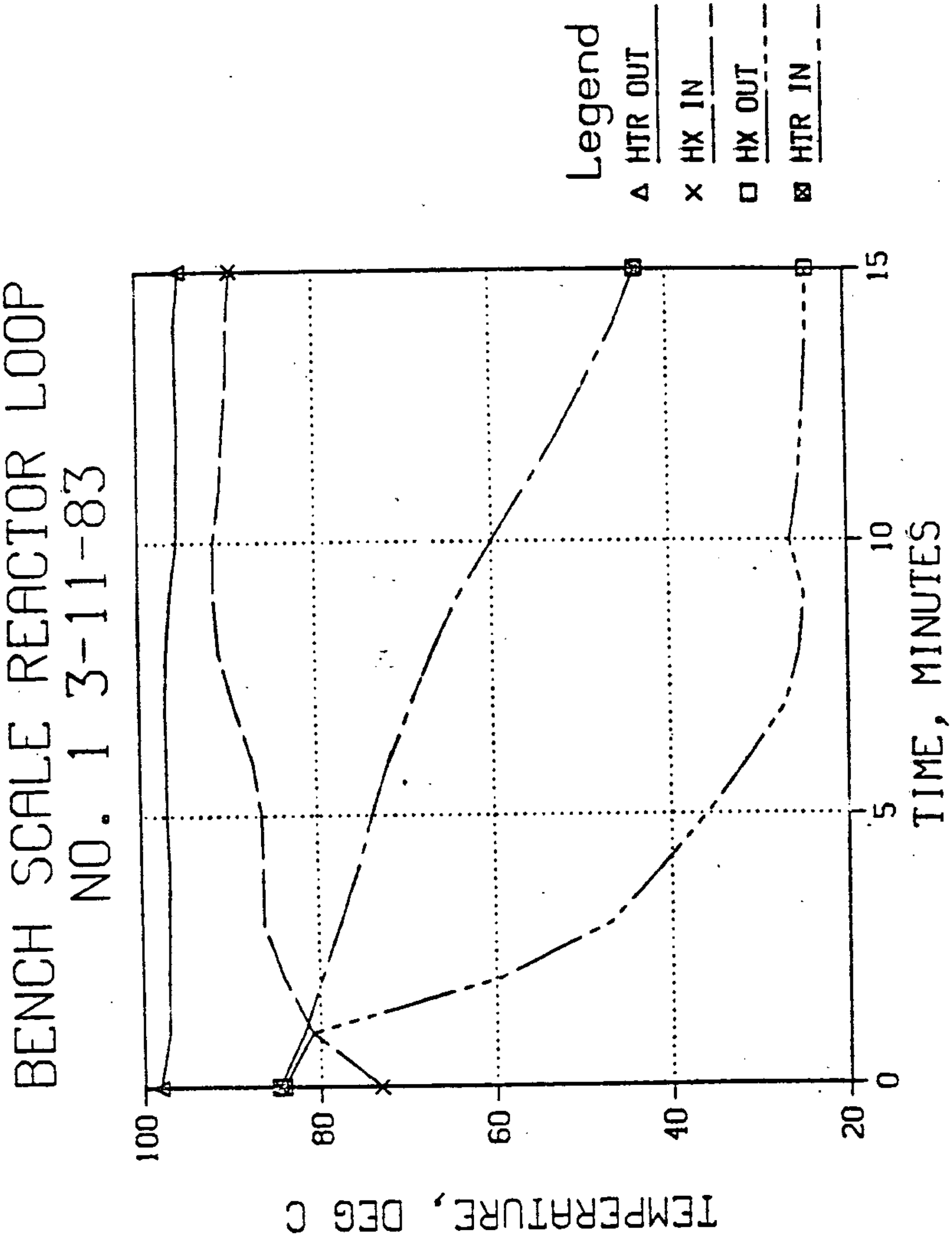

BENCH SCALE REACTOR LOOP
NO. 1 3-11-83
Legend
HTR OUT
HX IN
HX OUT
HTR IN
TEMPERATURE, DEG C
100
80
60
40
20
TIME, MINUTES
0
5
10
15

FIGURE 2a

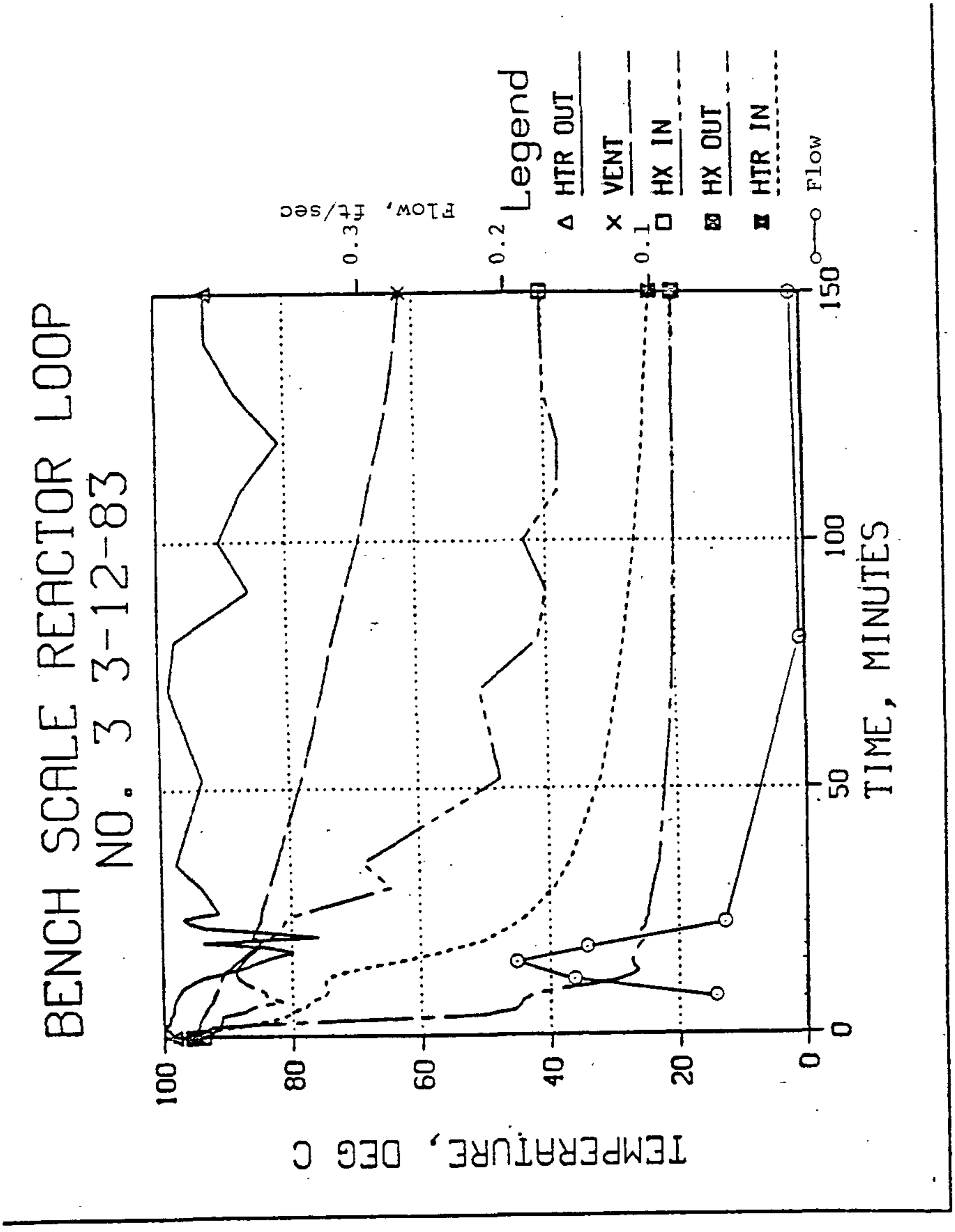

BENCH SCALE REACTOR LOOP
NO. 3 3-12-83
TEMPERATURE, DEG C
100
80
60
40
20
0
TIME, MINUTES
0
50
100
150
Flow, ft/sec
0.3
0.2
0.1
0
Legend
Δ HTR OUT
× VENT
□ HX IN
⊠ HX OUT
⧗ HTR IN
o—o Flow

FIGURE 3a

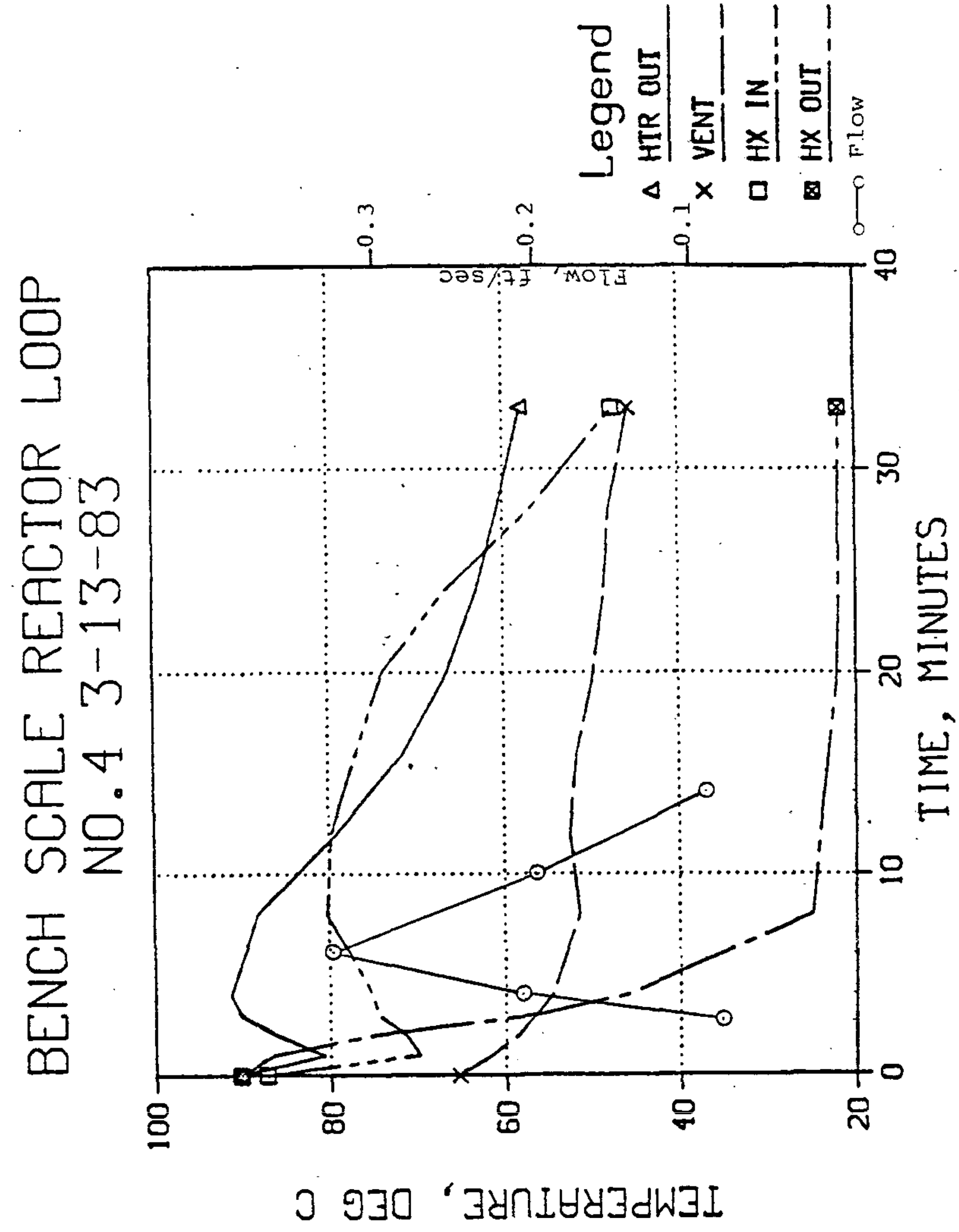

BENCH SCALE REACTOR LOOP
NO.4 3-13-83
TEMPERATURE, DEG C
100
80
60
40
20
TIME, MINUTES
0
10
20
30
40
Flow, ft/sec
0.3
0.2
0.1
Legend
HTR OUT
VENT
HX IN
HX OUT
Flow

FIGURE 4a

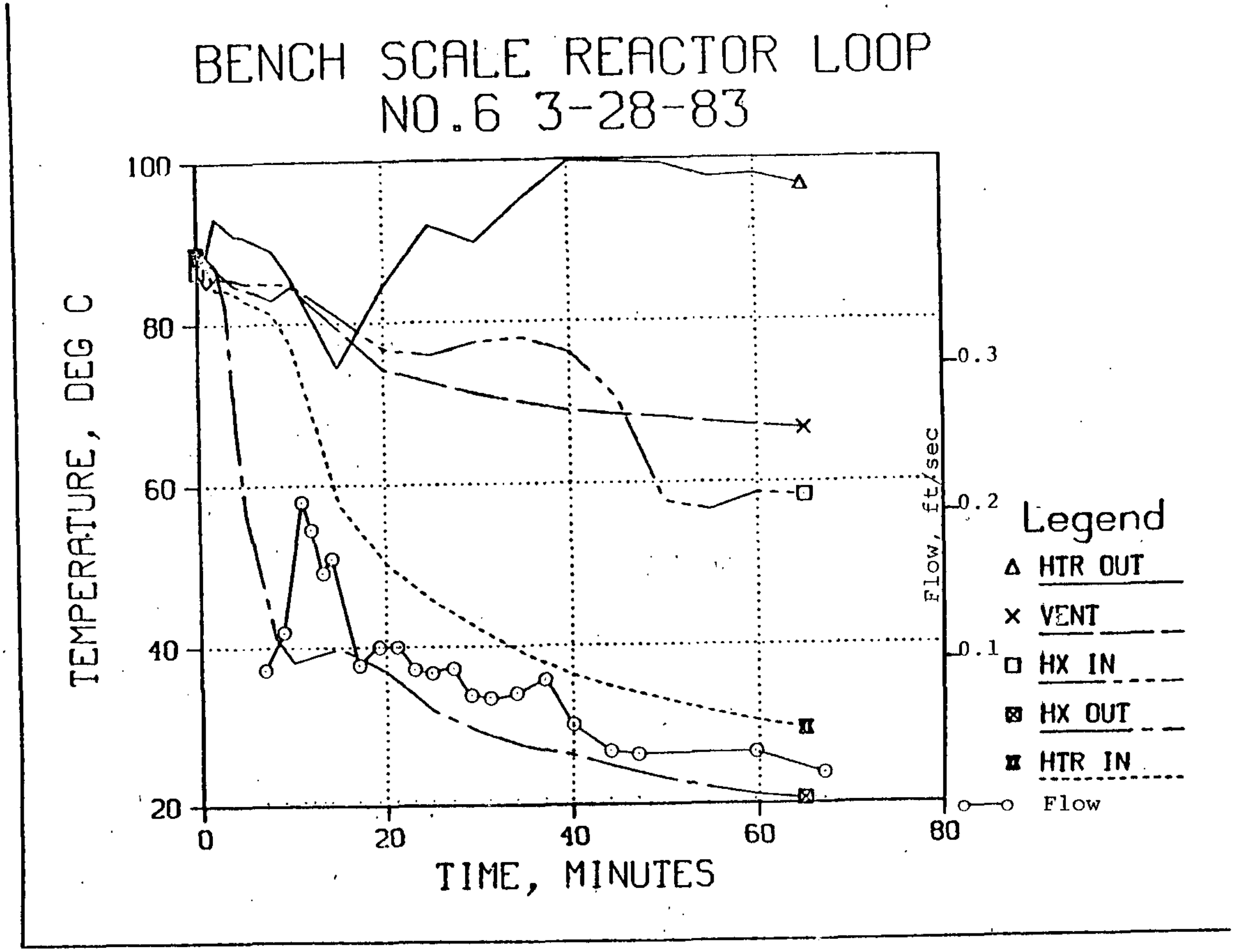

BENCH SCALE REACTOR LOOP
NO.6 3-28-83
TEMPERATURE, DEG C
100
80
60
40
20
0
20
40
60
80
TIME, MINUTES
Flow, ft/sec
0.3
0.2
0.1
Legend
△ HTR OUT
× VENT
□ HX IN
⊠ HX OUT
⧗ HTR IN
○—○ Flow

FIGURE 5a

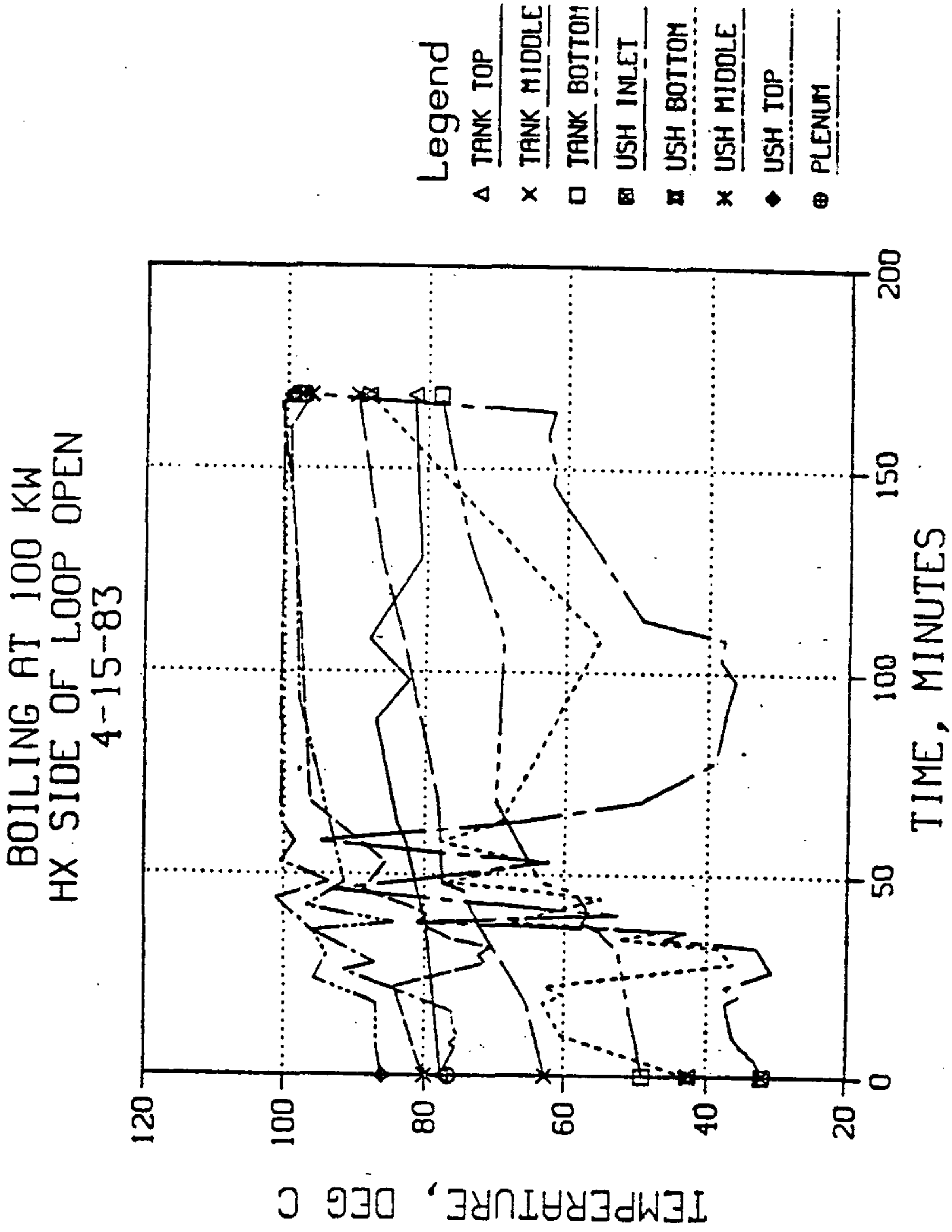

BOILING AT 100 KW
HX SIDE OF LOOP OPEN
4-15-83
Legend
△ TANK TOP
× TANK MIDDLE
□ TANK BOTTOM
⊠ USH INLET
⌧ USH BOTTOM
✱ USH MIDDLE
◆ USH TOP
⊕ PLENUM
TEMPERATURE, DEG C
120
100
80
60
40
20
TIME, MINUTES
0
50
100
150
200

FIGURE 6a

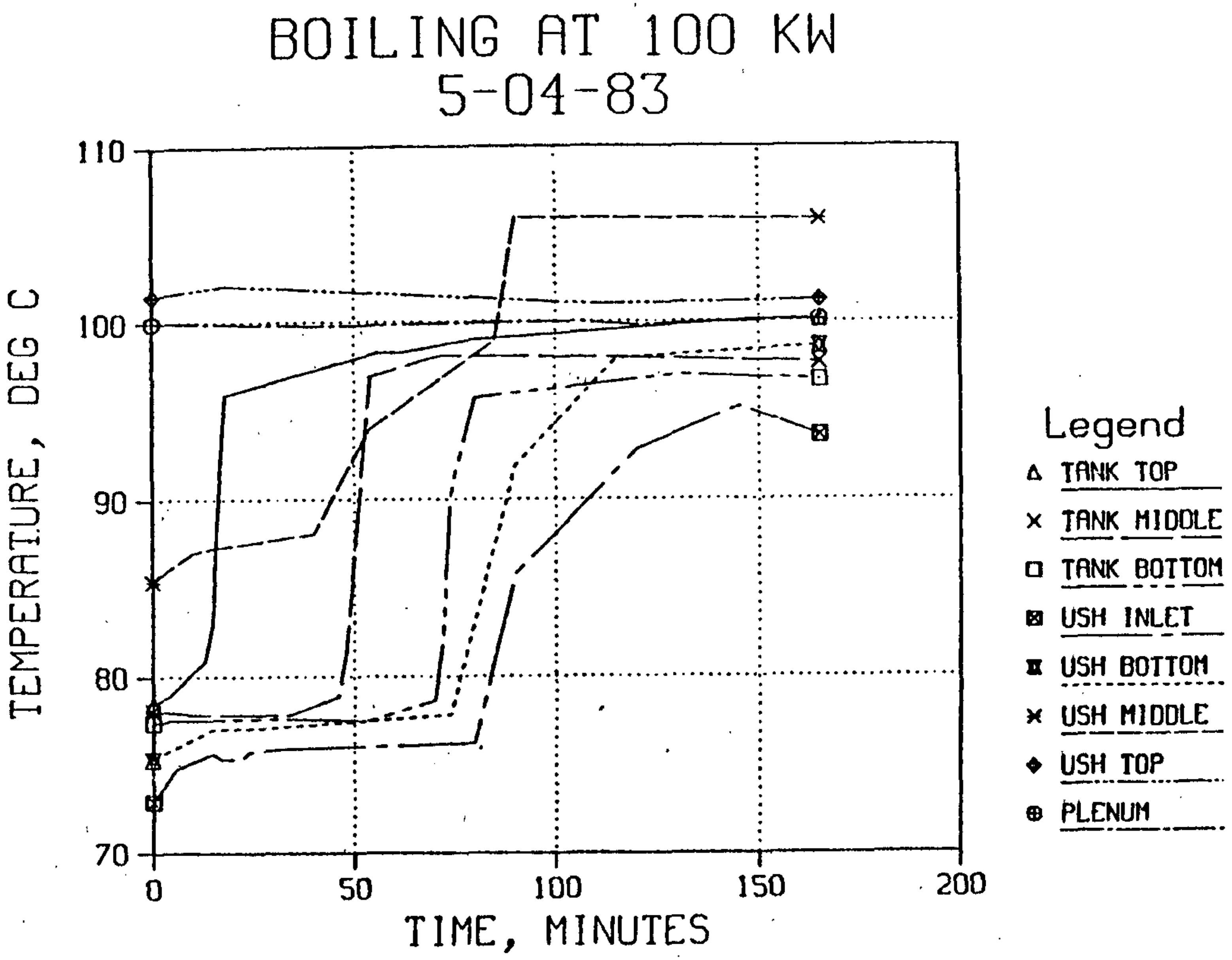

BOILING AT 100 KW
5-04-83
TEMPERATURE, DEG C
110
100
90
80
70
TIME, MINUTES
0
50
100
150
200
Legend
△ TANK TOP
× TANK MIDDLE
□ TANK BOTTOM
⊠ USH INLET
⧗ USH BOTTOM
✕ USH MIDDLE
◆ USH TOP
⊕ PLENUM

FIGURE 7a

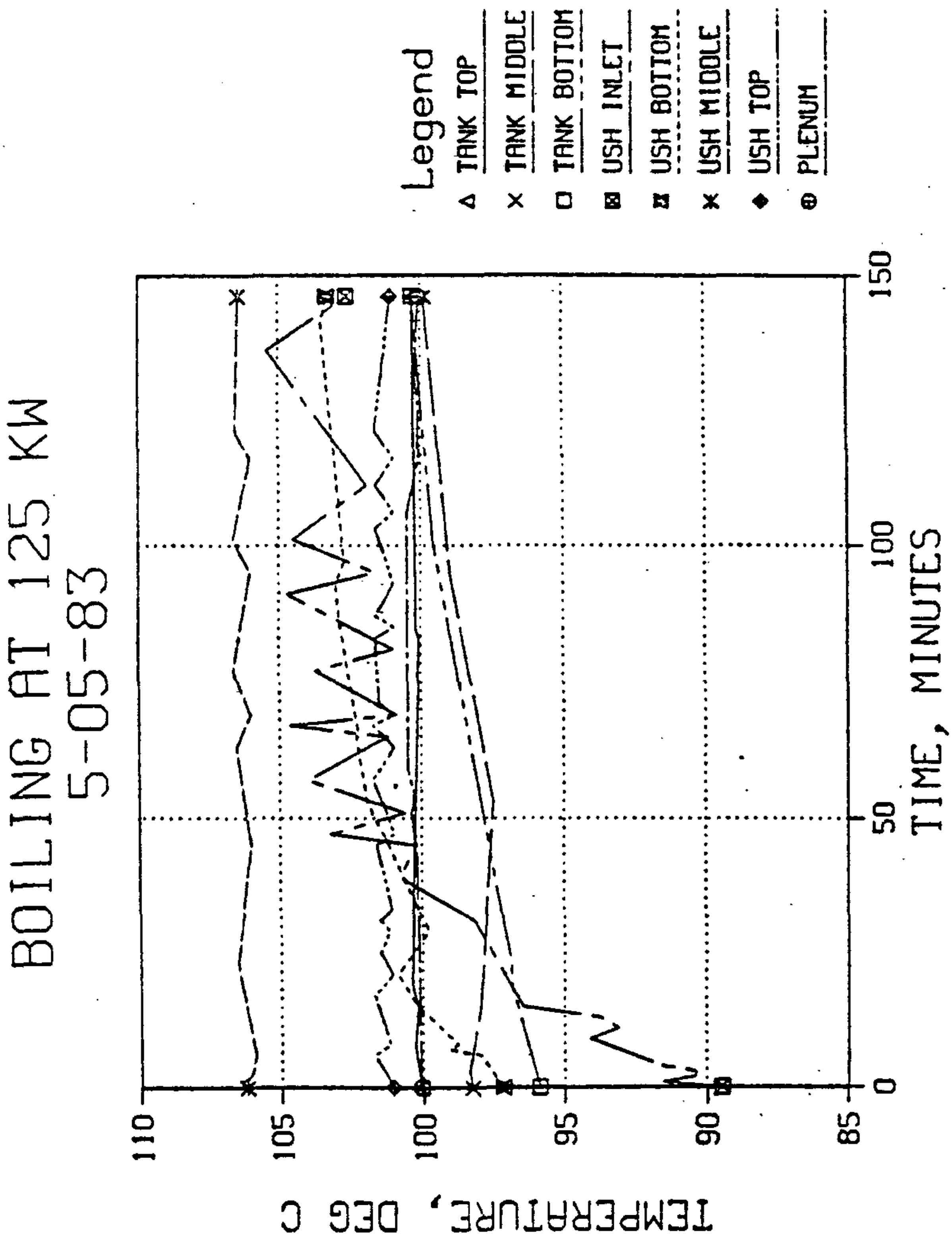

BOILING AT 125 KW
5-05-83
TEMPERATURE, DEG C
110
105
100
95
90
85
TIME, MINUTES
0
50
100
150
Legend
△ TANK TOP
× TANK MIDDLE
□ TANK BOTTOM
⊠ USH INLET
⧗ USH BOTTOM
✱ USH MIDDLE
◆ USH TOP
⊕ PLENUM

FIGURE 8a

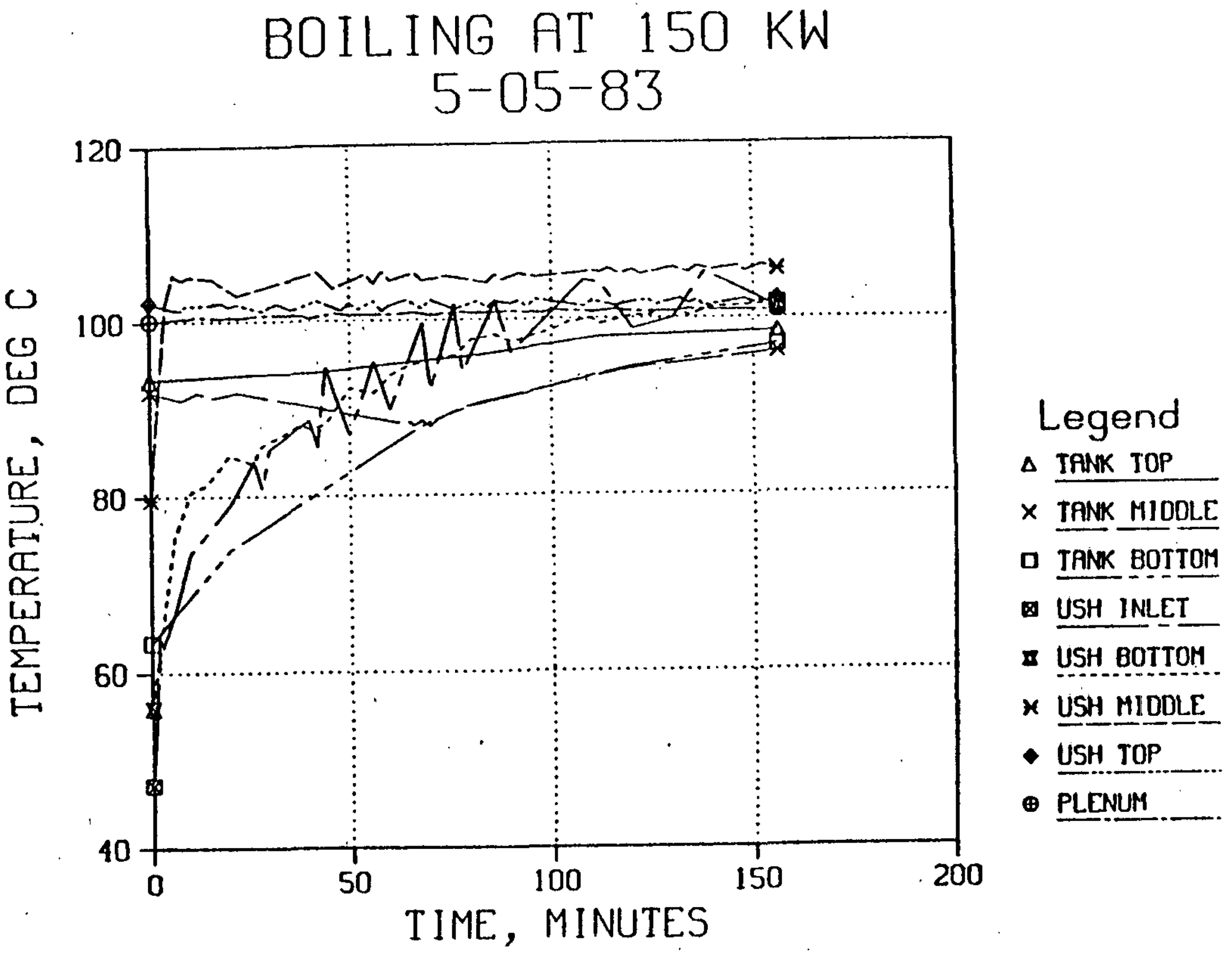
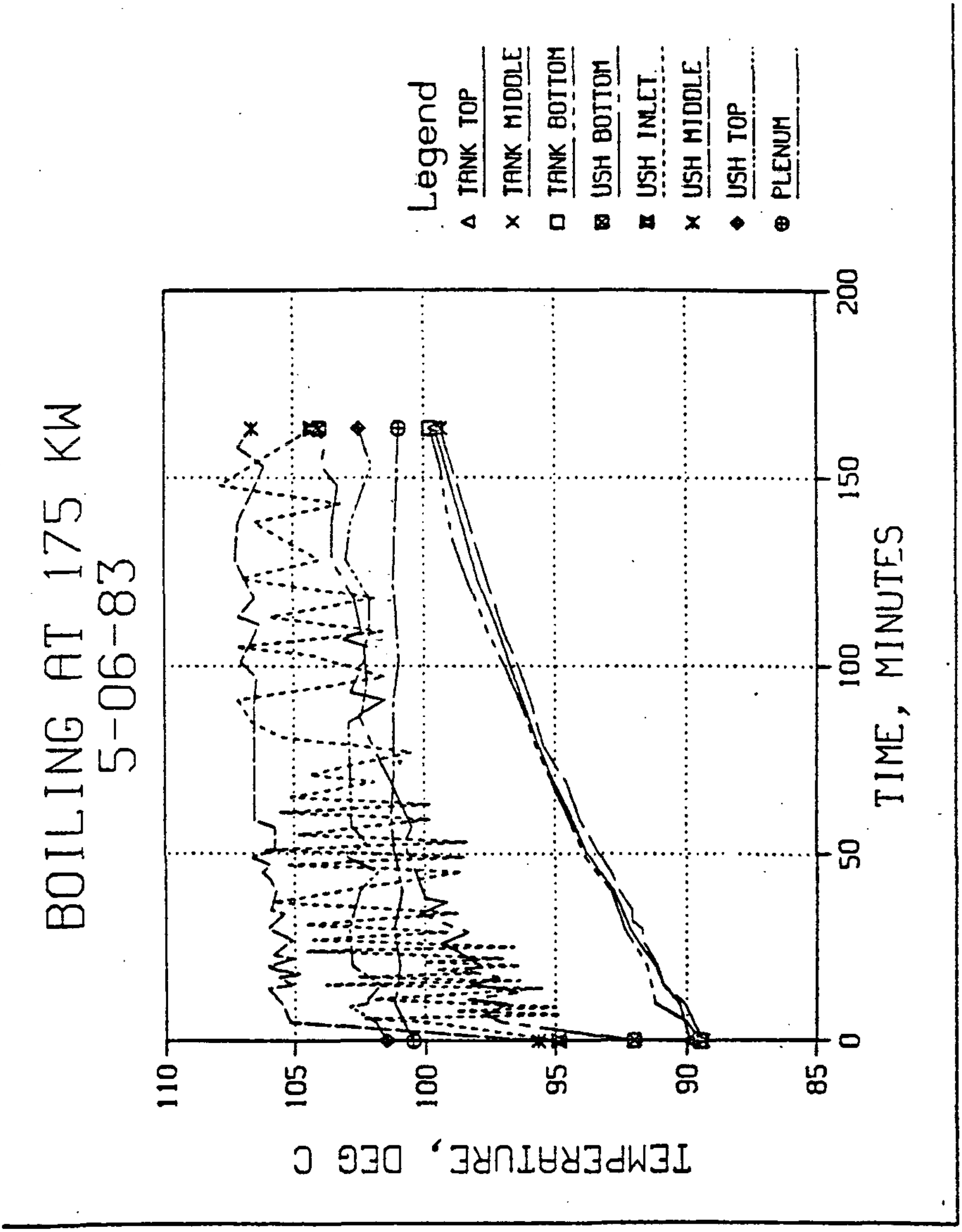

BOILING AT 150 KW
5-05-83
TEMPERATURE, DEG C
120
100
80
60
40
0
50
100
150
200
TIME, MINUTES
Legend
△ TANK TOP
× TANK MIDDLE
□ TANK BOTTOM
⊠ USH INLET
⌛ USH BOTTOM
✕ USH MIDDLE
◆ USH TOP
⊕ PLENUM

FIGURE 9a



BOILING AT 175 KW
5-06-83

FIGURE 10a

A-TANK NATURAL CONVECTION TEST AT 15 KW

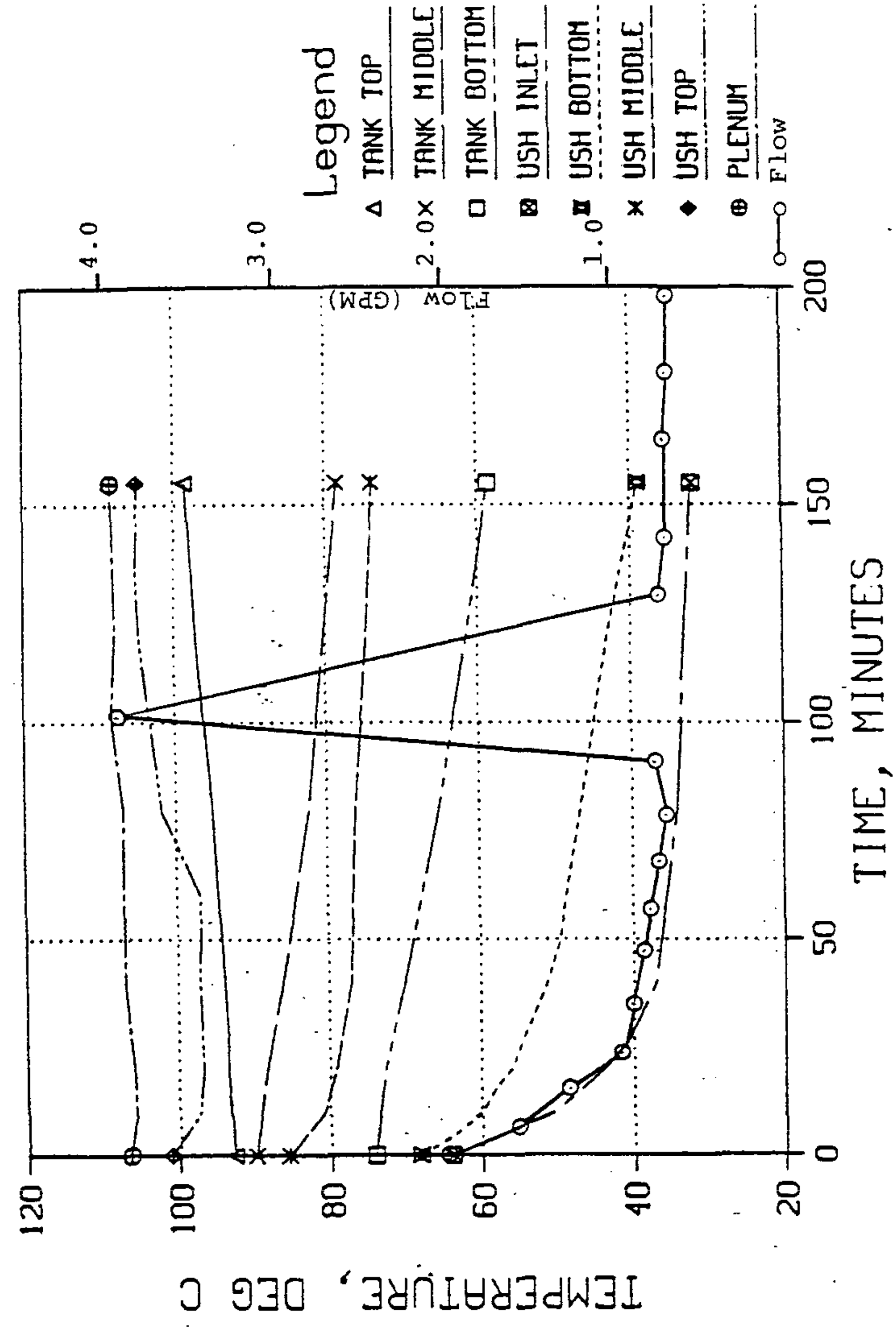


FIGURE 11a

A-TANK NATURAL CONVECTION TEST AT 25 KW

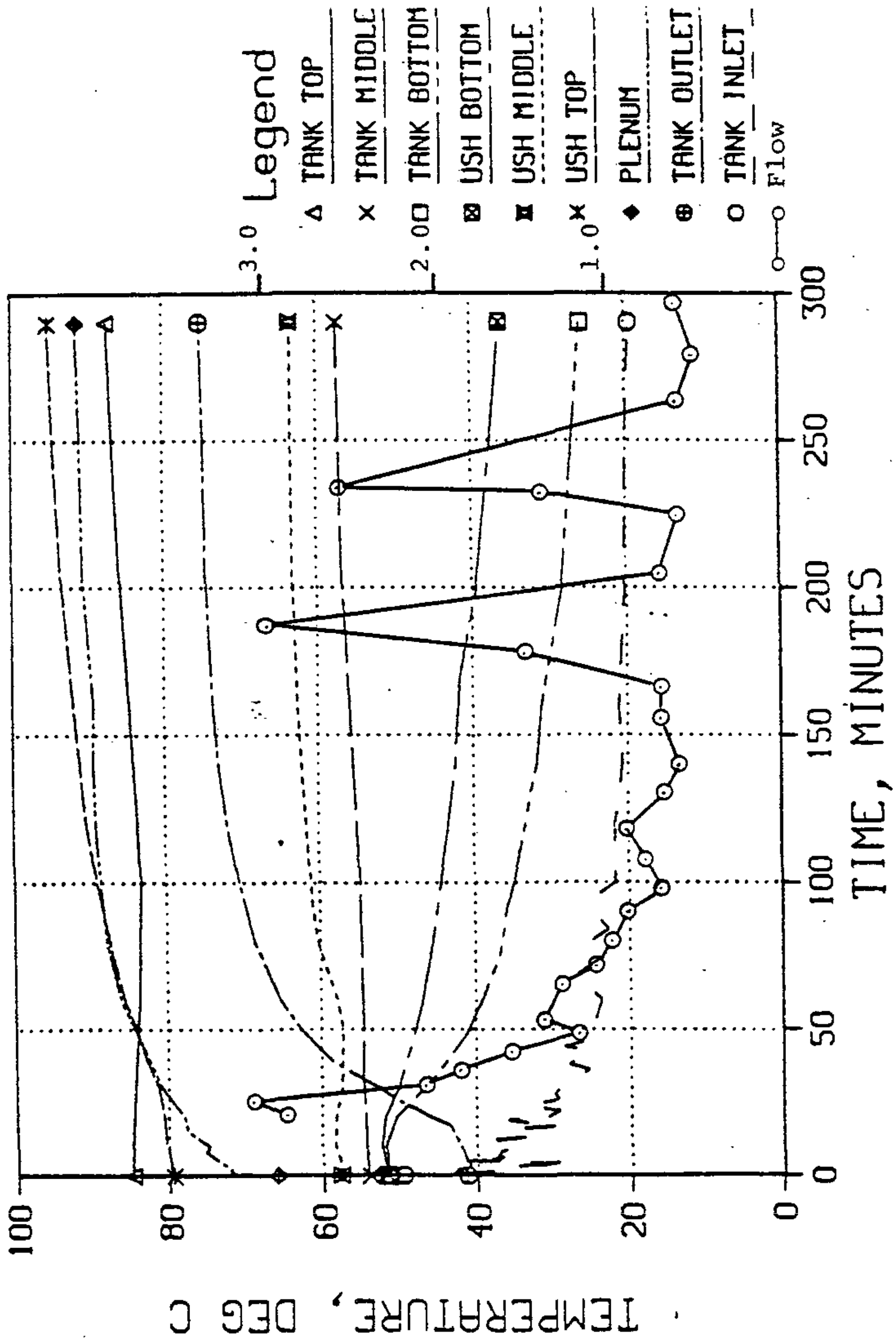


FIGURE 12a

A-TANK NATURAL CONVECTION TEST AT 30 KW

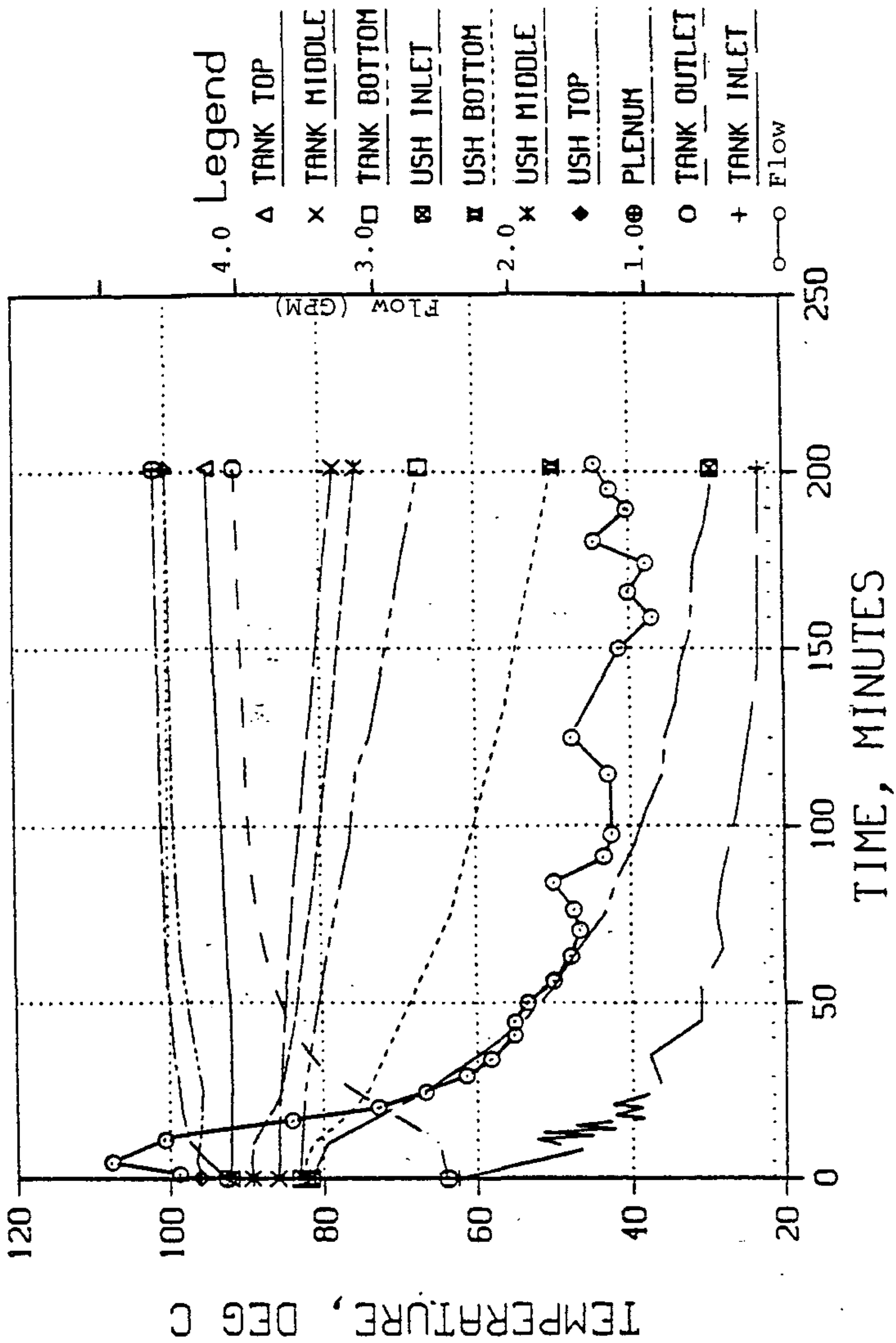


FIGURE 13a

A-TANK NATURAL CONVECTION LOOP WITH CONDENSER AT 40 KW

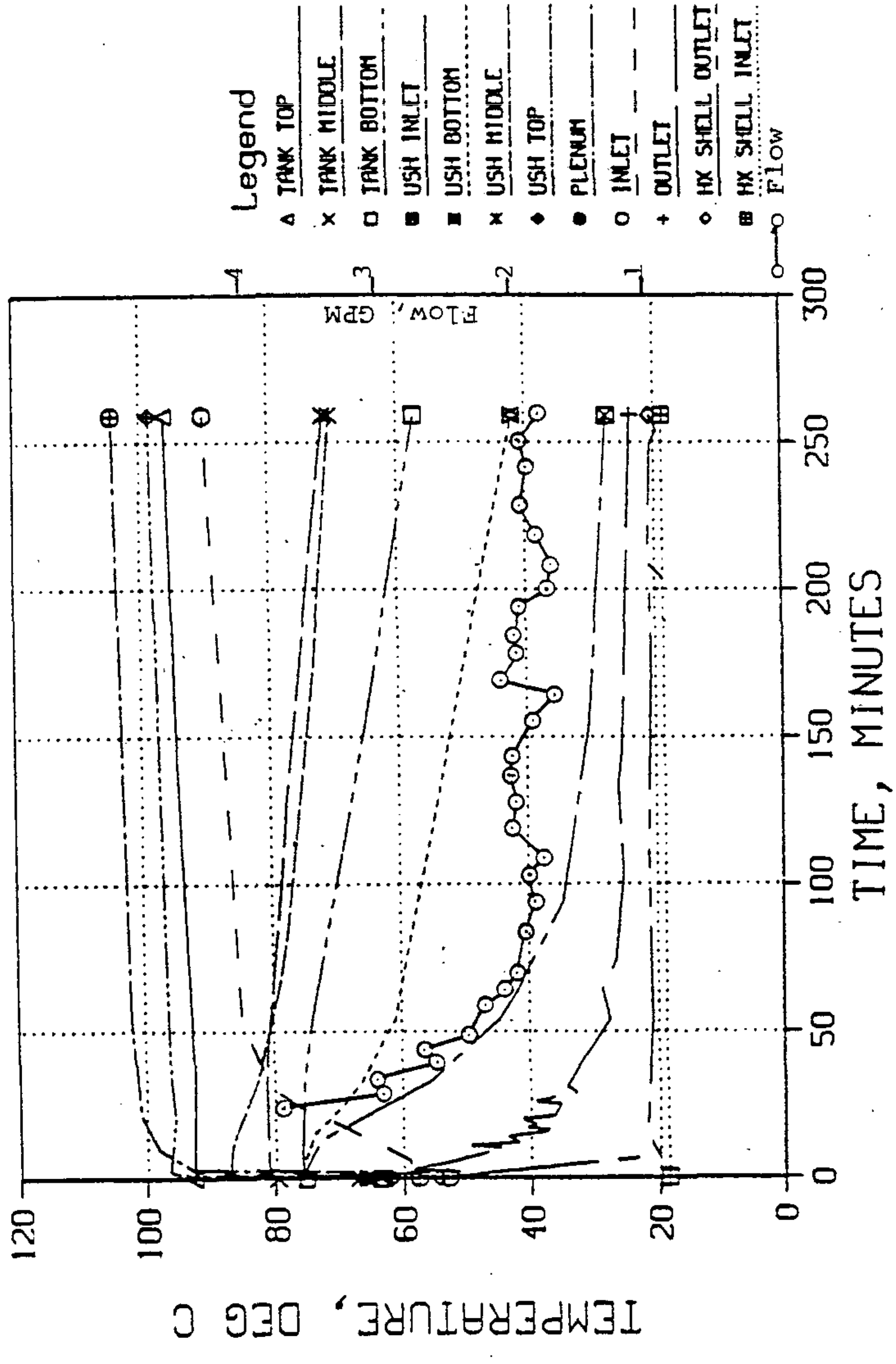


FIGURE 14a

A-TANK NATURAL CONVECTION LOOP WITH CONDENSER AT 50 KW

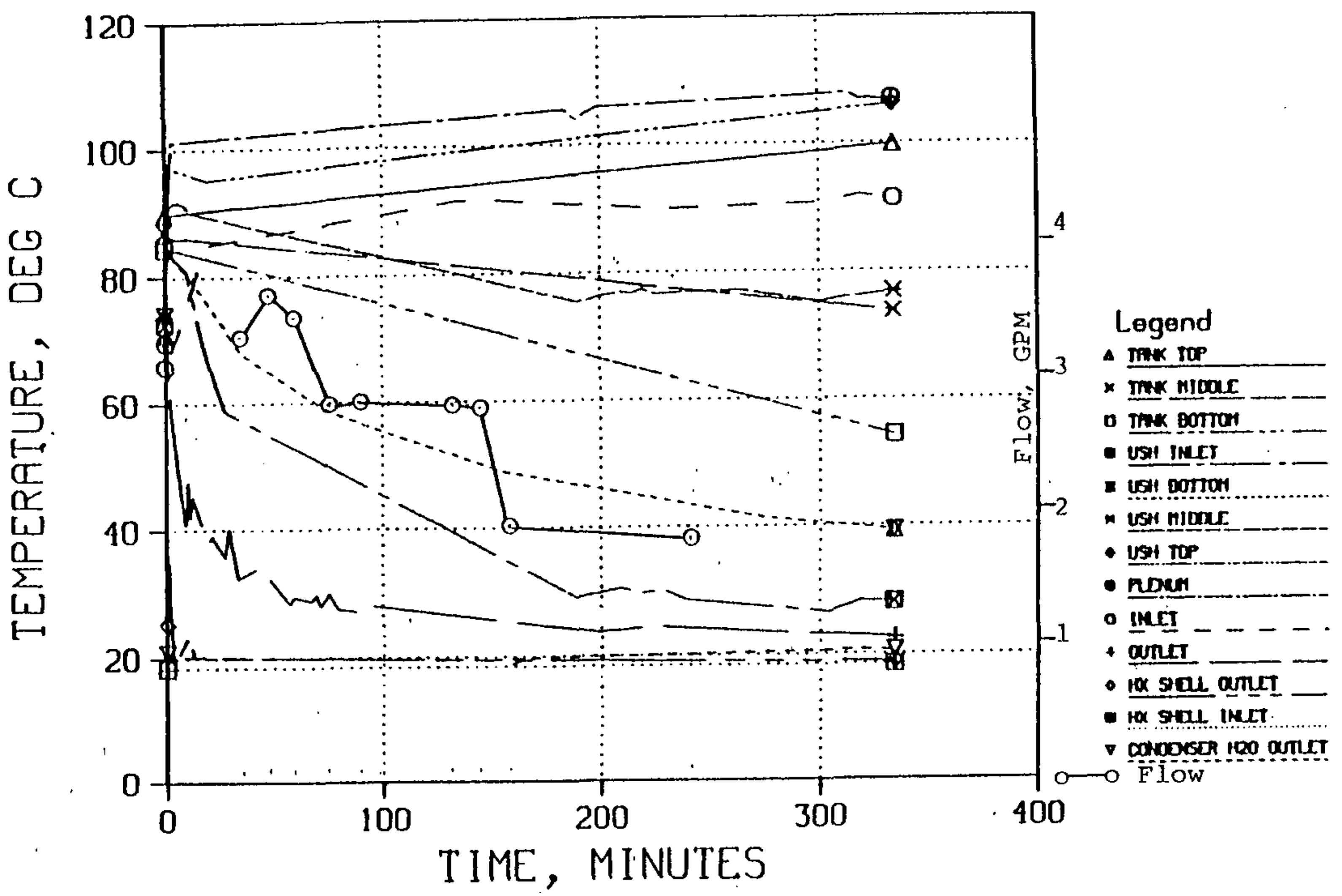
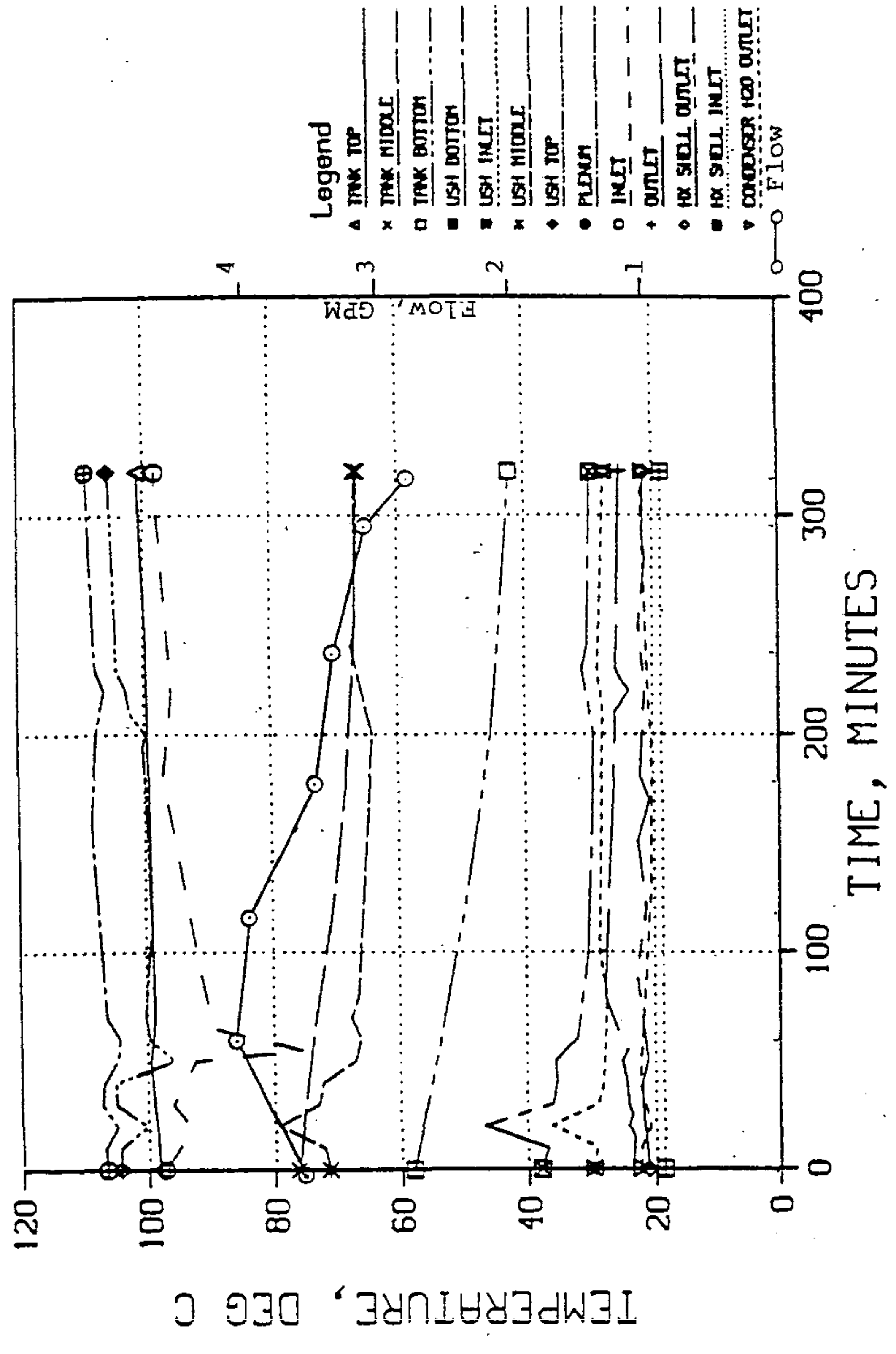


FIGURE 15a

A-TANK NATURAL CONVECTION LOOP WITH CONDENSER AT 75 KW



APPENDIX B

Boiling as a mechanism to cool SRP reactors has been shown to be very effective in laboratory tests. Mass transport of the generated steam from the plenum is a major limitation to the amounts of cooling that can be achieved. Only a small amount of steam pressure can be allowed in the plenum. The plenum can be vented only by removing USH plugs. Under normal shutdown conditions only one plenum plug at a time is removed.

The steam flow path from the plenum through the top of an assembly is shown in Figure 1b. Four resistances exist in the exit flow path; namely: 1) slots in the permanent sleeve, 2) annular space between USH and permanent sleeve, 3) holes in the top of the USH, and 4) the channel in the center of the USH. The slots in the permanent sleeve appeared to have the highest resistance to flow because they have the smallest cross sectional area of each of the flow restrictions. Calculations verified that the flow through the slots was indeed limiting, with choked flow expected to occur.

The equation shown below was used to calculate the flow rate as a function of pressure drop across each flow restriction.

$$G^2 = \frac{P_1\rho_1(0.5)(1 - (\rho/\rho_1)^2)}{\frac{0.25R}{C_p g_c}\left(\frac{\rho^2}{\rho_1^2} - 1\right) + \frac{R-2C_p}{2C_p g_c}\ln\left(\frac{\rho}{\rho_1}\right) + \frac{2fL}{D_{gc}}}$$

where:

G = mass flux
P = pressure
ρ = density
R = Gas Constant
C_p = Heat Capacity
L = length
D = diameter
f = friction factor
g_c = gravitational CONSTANT
Subscript 1 = inlet conditions

This equation assumes adiabatic flow, i.e., no heat exchange between the gas and its surroundings. The ideal gas assumption was made. This assumption was reasonable as the compressibility factor was determined to be $0.98 \leq Z \leq 1.00$.

Figure 2b shows a plot of the maximum mass flow rate of steam out of a vented USH from the plenum as a function of plenum pressure gauged to the process room. Assuming all decay heat goes to vaporize water and that decay heat is constant, the required number of USH plugs to be removed for a given reactor power can be determined.

Calculations show that for an average assembly decay power of 6 KW, removal of one plenum plug will be adequate for steam venting the reactor plenum. For an average assembly decay power of 20 KW, four plenum plugs must be removed. These calculations do not include conservatisms for safety consideration.

FIGURE 1b

STEAM FLOW PATH FOR PLENUM EXIT

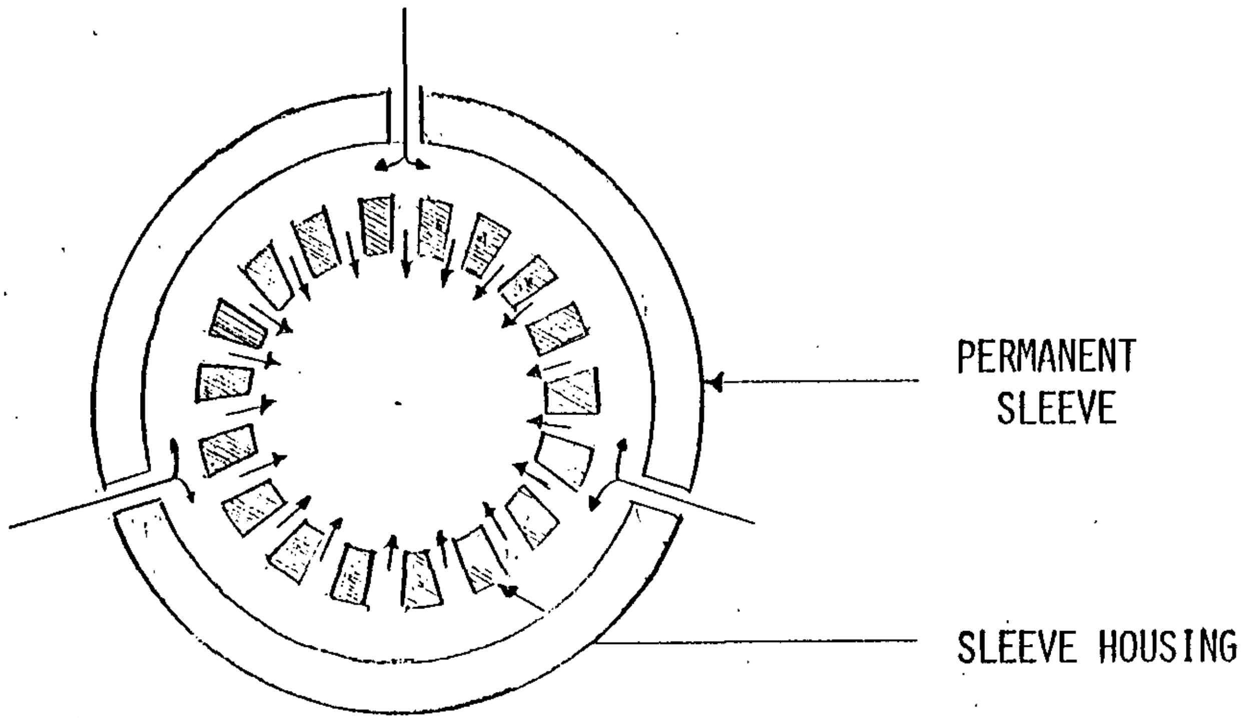


FIGURE 2b

Maximum Mass Flow Rate of Steam Out A Vented USH From The Plenum As a Function of Plenum Guage Pressure