CHAPTER 15

FLOW STABILITY IN THE CANDU PRIMARY HEAT TRANSPORT SYSTEM

P. Gulshani and N.J. Spinks

Atomic Energy of Canada Limited
CANDU Operations
Sheridan Park Research Community
Mississauga, Ontario L5K 1B2

ABSTRACT

Potential modes of flow oscillations in the CANDU figure-of-eight primary heat transport system (PHTS), under forced and natural circulation flow conditions are reviewed. The instability mechanism for each mode is explained. Experimental investigations of the oscillations and their findings are discussed. Thermohydraulic computer codes and simple algebraic models used to predict and explain the flow oscillations are described. Finally, the characteristics of the flow oscillations and means of suppressing them are pointed out.

15-1 INTRODUCTION

This chapter reviews potential modes of flow oscillations and their analysis in the CANDU figure-of-eight PHTS under forced and natural circulation flow conditions. Flow oscillations are undesirable in normal operation because they could cause control system response, and, if large enough, they could cause pressure setpoints to be periodically exceeded. They could also affect heat transfer reducing margin to dryout. To avoid them, it is necessary to understand the instability mechanism and know the conditions under which they exist.

In normal operation coolant flow around the loop is provided by the primary pumps. Under conditions which cause reactor trip and rundown of all primary pumps density differences between the cold and hot legs maintain coolant circulation around the loop. This natural convective flow at decay power levels is referred to as thermosyphoning.

Under normal operating conditions coolant boiling in each core pass, and the extent of void, are limited by design. In abnormal conditions, however, boiling and void formation can be large. Such a change of phase can occur due to heat addition in the core, and to pressure reduction (i.e., flashing) downstream of the core.

Flow oscillations are possible in both forced and thermosyphoning flow with voids in the PHTS. Because of fluid flow non-linearities, otherwise divergent flow oscillations are bounded (i.e., attain a limit cycle). Typically the amplitude of an oscillation is limited by the disappearance of void in some part of the system at some time during the cycle.

The basic cause of the flow oscillations is the response of the density in the two-phase region to changes in the upstream flow. The density response in turn affects the pressure, the pressure drop and the gravity head in the two-phase region. Depending on the thermohydraulic conditions, one or more of these effects dominates.

Three potential modes of flow oscillations, called parallel channel, pass-to-pass and system in-phase, have been identified in CANDU PHTS and are the subject of this chapter. These modes have been investigated experimentally and analytically.

Two analytical approaches have been used: numerical and algebraic solution of the conservation equations. The transient thermohydraulics codes in use solve the one-dimensional, time-dependent mixture conservation equations for the entire system using a finite difference numerical scheme. As is normal for such schemes, calculations must be space and time converged. However, in the study of flow oscillations, the requirements for spatial convergence are particularly demanding. This is because, with a coarse mesh, numerical diffusion attenuates signals emerging from a node and can therefore suppress a potential oscillation. Also, with a coarse mesh, numerical noise (such as pressure spikes associated with filling a steam-filled node) can sometimes excite a latent oscillation.

The advantage of using the computer codes in analyzing flow oscillations is their generality. Non-linear effects, which are responsible for limit cycle oscillations are, for instance, included. The code generality, however, makes it difficult to identify the important system parameters and dynamics which underlie the flow oscillations. To study the instability mechanism, linear algebraic models have been constructed. The models are based on linearization of the conservation equations about a given steady state. Because of the linearization, the models cannot, however, predict limit cycle amplitudes.

In the following sections each mode of flow oscillation is examined in detail under forced-flow and thermosyphoning conditions. The mode and the instability mechanism are first described. Then experimental evidence for the oscillation is presented. Computer codes and simple algebraic models and their predictions are discussed. Finally, characteristics of the flow oscillation and regions of instability are presented.

15-2 PASS-TO-PASS FLOW OSCILLATIONS - NORMAL OPERATING CONDITION

15-2.1 Description

With core boiling and the resulting desity change, the potential for pass-to-pass flow oscillations exists. In this mode the variation in the subcooled coolant flow rate in one pass is 180^{o} out-of-phase with that in the other pass (Figure 1) as are the pressure and quality (or void) variations in the two boiling regions.

The oscillations arise from the response of the pressure in the boiling region to a variation in the single-phase flow:

Normally with boiling, the steam volumes at each end of the reactor are equal. A small increase in the quantity of steam at one end, with a corresponding decrease at the other end, is accompanied by a corresponding difference in pressure. The pressure difference causes a difference in the flows in the two passes: the pass upstream of the end at high pressure sees reduced flow causing even more steam to accumulate at this end; the other pass, on the other hand, sees increased flow, causing even less steam to accumulate at the other end. This is the cause of the instability. The effect is analogous to a spring with a negative spring constant.

The steam accumulation is maximized if the quality at the steam generator oscillates out-of-phase with the quality at the core. This occurs if the oscillations have a half period equal to the boiling region transit time. Thus, the oscillation frequency is determined.

A significant restoring force analogous to that of a spring with a positive spring constant also exists: reduction of the flow in a pass results in reduced mass and, hence, pressure in the downstream boiling region. Similarily, increased flow in the other pass causes increased pressure due to increased mass in the boiling region downstream of that pass. This pressure difference between the two boiling regions is the restoring force.

Because of the restoring and damping forces, the flow may not be unstable.

If unstable, the oscillations grow to a limit cycle characterized by collapse of steam alternately in each boiling region (Figure 2). Figure 3 illustrates the sequence of PHTS void distribution in a half cycle of a limit-cycle oscillation.

15-2.2 Experimental Observation

Pass-to-pass flow oscillations were observed in a forced flow test in the scaled-down figure-of-eight loop facility, called RD-12, at Whiteshell Nuclear Research Establishment (WNRE) (Barclay et al, 1980). This loop, shown schematically in Figure 4, consists of one-or-two-per-pass horizontal electrically heated test sections connected to headers, pumps and steam generators as in CANDU. In the test, forced flow subcooled initial loop conditions were first established. The loop was then depressurized by bleeding steam from the pressurizer until pass-to-pass flow oscillations were observed (Figure 5).

Prediction of pass-to-pass flow oscillations in CANDU PHTS at normal operating conditions was verified in a commissioning test in the Point Lepreau-I plant (600 MW(e) nuclear generating station) (Garland, 1984). System pressure was reduced from the nominal value by bleeding steam at the pressurizer to induce boiling. Growing pass-to-pass flow oscillations, shown in Figure 6, were observed from the onset of void in the reactor outlet headers (ROH's). The oscillations were terminated by turning on the pressurizer heater thereby raising the system pressure.

In the Point Lepreau test the pipe connecting the ROH's was isolated. This pipe was designed to damp out potential pass-to-pass oscillations (Garland 1984). Indeed, in a companion test in the identical Gentilly-2 station, the flow oscillations were not observed when the pipe connecting ROH's was in service (Figure 6).

15-2.3 Models of Pass-to-Pass Flow Oscillations

The flow oscillations have been extensively analyzed using transient thermohydraulic computer codes and simple linearized algebraic models.

15-2.3.1 Computer Codes

Starting from a steady state boiling condition, the system response to a small asymmetric perturbation (for example, a short steam bleed from the pressurizer) is examined. The resulting oscillations are examined for degree of divergence (as expressed by damping ratio defined in terms of the ratio of consecutive amplitudes).

The validity of the code was verified by its ability to predict the observed flow oscillation characteristics (i.e., oscillation threshold thermohdraulic conditions, damping ratio and oscillation period) in Point Lepreau-I and Gentilly-2 nuclear generating stations.

15-2.3.2 Linear Algebraic Models

Algebraic models have been constructed (Hinds, 1982; Gulshani 1983; Ardron 1983; Khan 1984) to explain the instability mechanism and predict pass-to-pass flow oscillation. The model of Gulshani (1983) solves system conservation equations in closed form by linearizing them about a given steady-state condition. This condition is defined by the values of the core power $\dot{Q}$, the primary pressure P_o and the core inlet subcooled enthalpy h_s or equivalently the secondary side temperature T_{sec}. For simplicity the core and steam generator is represented by a point source and sink respectively as shown in Figure 7.

A detailed derivation of the model flow characteristic equation is given elsewhere (Gulshani, 1983). Briefly, the equation is derived by solving the momentum equation to calculate the response in pressure drop to flow change in the subcooled regions. The mass and energy equations are also solved to calculate the difference in pressures in the boiling regions resulting from the flow change. This pressure difference is then equated to the response in the single-phase pressure drop.

The result is the flow characteristic equation in the Laplace variable:

$$s^2 + 2\,\nu.s + \mu - \lambda.(1 - e^{-s\tau}) = 0 \qquad (1)$$

where the real and imaginary parts of the complex Laplace parameter s ($\equiv \sigma + j\omega$) are respectively the divergence parameter and oscillation frequency. The positive parameter ν is proportional to the single-phase friction coefficient and includes the pump term. τ is the fluid transit time in the boiling region. The parameters μ and λ have the following definitions:

$$\mu \equiv \frac{4A}{V.\ell} \left(\frac{\partial P_o}{\partial \rho_o} \right)_{h_o} > 0$$

$$\lambda \equiv \frac{2A.\dot{q}}{V.\ \ell.W_o} \left(\frac{\partial P_o}{\partial h_o} \right)_{\rho_o} > 0$$

where A is an average cross-sectional area in the single-phase region, V is the volume of the boiling region and $\dot{q}$ and W_o are respectively the power and mass flow rate per pass. The pressure P_o in the boiling region is taken to be a function of density ρ_o and enthalpy h_o. The subscript "o" denotes a steady-state condition.

The μ and λ terms represent respectively the difference in the boiling region pressures due to mass and enthalpy changes in these regions. The first part of the λ term represents the core outlet enthalpy change and the second part ($\lambda\ e^{-s\tau}$) represents that at the steam generator.

The quantity μ is positive and so the mass term gives a negative response. The quantity λ is also positive and so the first part of the λ term gives a positive response, whereas the second part gives a response whose sign depends on the frequency of the oscillation. For a sinusoidal flow change ($s=j\ \omega$) the total enthalpy term is never negative. This term will be seen below to be destabilizing.

If changes in the subcooled region pressure drop, i.e., the term $s^2 + 2\ \nu.s$, are assumed negligible, equation (1) reduces to:

$$a - 1 + e^{-s\tau} = 0 \qquad (2)$$

where $a \equiv \mu/\lambda$.

The characteristic equation (2) is readily solved for σ and ω. One finds:

$$\omega.\tau = n.\Pi \qquad \text{and } \sigma = -\frac{1}{\tau} \ln |1-a| \qquad (3)$$

where n is an even integer (including zero) if a > 1 and an odd integer if a > 1. (The system is seen to be most unstable at a = 1. The singularity of equation 3 at a = 1 reflects the omission of the stabilizing terms of equation 1.)

For divergent flow oscillations σ must be positive and, hence, a < 2 or μ < 2λ. Therefore, the mass and enthalpy terms μ and λ in equation (2) are respectively stabilizing and destabilizing.

From the definition of μ and λ, the instability criterion a < 2 becomes:

$$(h_f - h_s) > \frac{h_{fg} \cdot \upsilon_f}{\upsilon_{fg}} \qquad (4)$$

where h_s is core inlet subcooled enthalpy and the remaining quantities have their usual meanings. At the threshold of divergent oscillation (i.e., for σ = 0 or a = 2) the period of the dominant mode is 2τ.

The physical significance of this characteristic frequency can be deduced from equation (2). The boiling region pressure response to a sustained (i.e., σ = 0) flow oscillation of frequency ω is:

$$F(j\omega) \equiv -\mu + \lambda.(1-e^{-j\omega\tau}).$$

At the characteristic frequency:

$$F(j\omega) = -\mu + 2\lambda,$$

that is, the enthalpy change at the outlet of the boiling region is 180° out-of-phase with that at the inlet causing a maximum response in the boiling region enthalpy. Thus, the destabilizing enthalpy term is maximum at the characteristic frequency.

Note that the boiler secondary side temperature effectively determines h_s and that the primary pressure determines the remaining quantities in equation (4). For a given secondary temperature it turns out that a primary pressure exists above which the system is unstable, provided there is boiling in the core.

15-2.4 Instability Regions and Characteristics

As discussed above, experiments show divergent pass-to-pass flow oscillations of about 14 second period. So do the codes - see Figure 8. As the pressure is decreased and quality is increased, the oscillations become more divergent. Below some pressure, however, decreasing the pressure is stabilizing. Thus below a threshold pressure of about 8.5 MPa the flow is predicted to be stable.

The simple criterion (4) predicts unstable flow oscillations of 11 second period with core boiling and it predicts stable flow below 5.6 MPa pressure. The lower system stability predicted by the simple criterion (4) is attributed to the neglect of inertia and friction terms in equation (2) (and fuel heat capacity). These have important stabilizing effects at normal operating conditions because the transit time τ in equation (3) is small (typically 2 seconds) and, hence, the oscillation frequencies ω and the term $(s^2 + 2\nu s)$ are large. The parameters μ and λ in equation (1) decrease with quality. It follows that, for normal operating condition, increasing quality is stabilizing.

CANDU PHTS is, however, stable to pass-to-pass mode of flow oscillation as the pipe connecting the ROH's tends to reduce the pressure difference between the two passes and, hence, the force driving the oscillation.

15-3 PASS-TO-PASS FLOW OSCILLATION - THERMOSYPHONING CONDITIONS

15-3.1 Description

In two-phase thermosyphoning scenarios, pass-to-pass flow oscillations are possible. For a given condition, the oscillations grow to a limit cycle with the characteristic cyclic void collapse in alternate passes (Figures 9 and 10), as in forced-flow condition. However, the limit cycle amplitudes can be much larger (percentage wise) in thermosyphoning because larger system void fractions can be generated.

The mechanism for pass-to-pass flow oscillation under two-phase thermosyphoning is the same as that described in Section 15-2.1.

15-3.2 Experimental Observation

The flow oscillations were observed in a series of two-phase thermosyphoning tests in the RD-12 loop (Ardron, 1983). Following pump rundown, two-phase thermosyphoning was established by fluid drainage from the loop. The drainage was continued until, at a threshold mass inventory, the flow oscillations appeared (Figure 11).

15-3.3 Models of Flow Oscillations

15-3.3.1 Computer Codes

A transient thermohydraulic computer code has been used to study pass-to-pass flow oscillation under two-phase thermosyphoning conditions in the RD-12 and CANDU PHTS. The code validity for two-phase thermosyphoning condition was verified by its ability to predict the observed features (i.e., thermohydraulic conditions, oscillation period and limit cycle behaviour) of the oscillation in the RD-12 loop (compare Figures 9 and 12).

15-3.3.2 Simple Algebraic Models

The simple linear model of the oscillations given in Section 15-2.3.2 for normal operating conditions is also applicable to the oscillations under thermosyphoning condition (except that the parameter ν in equation (1) does not include any pump term). For thermosyphoning conditions the model becomes even simpler because the single-phase pressure drop in equation (1) is negligibly small. Thus, equations (3) for the oscillation frequency and divergence parameter and the inequality (4) for the instability criterion are more applicable for thermosyphoning conditions.

15.3.4 Instability Regions and Characteristics

PHTS thermosyphoning depends on the system coolant inventory (or void fraction), secondary side temperature and power. Pass-to-pass flow oscillations with periods in the range of 50 - 200 seconds have been observed and predicted over a range of thermosyphoning conditions from the onset of boiling up to about 20% (integrated) void fraction.

Figure 13 shows the stability threshold boundaries, at fixed power, predicted for CANDU-600 system by the code and the simple criterion (4) (using PHTS pressure predicted by the code). The code indicates two regions of stability separated by a region of instability (shaded area). The upper threshold boundary corresponds to high primary pressure and the lower boundary to low primary pressures (noting that the primary pressure follows the secondary side temperature for a fixed void).

The simple criterion captures the upper (high pressure) but not the lower (low pressure) boundary of the region of instability. The lower boundary coincides with the onset of boiling in the core. Below this line, void is solely due to flashing downstream of the core. The simple model ignores flashing and, therefore, cannot predict this line.

The first two terms (i.e., the single-phase pressure drop) on the L.H.S. of equation (1), which are neglected in deriving the criterion (4), depend on s ($s = j\omega$ at the threshold). These terms are negligible for high pressure thermosyphoning because the boiling region transit time τ is large (50 - 200 seconds) and, therefore, the frequencies ω are small. As the pressure is lowered, the flow increases, τ decreases, and these terms become progressively more important. At low pressures and with core boiling, flashing of the coolant in the outlet feeders also influences the flow stability.

For pass-to-pass flow oscillation under thermosyphoning conditions, particularly at high pressures, the pressure oscillations in the boiling regions and, hence, at the outlet headers are small. This accounts for the validity of the instability criterion (4) at these pressures.

15-4 PARALLEL CHANNEL FLOW OSCILLATIONS - NORMAL OPERATING CONDITION

15-4.1 Description

In a multi-channel core a mode of flow instability can be envisaged wherein the flow in a particular channel is oscillatory. Being one of many channels, the particular channel does not affect the system flow which is steady. Alternatively a flow oscillation in a group of channels could be compensated by an out-of-phase oscillation in another group of channels. More generally the parallel channel mode is defined as one which has no effect on the system. If it did have such an effect, it would be a pass-to-pass or system in-phase oscillation.

In CANDU under normal forced-flow conditions it is required that the power at which any channel becomes unstable be at least as large as the power to dry out. Otherwise an oscillation would induce a premature dryout. The limiting channel turns out to be a central channel with no inlet orificing. By ensuring that such a channel is stable with adequate margin, all channels are stable.

An analysis of flow oscillations in a single channel at constant header conditions (pressures and temperatures) is thus carried out. Typical predicted small amplitude flow oscillations in a channel with overpower are shown in Figure 14. The instability mechanism is dominated by the delayed response of the two-phase frictional pressure drop to flow change. The delay is due to channel fluid transport time.

In steady state the total frictional pressure drop (single-plus two-phase) normally increases as the flow increases and so the flow is stable. Under some conditions, however, the pressure drop can decrease when the flow increases and so the flow can be unstable. This is possible even in steady state and is called Ledinegg instability. CANDU fuel channels are stable to this type of instability for powers higher than the threshold power to dynamic instabilities. Ledinegg instability will not, therefore, be discussed further. In a dynamic situation, the pressure drop can decrease with increasing flow due to transport delays as will be discussed below.

15-4.2 Experimental Observation

The threshold power to flow oscillation in parallel channels was measured in several pumped-flow tests in experimental loops, called SWIFT (Collins et al, 1971) and SAWFT (Parsons, 1973), at Westinghouse Canada Limited. The loops consisted of one, two or three vertical parallel, electrically heated sections with or without a bypass pipe connected to inlet and outlet headers by feeder pipes. In many of the tests periodic dryout, indicated by periodic rise in heater surface temperature, occurred without significant flow oscillation. It is speculated that the test section power was close enough to the oscillation threshold power that boiling noise could excite small signal flow oscillation and cause periodic dryout. In some tests significant flow oscillations were observed before periodic dryout (Figure 15).

15-4.3 Models of Parallel Channel Flow Oscillations

15-4.3.1 Computer Codes

A transient thermohydraulic computer code has been used to compute oscillation threshold power in the horizontal fuel channels. The code was first verified against the SWIFT and SAWFT tests mentioned in Section 15-4.2. For a constant header-to-header pressure drop and for a given channel power, the steady state is first generated. The state is then perturbed by a small change in the header-to-header pressure drop to excite the flow oscillation. This procedure is repeated with gradually higher power until divergent flow oscillations are obtained. Figure 16 gives the comparison between the observed and predicted threshold powers. The agreement is within 15%.

15-4.4 Instability Regions and Characteristics

The code predictions show that the channel is unstable only at powers much higher than dryout. The fuel heat capacity has a large stabilizing effect on the flow oscillation as the fuel time constant is large compared to the oscillation period of 2 seconds.

Orificing the inlet feeder and, thereby, increasing the single-phase frictional pressure drop is stabilizing because this pressure drop is always in phase with the flow. Orificing the outlet feeder and, hence, increasing the two-phase frictional pressure drop is destabilizing because this pressure drop is not, in general, in-phase with the flow due to transport delays. Note that CANDU uses inlet orifices to match the core flow to core power distribution. The high power, high flow channels are not orificed and, therefore, these channel are least stable.

The limit cycle behaviour of the channel flow oscillations is of no practical interest because the channel is designed to be stable even to small disturbances.

15-5 PARALLEL CHANNEL FLOW OSCILLATIONS - THERMOSYPHONING CONDITIONS

15-5.1 Description

Parallel channel flow oscillations are possible under thermosyphoning conditions. The mode is similar to that of forced flow parallel channel oscillations in that the flow in the system is not affected. However, the mechanism is somewhat different in that the instability is caused by a delayed response of outlet feeder gravity head rather than a delayed response of two-phase frictional pressure drop:

In a steady state situation, an increase in the channel inlet flow increases the two-phase density in the outlet feeder reducing the gravity head and, hence, restoring the flow. In a dynamic situation, where the flow is changing, the response of the two-phase density and, hence, the gravity head to a flow change is delayed by the fluid transport time in the channel. The delay can augment the change in the flow.

Figures 17 and.18 show limit cycle oscillations in the inlet feeder flow and outlet feeder void respectively for nearly zero header-to-header pressure drop and subcooled, nearly stagnant initial channel conditions. Periods of large flows in Figure 17 are seen to coincide with the cyclic appearance of void in the outlet vertical feeder in Figure 18. The sequence of events leading to each period of large flow is shown schematically in Figure 19. The steam generated in the channel expands and eventually heats up the entire channel assembly to the saturation temperature. When it penetrates to the vertical feeder, the resulting buoyancy force induces large flows. The channel is refilled and the void is flushed out. The cycle is then repeated.

15-5.2 Experimental Observation

Parallel channel flow oscillations have been studied in the Cold Water Injection Test (CWIT) facility at Westinghouse Canada Ltd. (Figure 20) for the standing-start initial conditions (i.e., subcooled, stagnant initial channel conditions). In each of the standing-start tests the loop was brought to the desired initial condition in temperature and pressure at zero power. The power was then stepped up.

Typical observed limit cycle oscillations are shown in Figures 18 and 19. Stability thresholds were not studied. Such a study would need tests with steady-state initial conditions. Such tests are planned but meanwhile, the limit cycle behaviour of the standing start tests is certainly relevant.

In a two-phase thermosyphoning test in the RD-12 loop with two test sections per pass, parallel channel together with pass-to-pass flow oscillations were observed (Figure 21) (Ardron, 1983). Pass-to-pass flow oscillations began at relatively low system void as the loop was drained. Figure 21 shows intervals of higher frequency parallel channel flow oscillations superimposed on the pass-to-pass oscillations. Each interval begins when the pass void becomes high enough during a pass-to-pass oscillation.

15-5.3 Models of Parallel Channel Flow Oscillations

Thermohydraulic computer codes have been used to study the flow oscillations in a channel at various elevations and powers and for various constant values of the header-to-header pressure drop and channel inlet subcooling.

15-5.4 Instability Regions and Characteristics

Standing-start tests and code predictions have shown the three channel flow patterns shown in Figure 22: steady single-phase at high inlet subcooling, oscillatory at intermediate subcooling and steady two-phase at low subcooling. The period of the oscillations is proportional to the subcooling and decreases with the channel power.

Figure 23 shows the stability threshold boundary for a fixed channel power and ROH pressure in the space of header-to-header pressure drop and the channel inlet (subcooled) temperature as predicted by a thermohydraulic code. The three flow patterns mentioned above are predicted for small positive header-to-header pressure drops. For large negative header-to-header pressure drop the code predicts a region of divergent flow oscillations at the end of the simulation. It is expected that a reverse flow would develop.

15-6 SYSTEM IN-PHASE FLOW OSCILLATIONS - THERMOSYPHONING CONDITIONS

15-6.1 Description

This mode of flow oscillation has been observed in test rigs and predicted by a code under some thermosyphoning conditions. In this mode the corresponding flow variables (i.e., the flow and pressure) in the two passes oscillate in phase with one another (Figures 24 and 25). It is predicted to occur with core boiling and when the void extends into the steam generator cold leg beyond the top of the U-tubes.

The oscillation is caused by buoyancy head feed-back to flow change. A decrease in core flow increases the void which penetrates farther into the steam generator cold leg. This reduces the buoyancy head and, hence, the flow (i.e., a destabilizing effect). The reduction in the flow is, however, opposed by an increased system pressure and, hence, temperature and heat transfer to the steam generator tending to reduce the void and thereby generating the limit cycle.

15-6.2 Experimental Observation

System in-phase flow oscillations have been observed in the RD-12 loop (Ardron, 1983) and in a glass figure-of-eight rig at Whiteshell Nuclear Research Establishment. In the glass rig the system flow oscillations were observed when void was present at the top of the cooling U-tube and were accompanied by large oscillations in the loop pressure (Phuoc Tran, 1983).

15-6.3 Instability Region and Characteristics

In a CANDU thermosyphoning calculation a thermohydraulic computer code has predicted system in-phase flow oscillation at void (above 20%) extending beyond the top of the steam generator U-tube. Figure 26 shows the predicted instability region for this mode at fixed power in the space of system void and secondary side temperature. The oscillations are more stable at higher system pressure and secondary temperature.

As these oscillations require high system void, they are not commonly encountered. They are certainly not encountered at normal operating conditions.

15-7 CONCLUSIONS

A figure-of-eight PHTS has three possible modes of two-phase flow oscillations: parallel channel, pass-to-pass and system in-phase flow oscillations which can appear if conditions permit.

Pass-to-pass flow oscillation is possible in both forced and thermosyphoning flow conditions. In this mode the variations in the flow rate, boiling region pressure and quality in one pass, are out-of-phase with those in the other pass. The oscillations arise from the response of the pressures in the boiling regions to a flow change. The period of the oscillations is about 10 to 20 seconds in forced and about 50 - 200 seconds in thermosyphoning conditions.

Parallel channel flow oscillations by definition do not have any effect on the system flow. In forced-flow conditions the oscillations arise from the delayed response of the two-phase frictional pressure drop to a flow change. Inlet feeder orificing and heater (or fuel) heat capacity have significant stabilizing effects on the oscillation. The oscillation period is of the order of 2 seconds. In thermosyphoning conditions, on the other hand, the oscillations arise from the delayed response of the outlet feeder gravity head to a flow change.

System in-phase flow oscillation can occur in thermosyphoning, but not in forced-flow, conditions as it requires high void. It appears when void extends beyond the top of the steam generator U-tube into the cold leg side.

Generally the oscillation amplitude in any of the modes is bounded by the limit cycle due to the fluid flow non-linearities, the amplitude being larger at higher void. The limit cycle oscillation is often characterized by cyclic collapse of void in some part of the circuit.

In CANDU system, at normal operating conditions, pass-to-pass flow oscillations are suppressed by connecting a by-pass between the reactor outlet headers. The PHTS is, furthermore, inherently stable to parallel channel flow oscillations. System in-phase flow oscillation cannot occur at normal operating conditions as it requires a high system void.

Under thermosyphoning conditions the potential for the flow oscillations in CANDU exists but they have no serious consequences.

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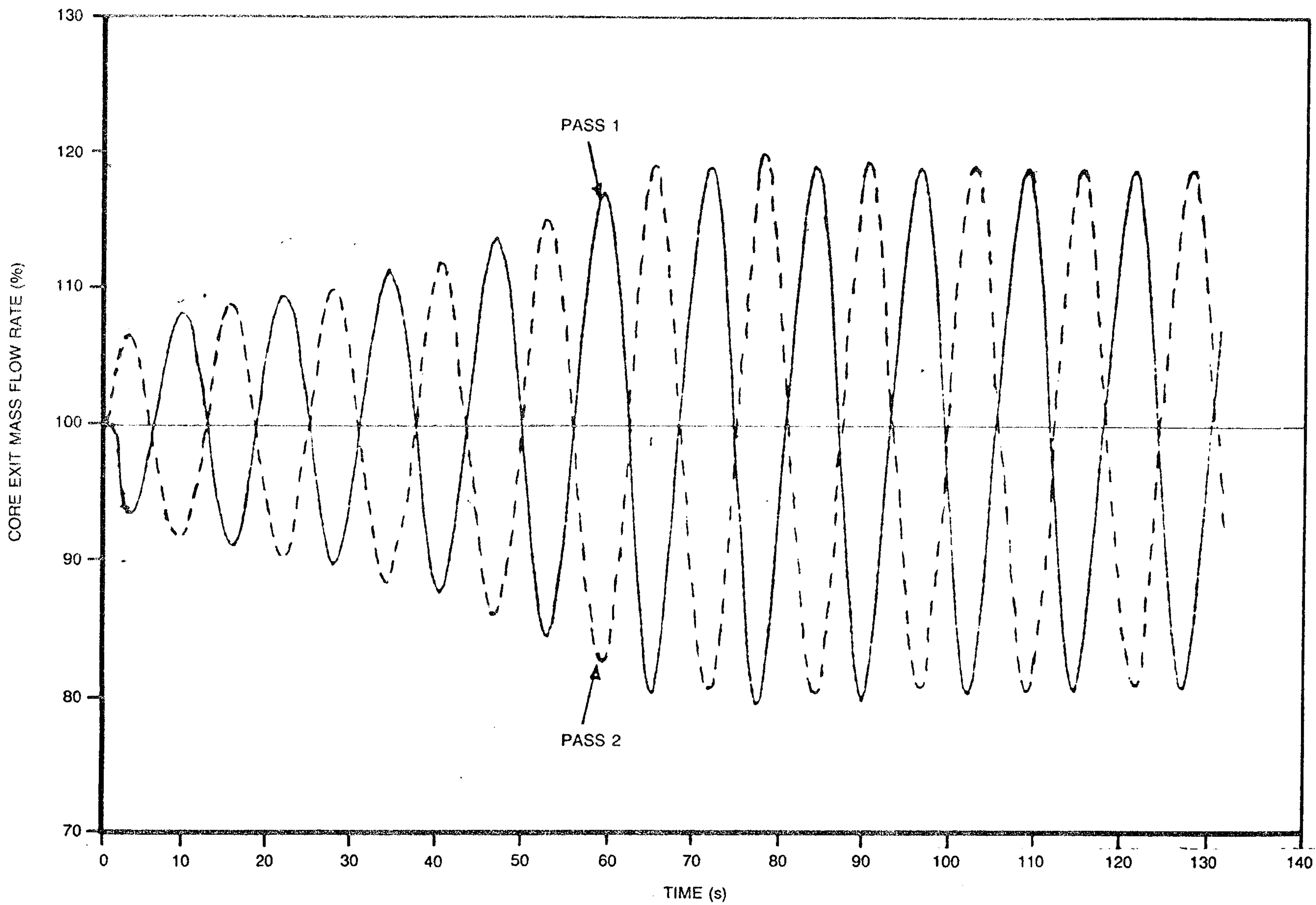


FIGURE 1 PHTS PASS-TO-PASS FLOW OSCILLATION

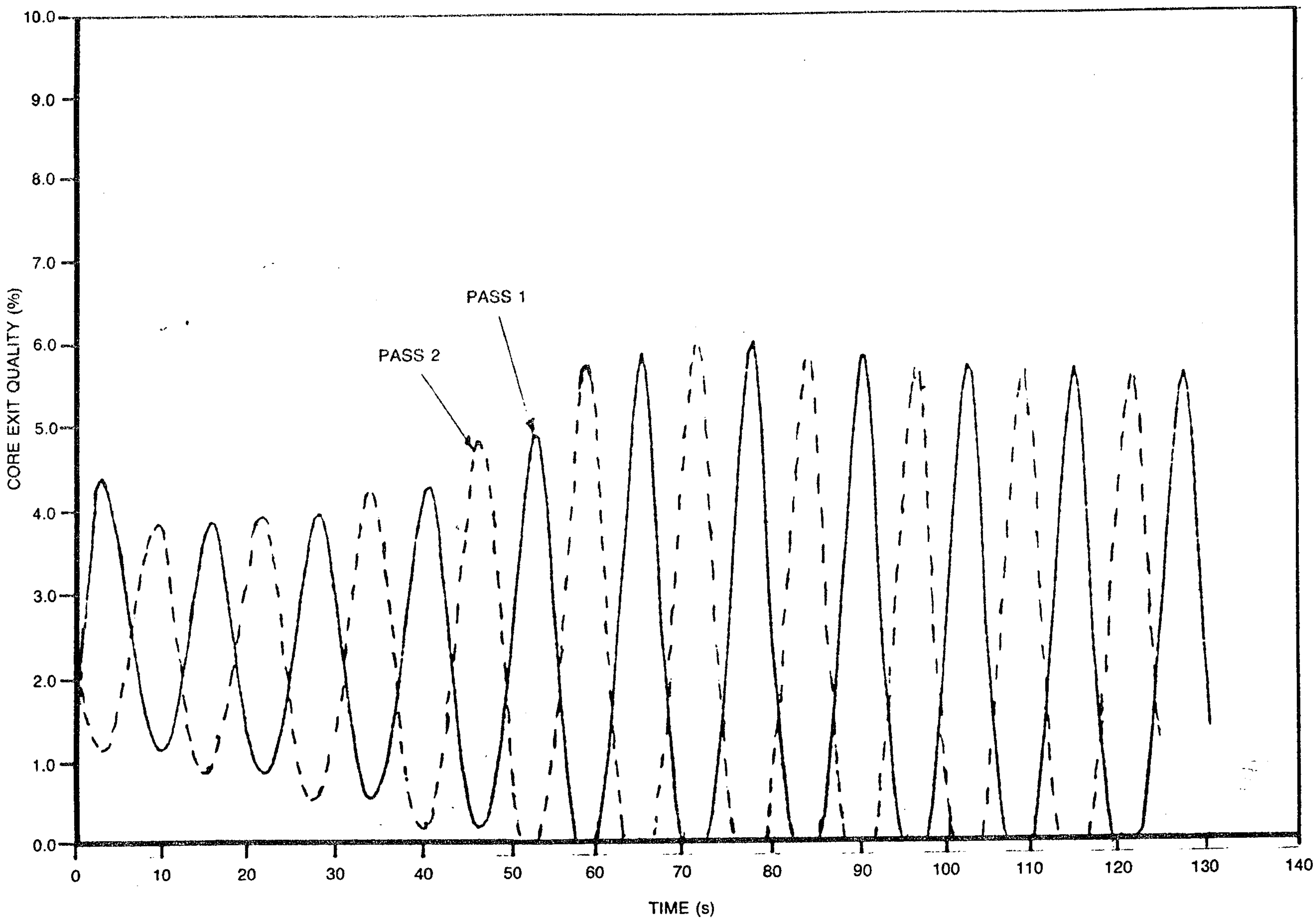
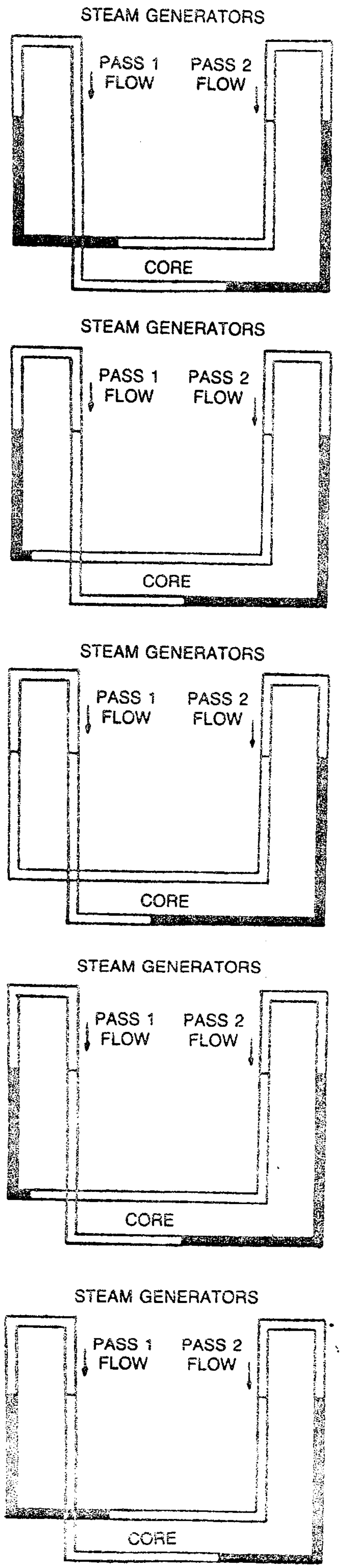


FIGURE 2 PASS-TO-PASS QUALITY OSCILLATION



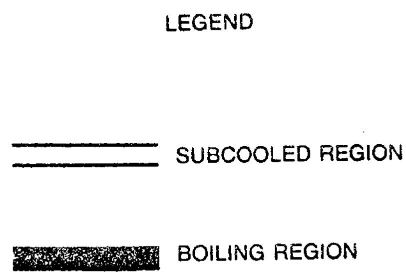


FIGURE 3 PHTS PASS-TO-PASS LIMIT CYCLE

VOID DISTRIBUTION DURING HALF CYCLE

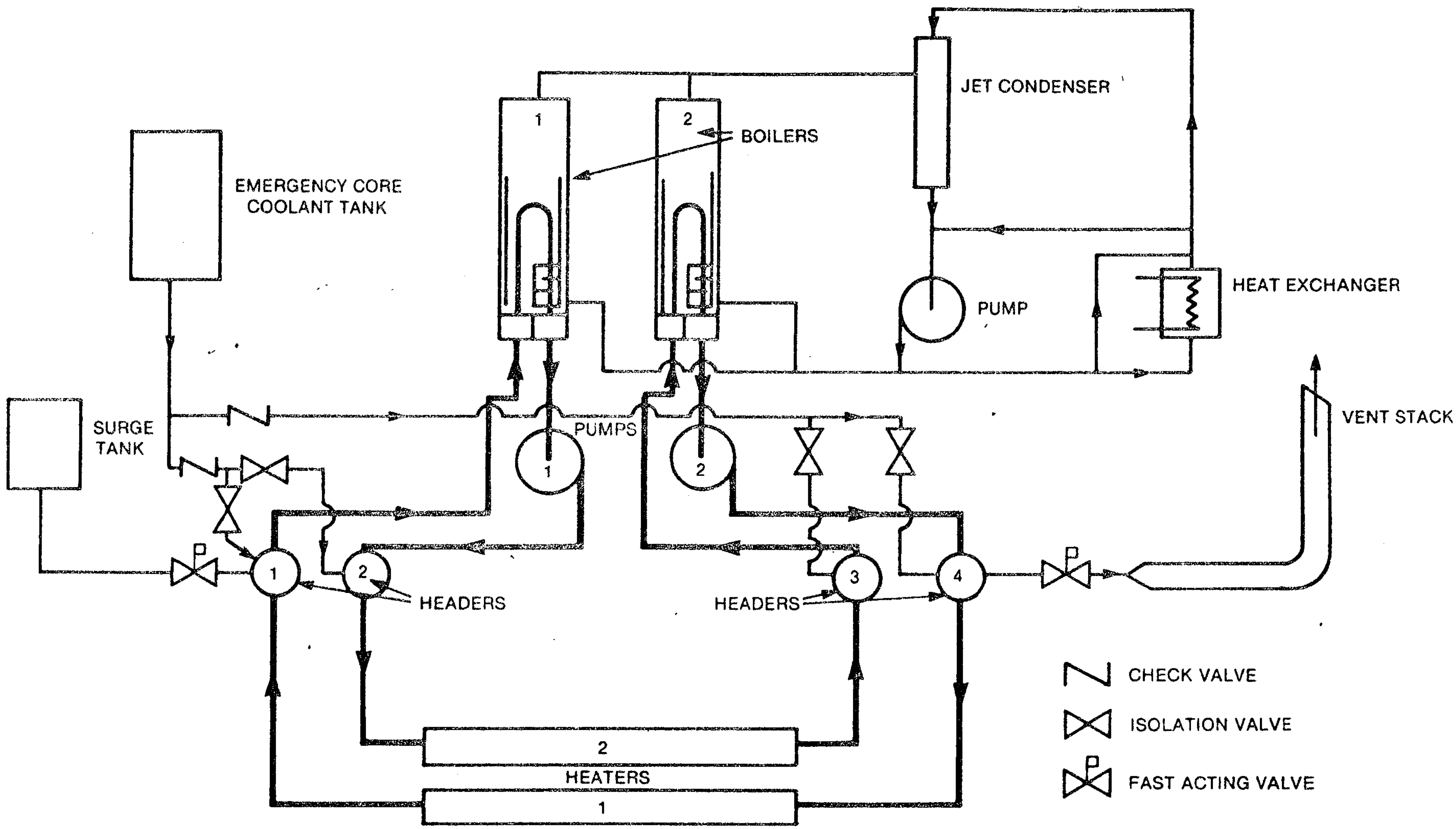


FIGURE 4 : RD-12 LOOP SCHEMATIC DIAGRAM

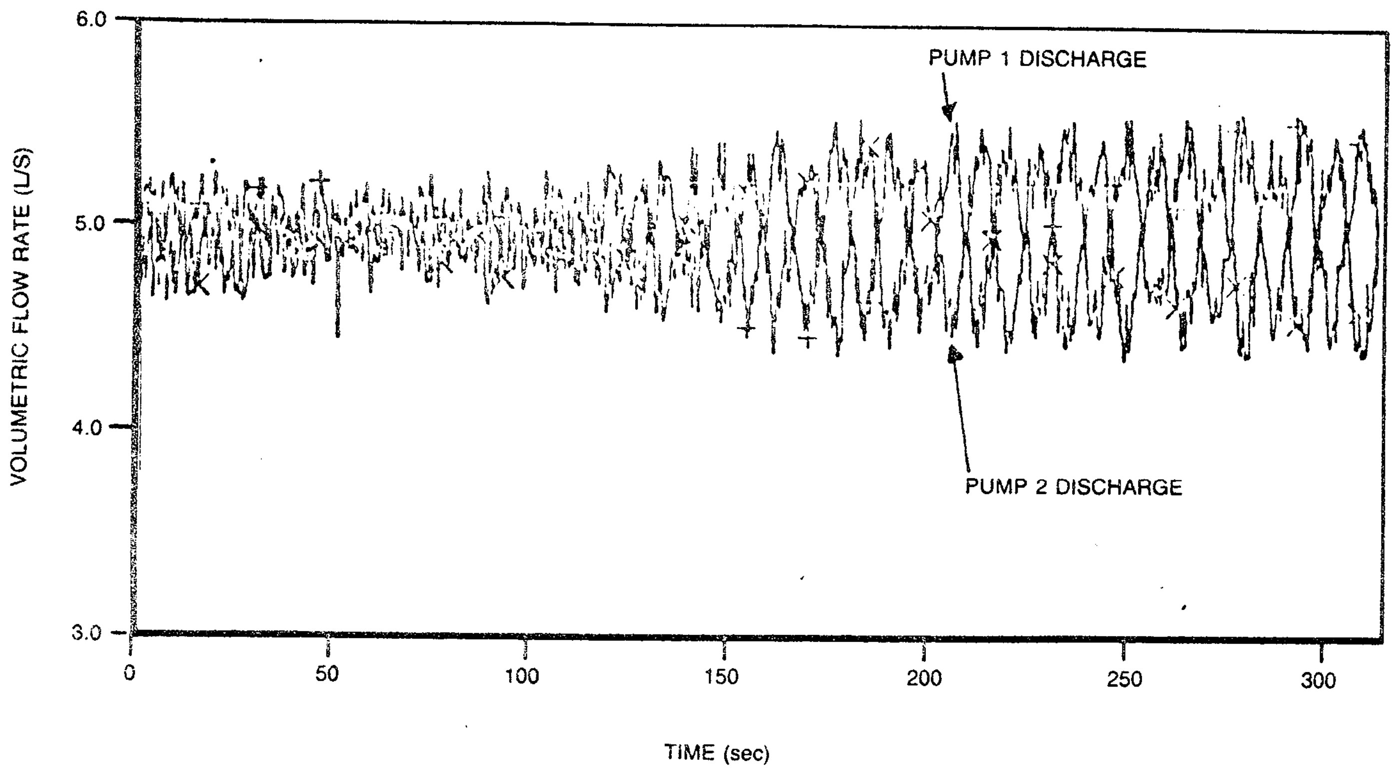


FIGURE 5 OBSERVED FORCED-FLOW PASS-TO-PASS FLOW OSCILLATION IN RD-12 LOOP

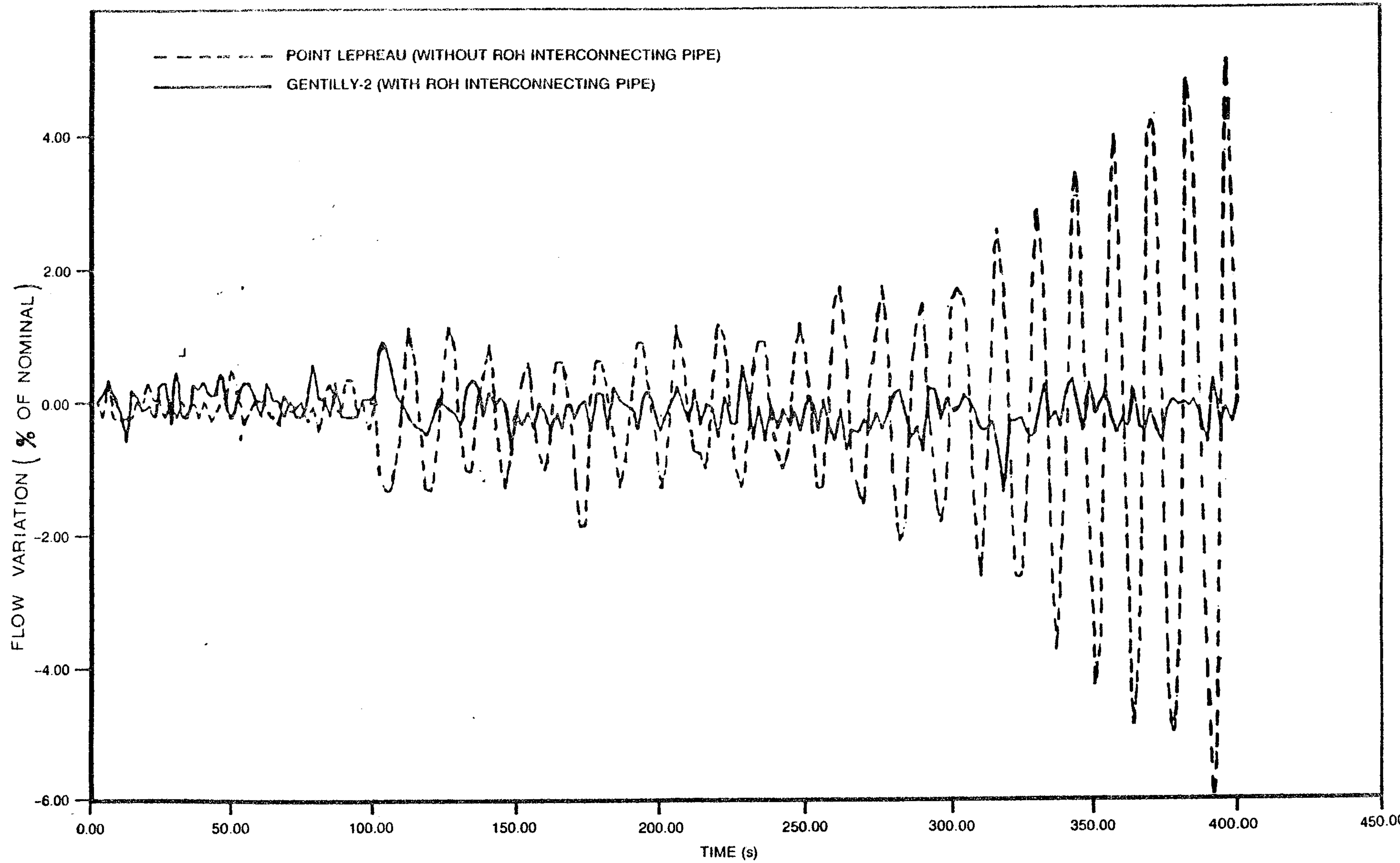


FIGURE 6 PASS-TO-PASS FLOW OSCILLATION OBSERVED IN REACTOR STABILITY TESTS

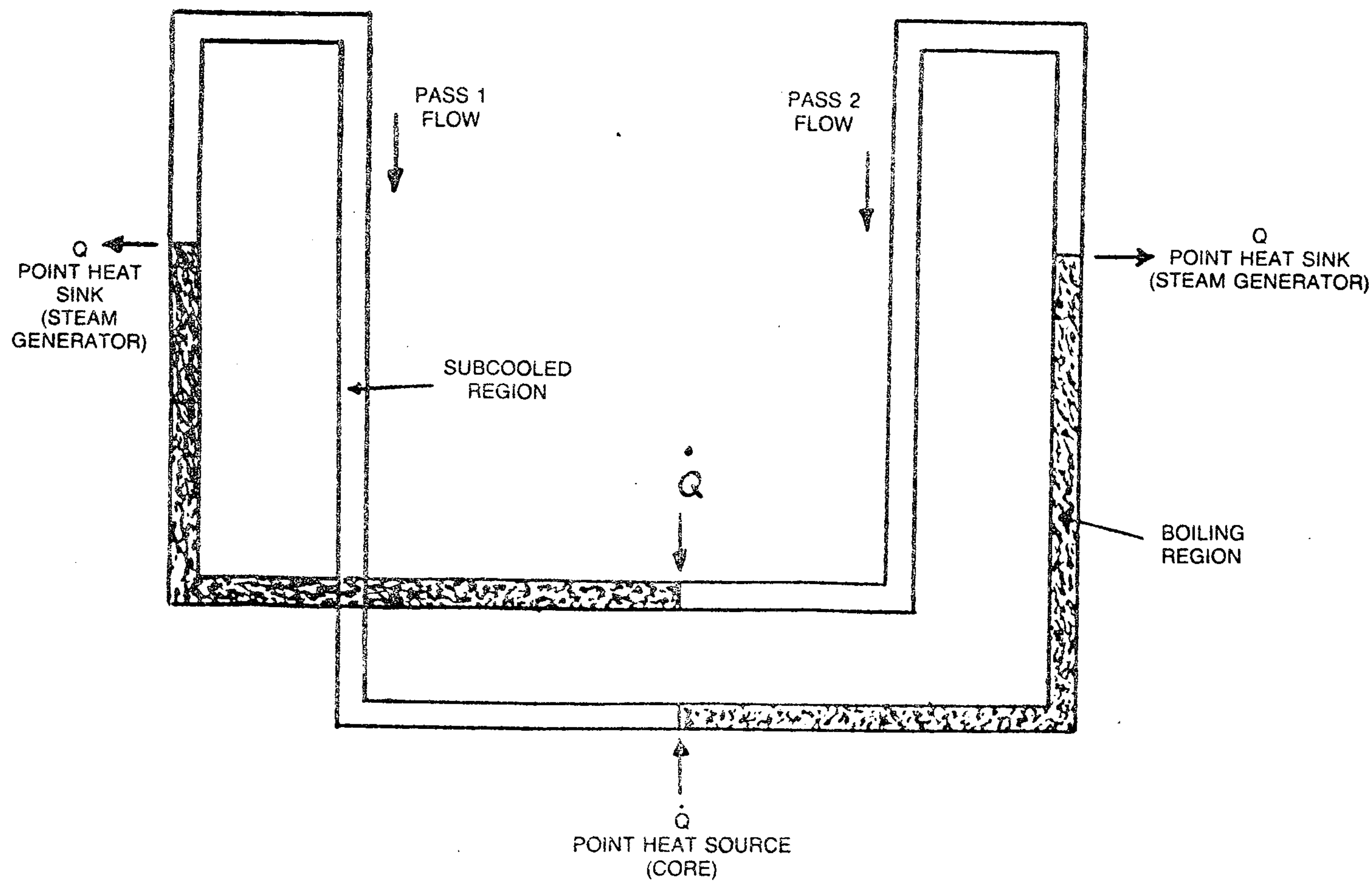


FIGURE 7 SIMPLIFIED PHTS

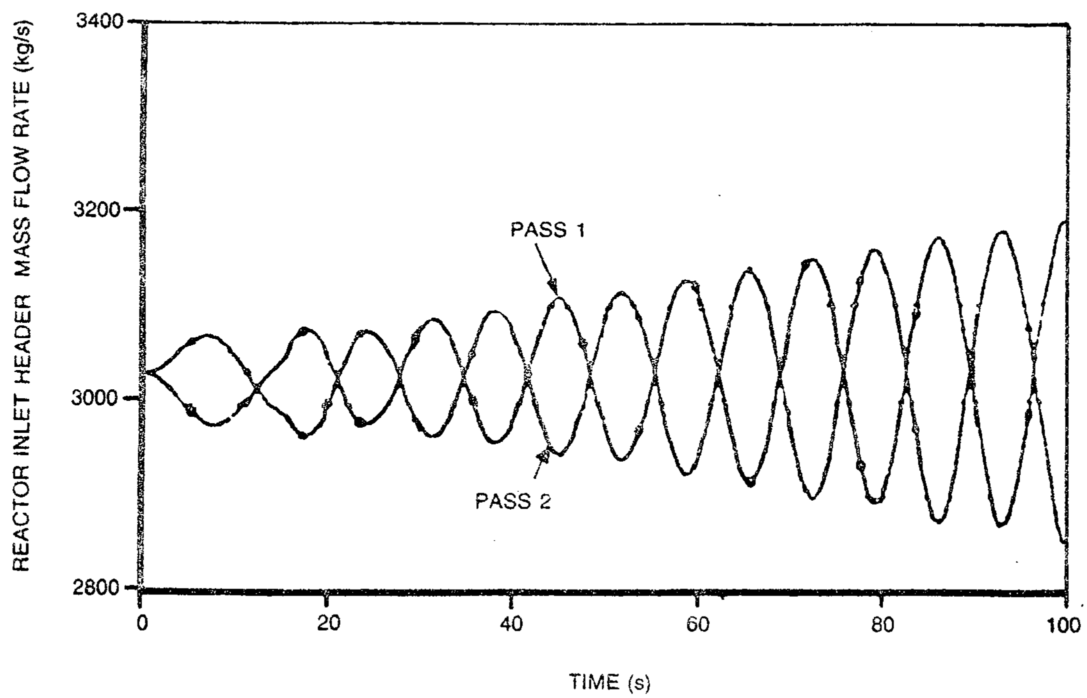


FIGURE 8 PREDICTED PASS-TO-PASS FLOW OSCILLATION IN REACTOR NORMAL OPERATING CONDITION

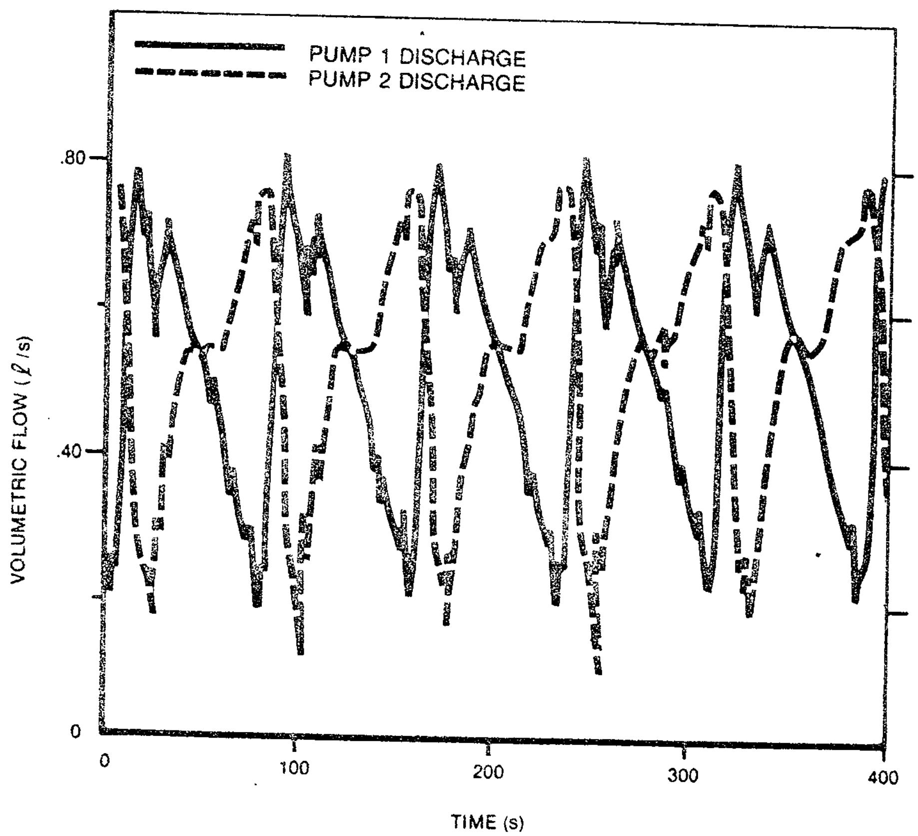


FIGURE 9 PREDICTED THERMOSYPHONING PASS-TO-PASS FLOW OSCILLATION FOR RD-12 LOOP

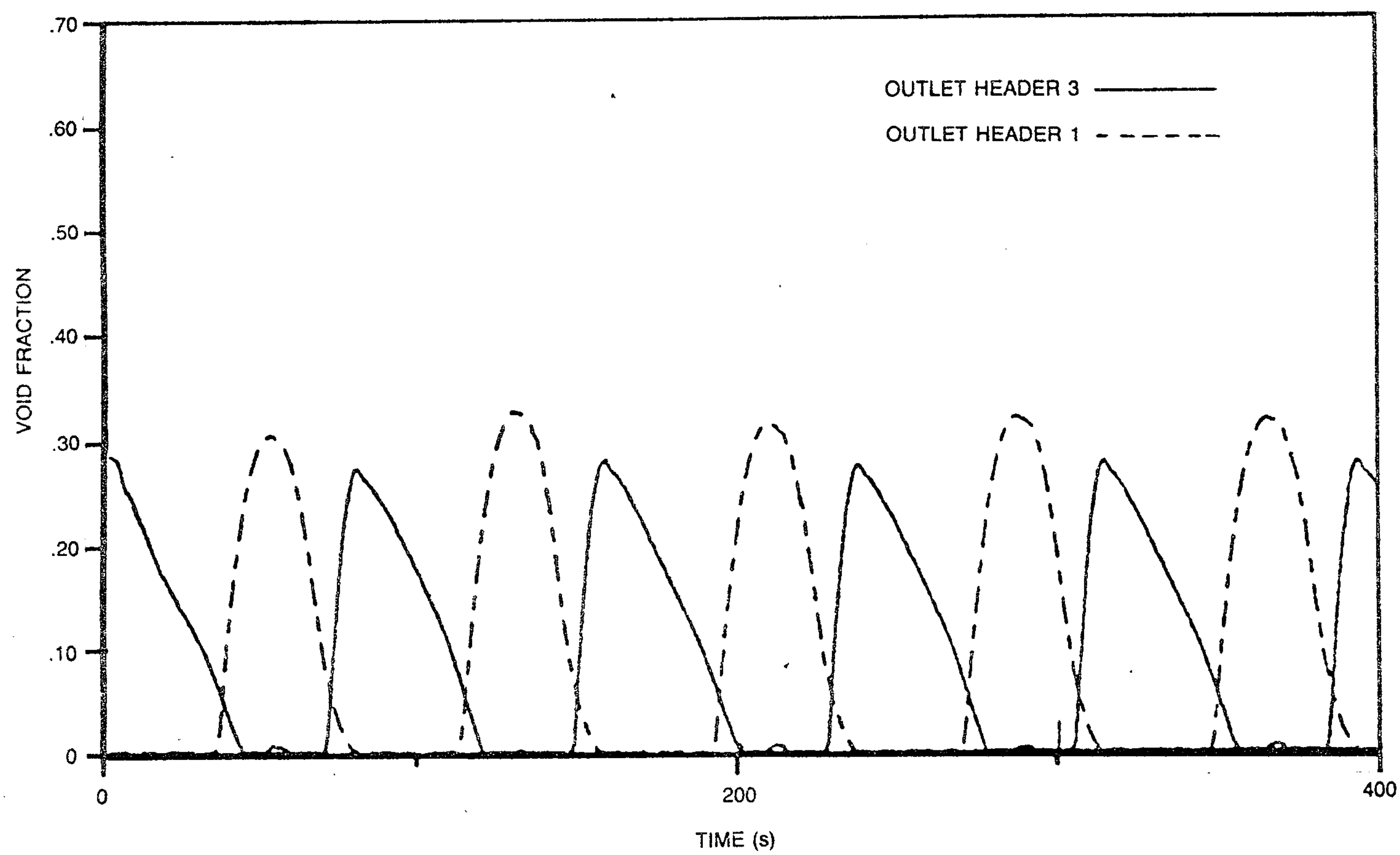


FIGURE 10 PREDICTED OUTLET HEADER VOID IN THERMOSYPHONING PASS-TO-PASS FLOW OSCILLATION FOR RD-12 LOOP

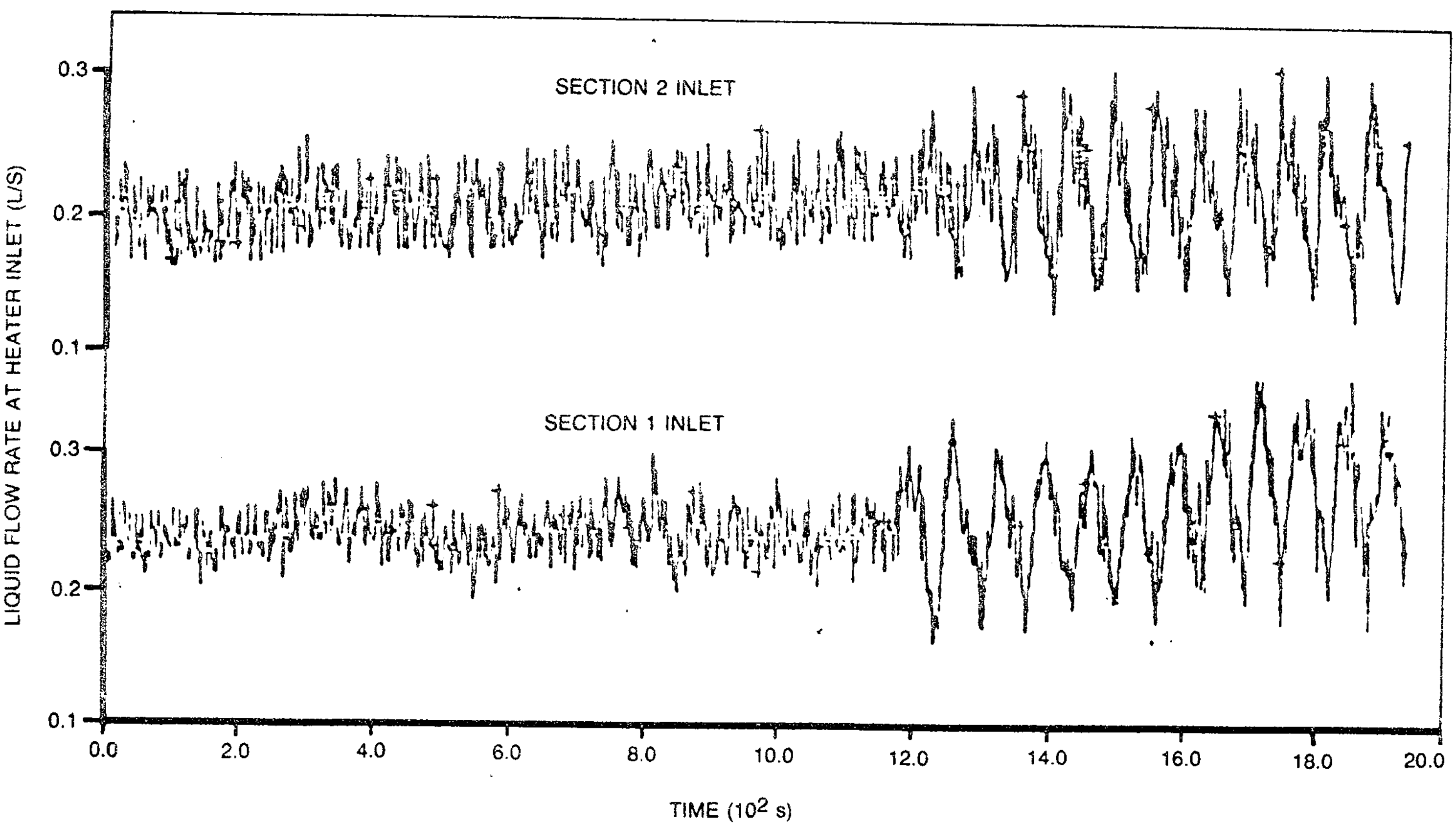


FIGURE 11 OBSERVED THERMOSYPHONING PASS-TO-PASS FLOW OSCILLATION IN RD-12 LOOP

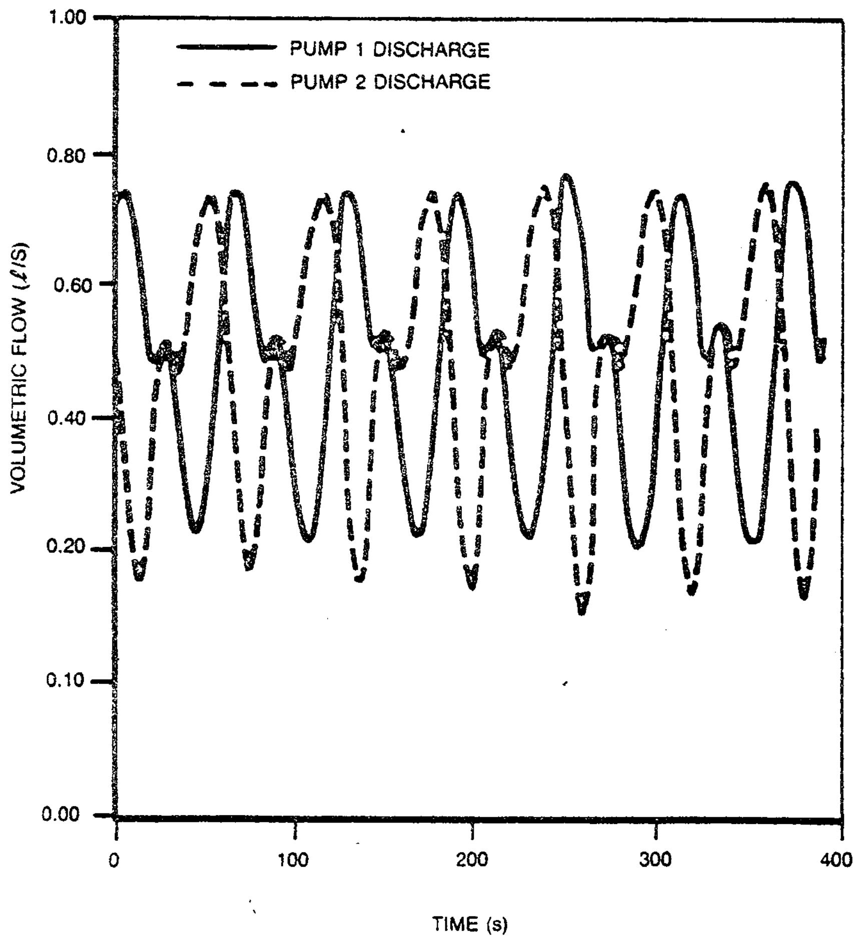


FIGURE 12 OBSERVED THERMOSYPHONING PASS-TO-PASS FLOW OSCILLATION IN RD-12 LOOP

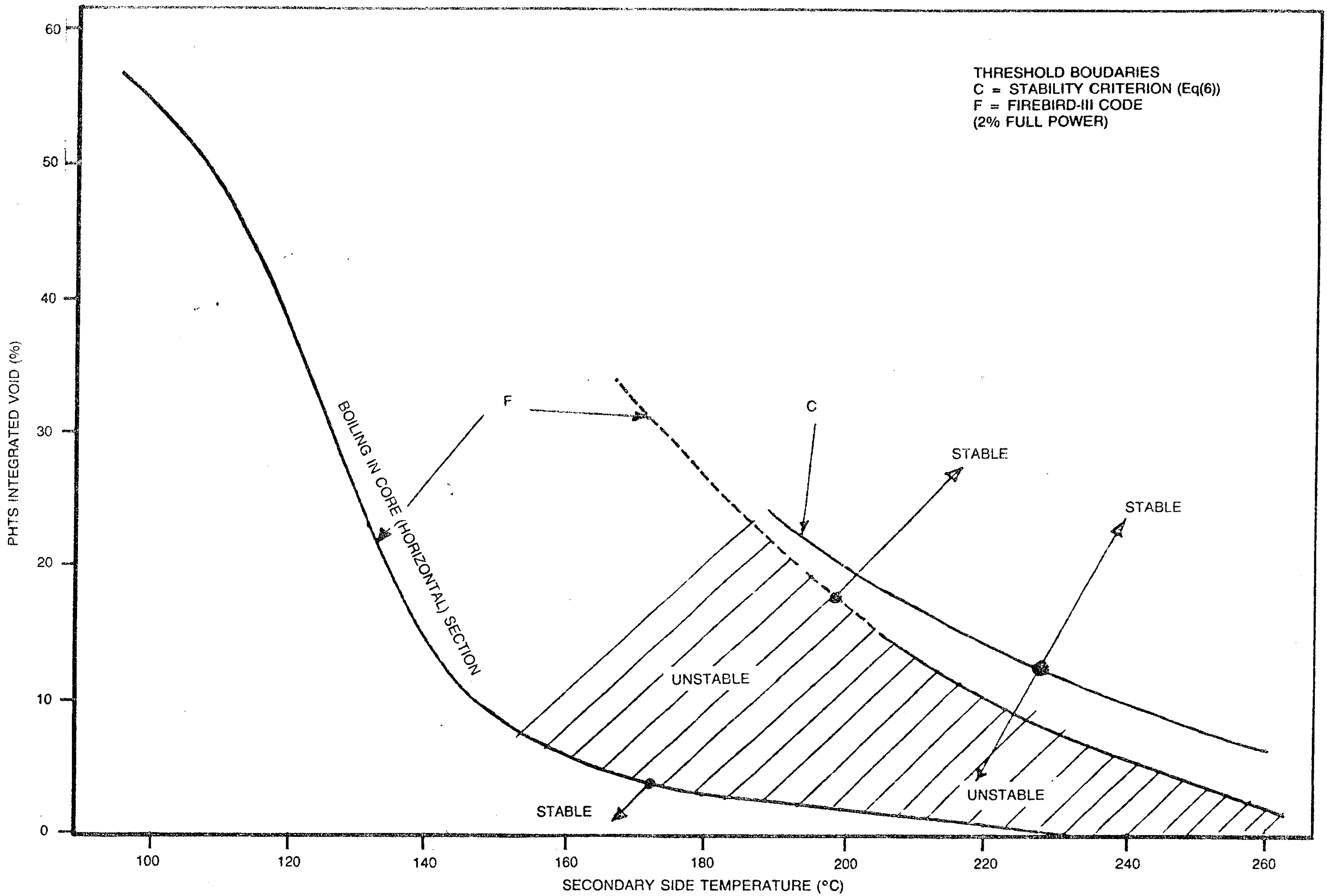


FIGURE 13 PREDICTED PASS-TO-PASS FLOW OSCILLATION STABILITY MAP (THERMOSYPHONING CONDITION)

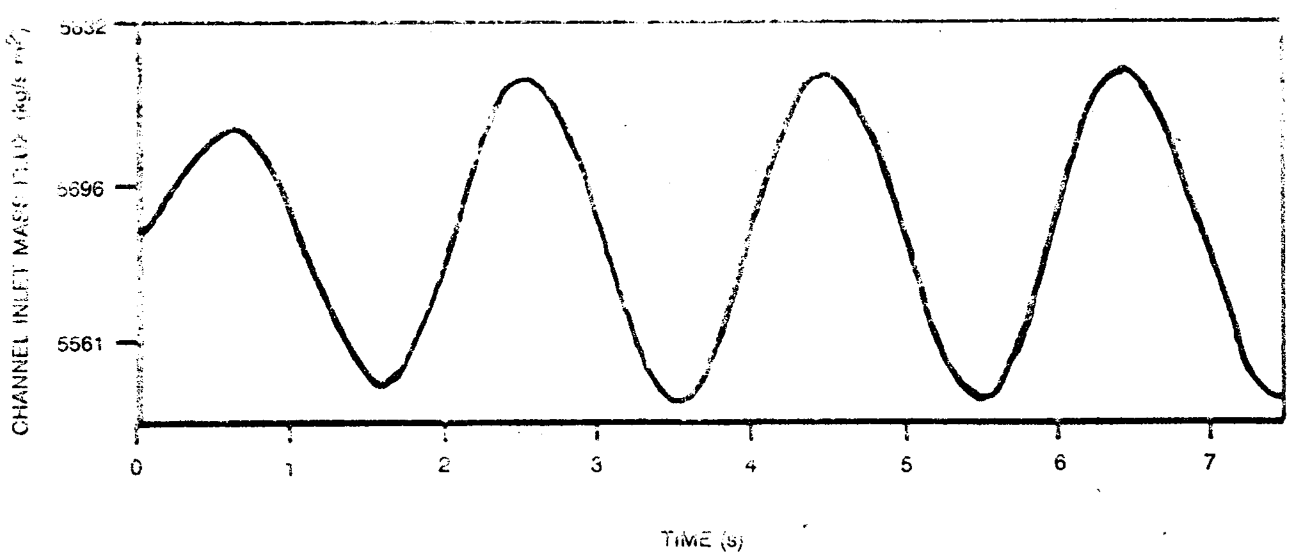


FIGURE 14 SMALL SIGNAL CHANNEL FLOW OSCILLATIONS

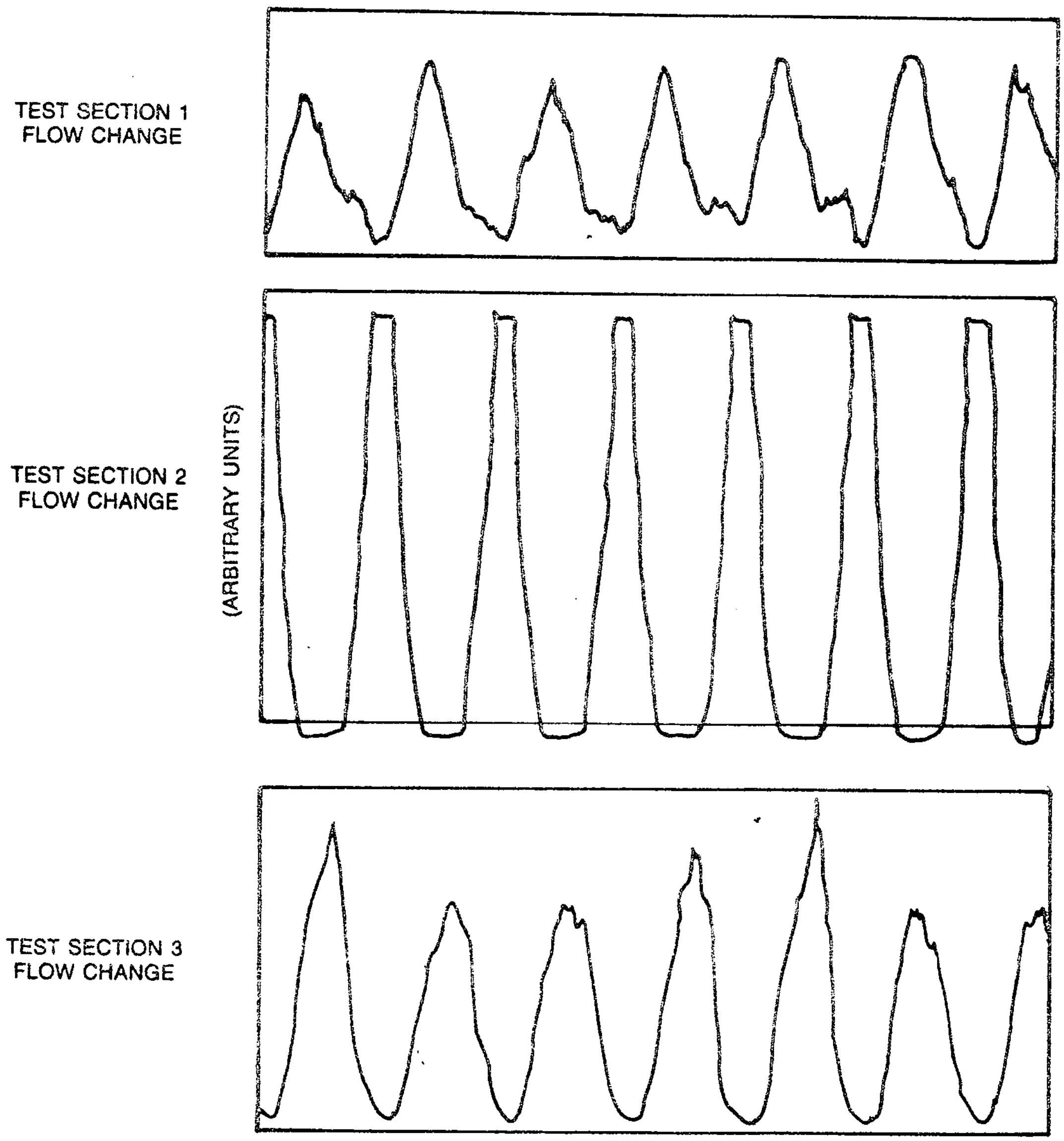


FIGURE 15 OBSERVED FORCED-FLOW PARALLEL CHANNEL OSCILLATIONS IN SAWFT (THREE CHANNEL) LOOP

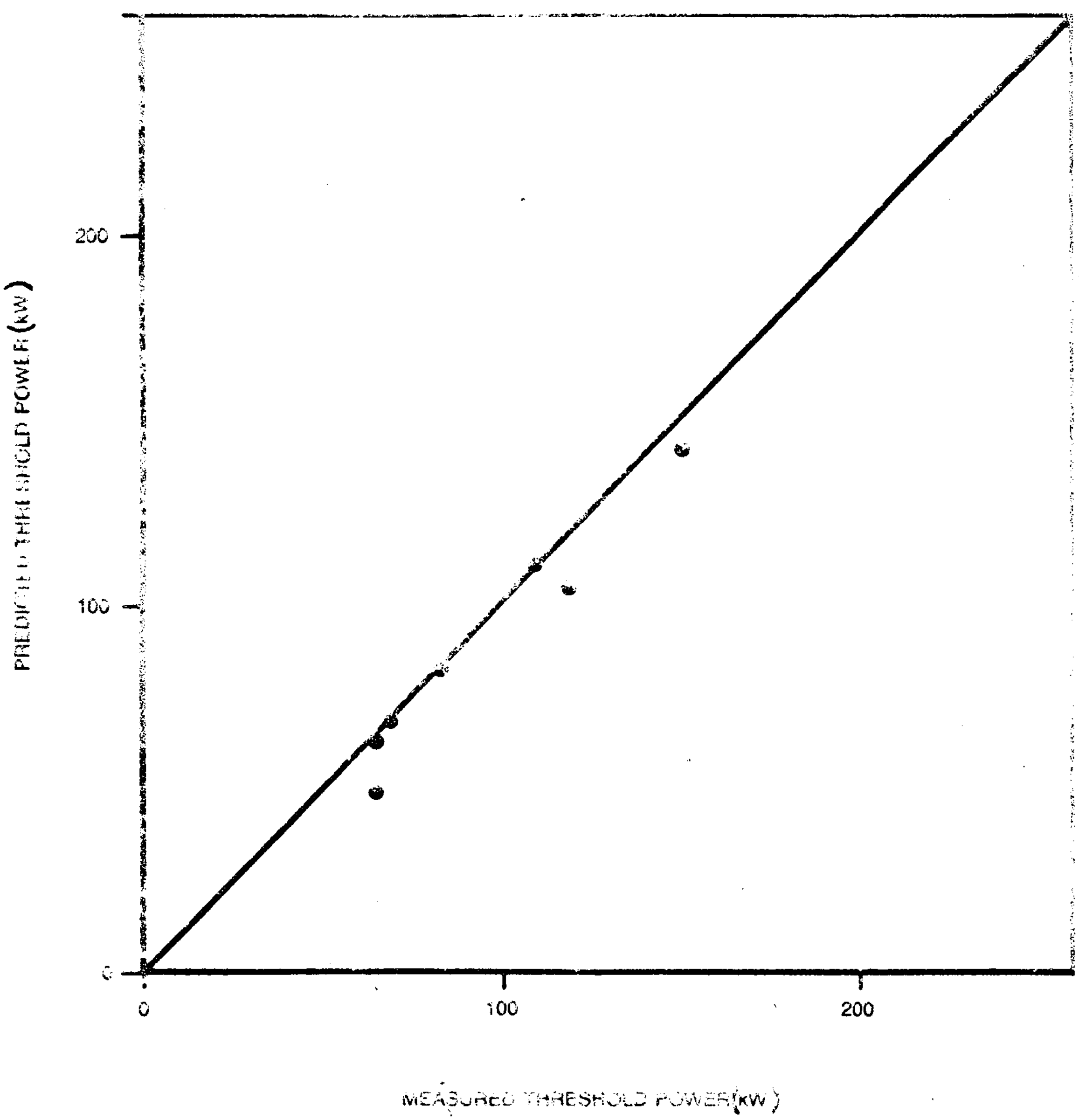


FIGURE 16 COMPARISON OF MEASURED AND PREDICTED THRESHOLD POWERS FOR SAWFT FORCED-FLOW TEST

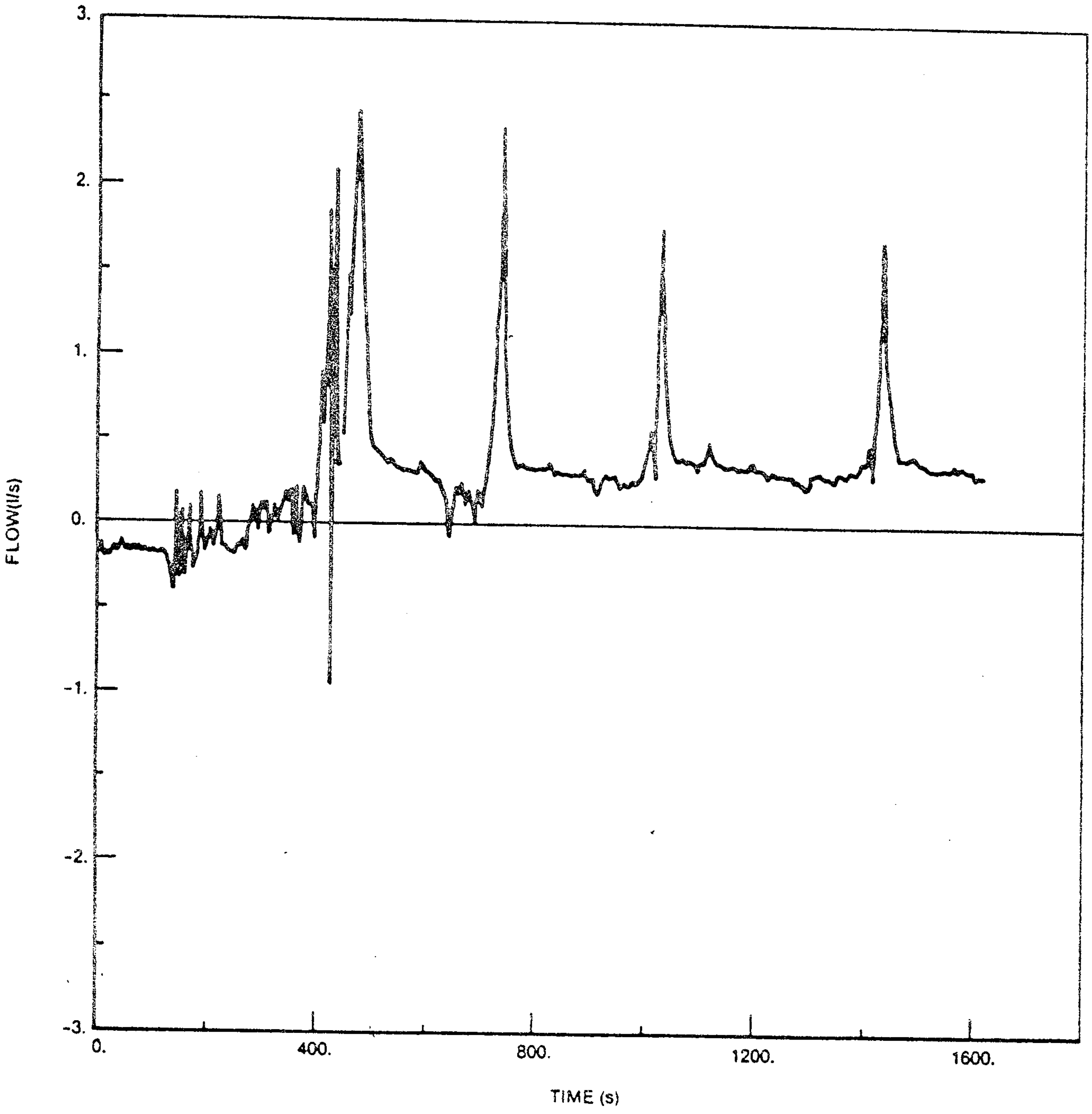


FIGURE 17 OBSERVED INLET FEEDER FLOW IN CWIT CHANNEL FLOW TEST

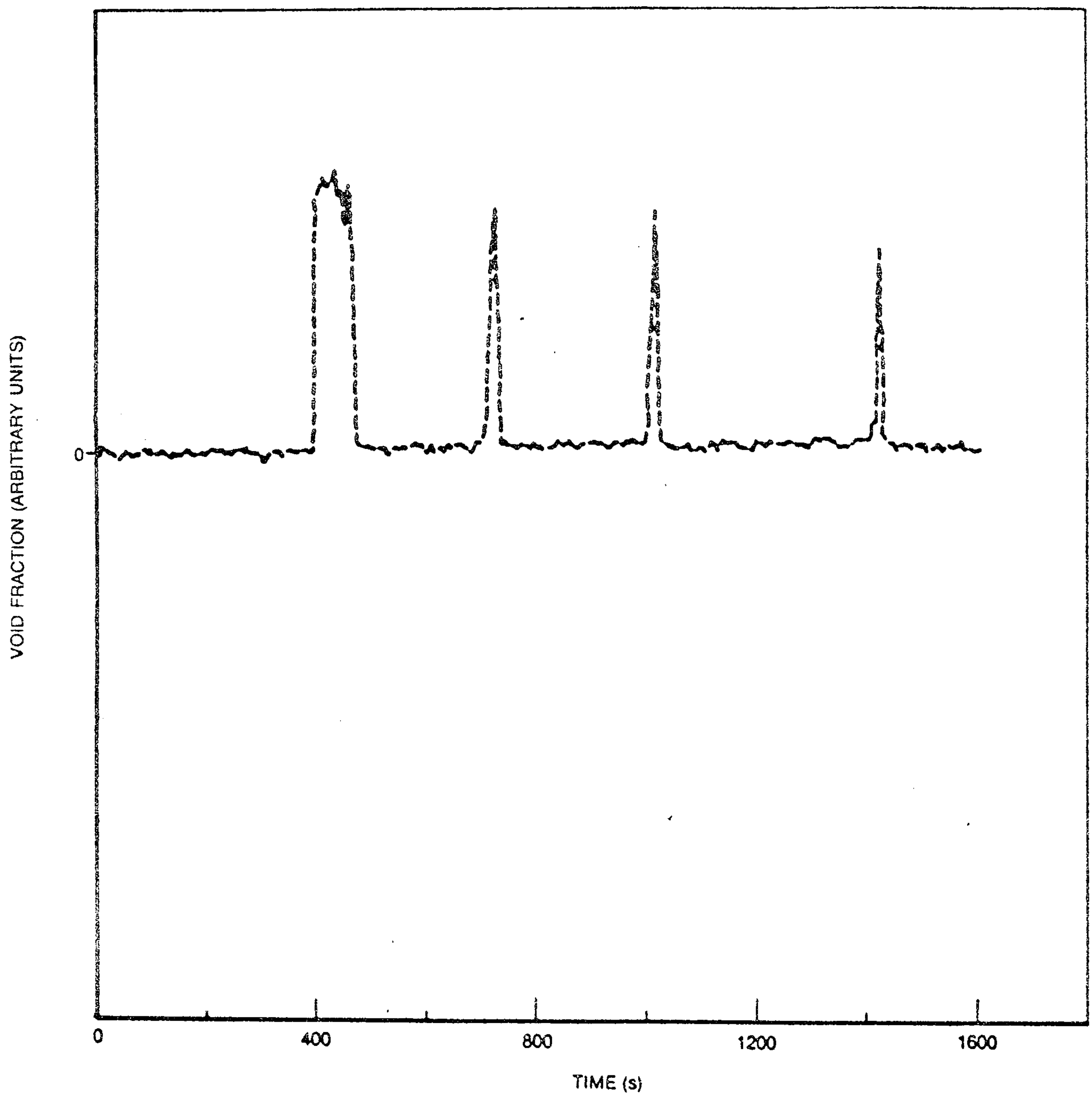


FIGURE 18 OBSERVED OUTLET FEEDER VOID FRACTIONS IN CWIT CHANNEL FLOW TEST

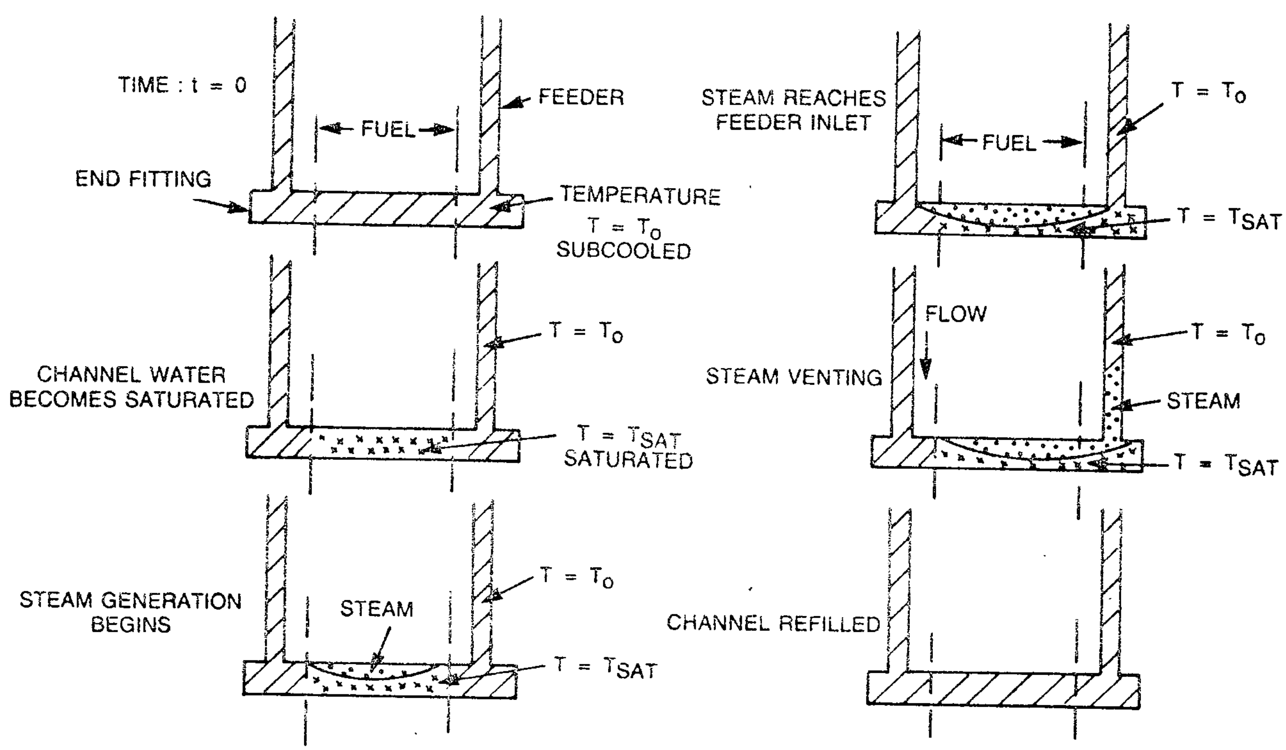
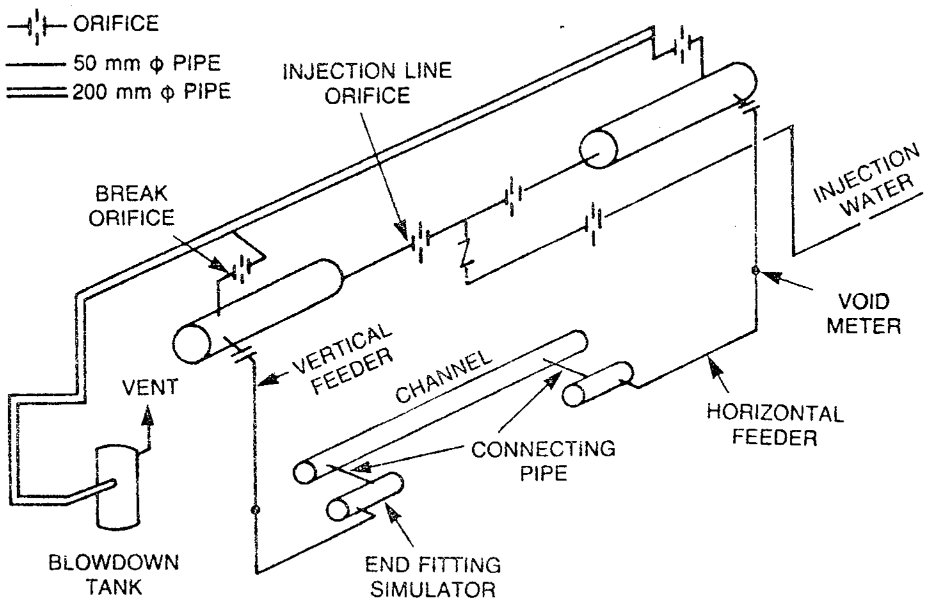


FIGURE 19 CHANNEL-REFILLING SEQUENCE OF EVENTS



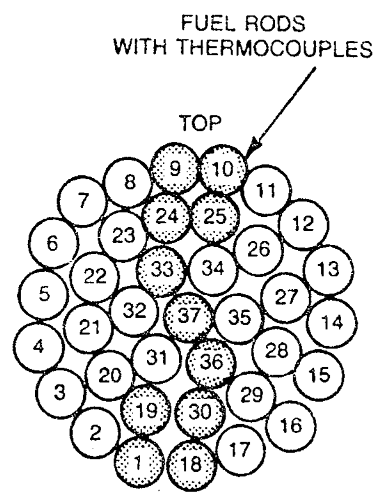


FIGURE 20 SCHEMATIC OF CWIT FACILITY

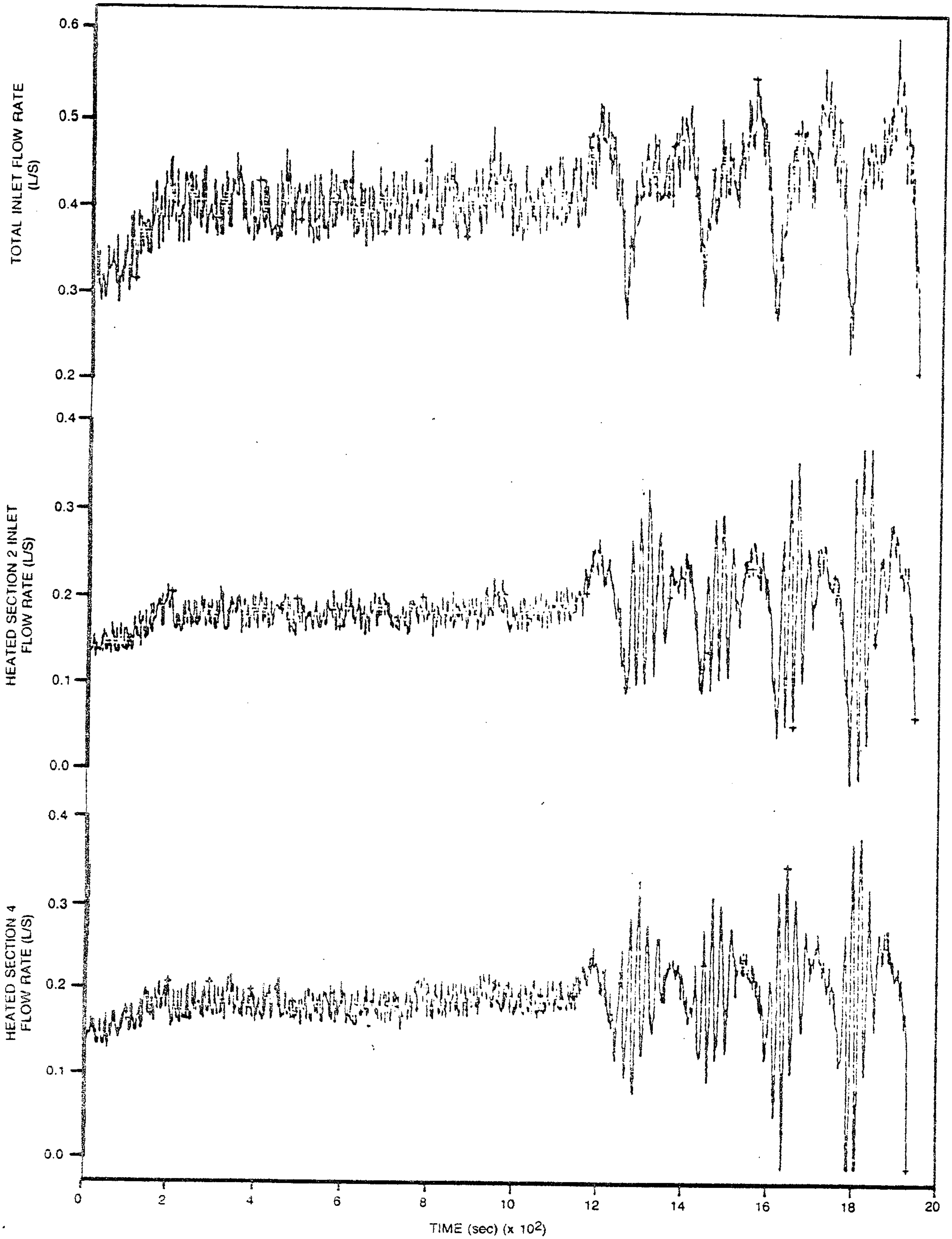


FIGURE 21 FLOW RATE TRANSIENTS IN PARALLEL CHANNEL THERMOSYPHONING

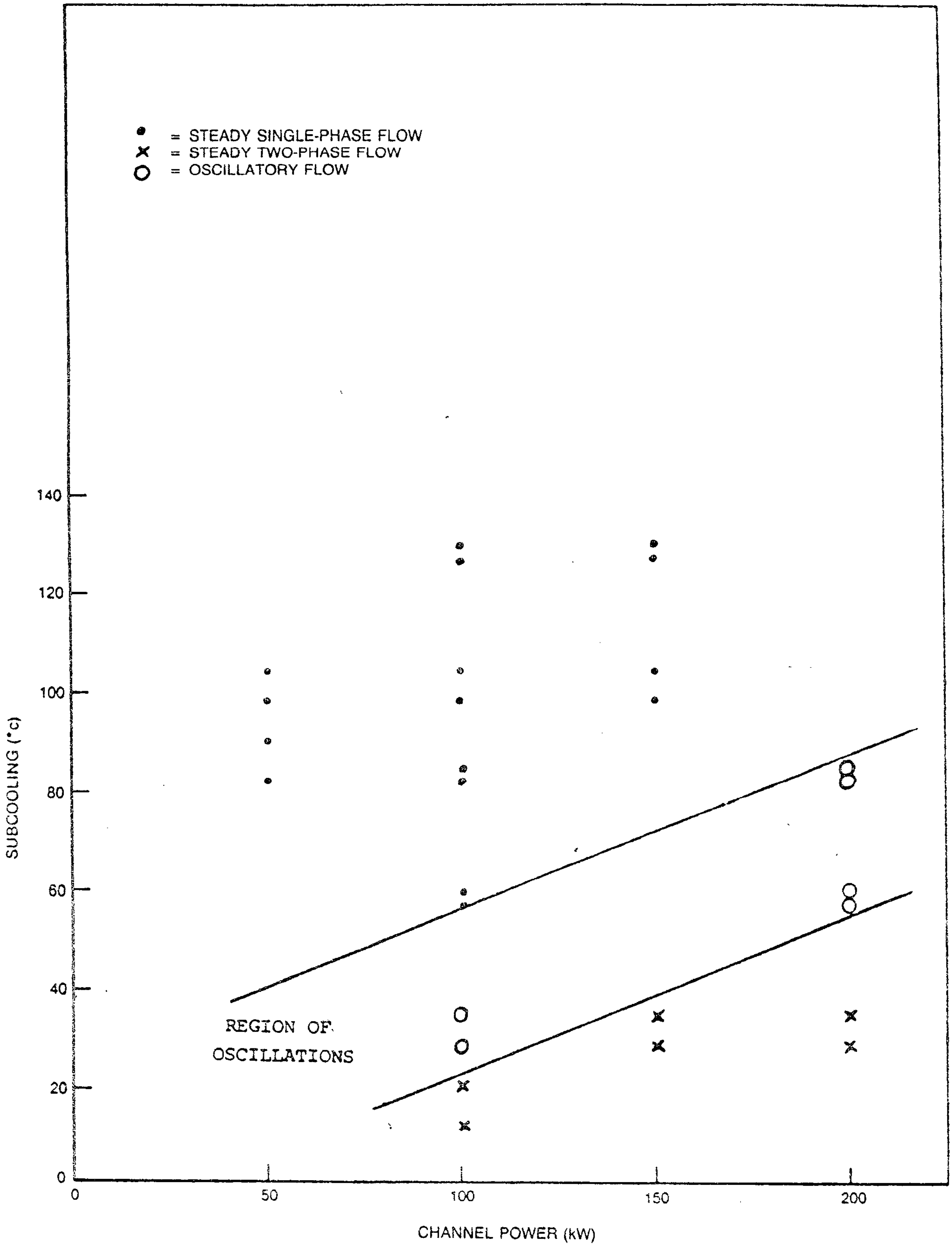


FIGURE 22 OBSERVED PARALLEL CHANNEL FLOW MAP

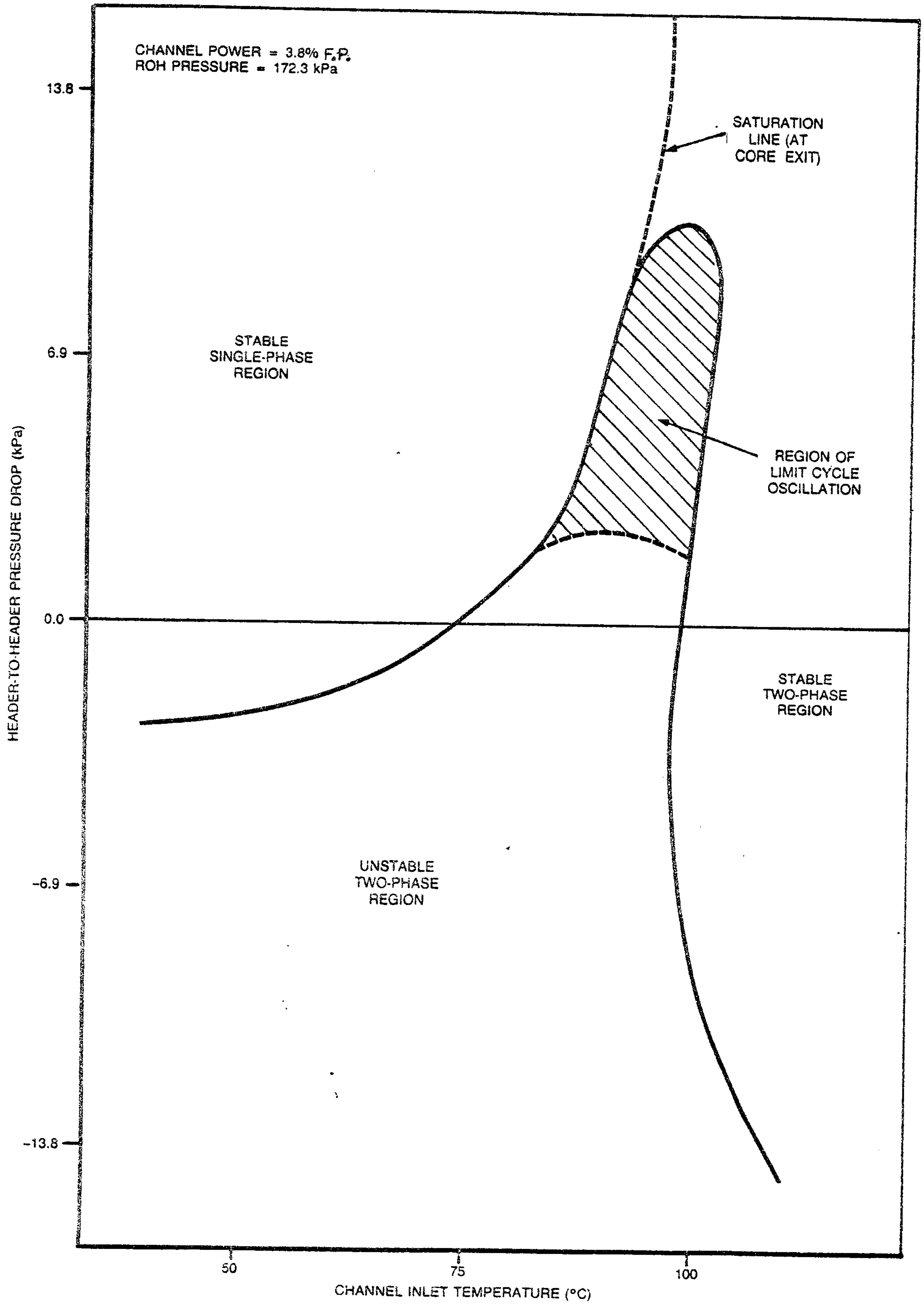


FIGURE 23 PREDICTED CHANNEL FLOW MAP

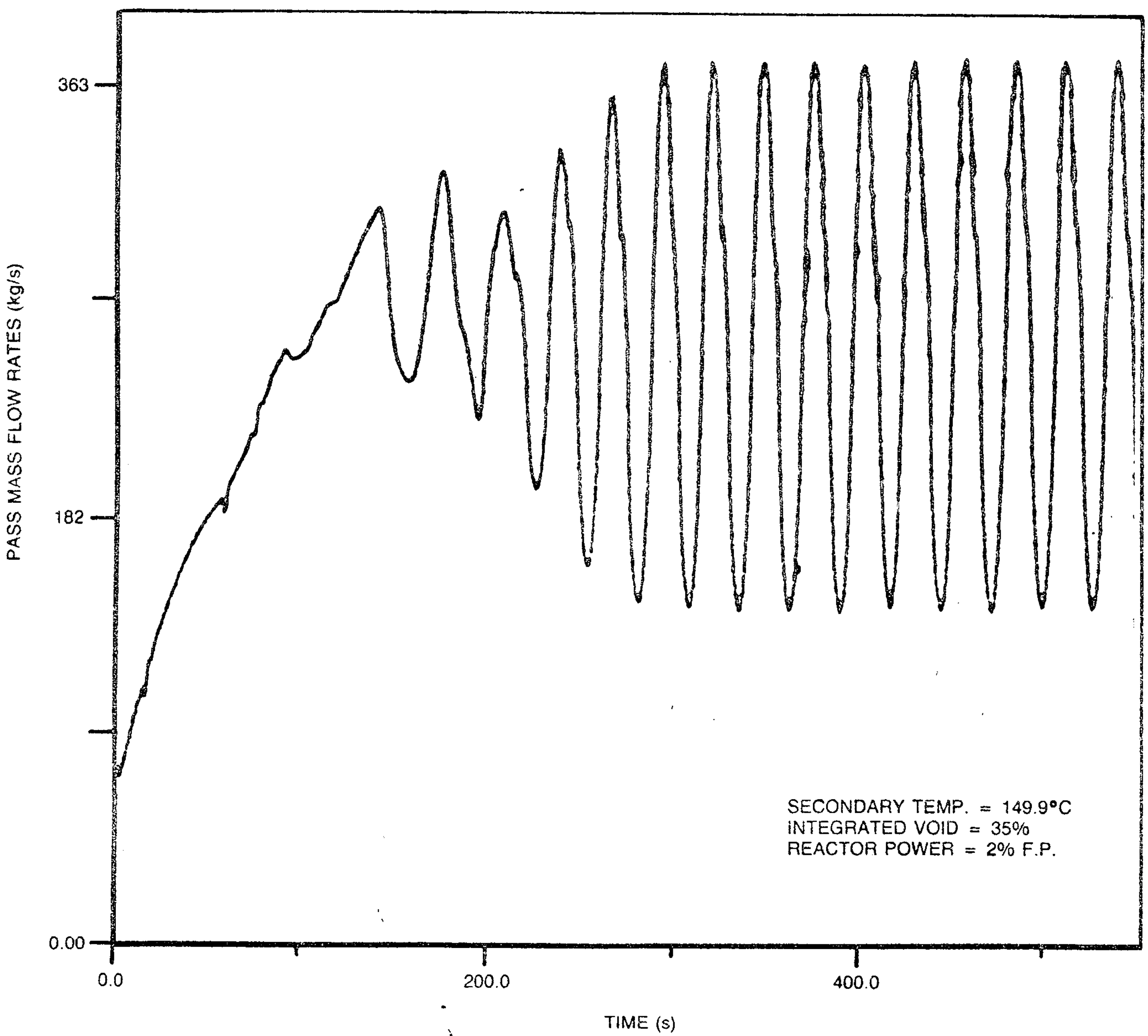


FIGURE 24 SYSTEM IN-PHASE FLOW OSCILLATIONS

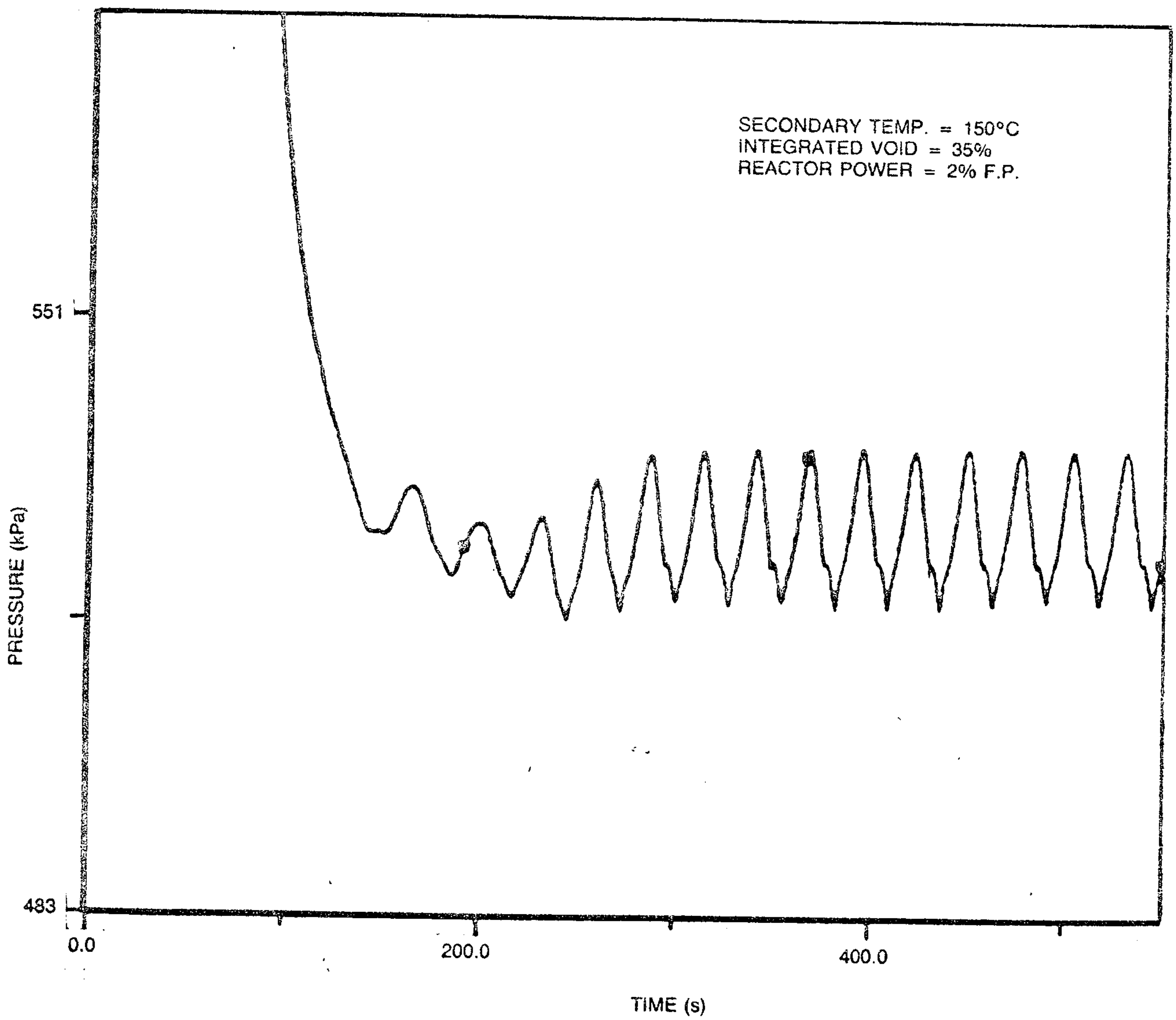


FIGURE 25 SYSTEM IN-PHASE RCH PRESSURE OSCILLATIONS

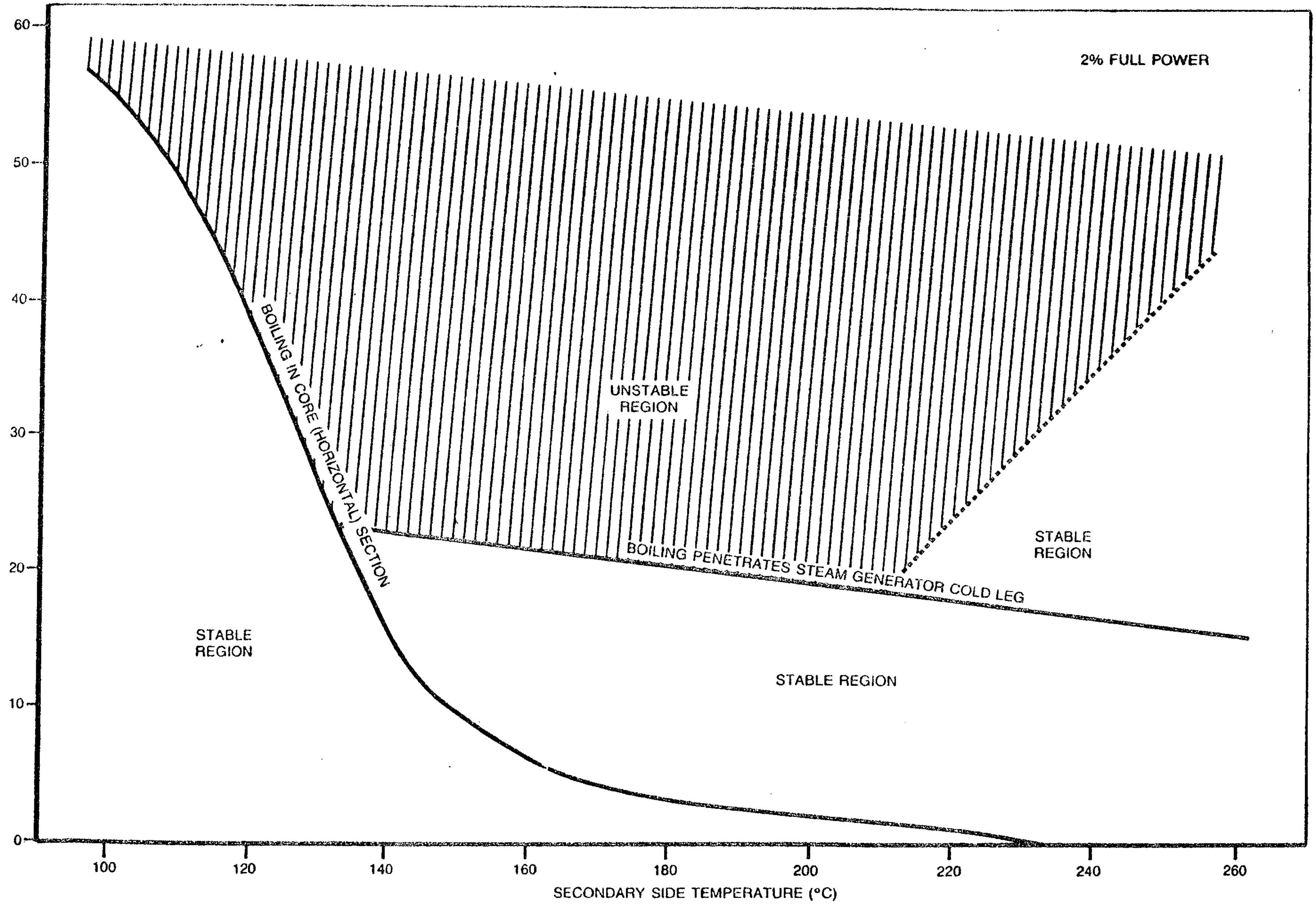


FIGURE 26 PREDICTED SYSTEM IN-PHASE FLOW OSCILLATION STABILITY MAP (THERMOSYPHONING CONDITION)