

DYNAMIC SIMULATION OF THE TWO-PHASE ABSORBER CONTROL SYSTEM

by

C.B. Lawrence
Atomic Energy of Canada Limited, Chalk River

ABSTRACT

A simulation of the Two-Phase Absorber Control (TOPAC) System to study normal and abnormal operational transients and postulated accident conditions has been performed on the Dynamic Analysis Facility in the Reactor Control Branch at CRNL. The simulation consists of a lumped-parameter model of each major component in the system. The simulation has been used to study the consequences of:

- a sudden rupture of a large diameter pipe connected to either the gas or liquid side of the high- or low-pressure tank,
- failure of all water pumps,
- failure of all compressors.

The results of the study have been used to assist in selecting parameters that provide reliable indications of the effectiveness of the TOPAC System.

NOMENCLATURE

VARIABLE

A	area
a_i	coefficient
b_i	coefficient
C_o	distribution parameter
F	function
G	mass flux
g	acceleration due to gravity
H	height
L	(i) valve lift (ii) length
M	momentum
P	pressure

p	differential pressure
p_w	wetted perimeter
Q_ℓ	volume flow of liquid
t	time
U	void propagation velocity
u	velocity
z	distance
α	void fraction
α_1	U-tube inlet void fraction
$\overline{\alpha_2}$	average U-tube void fraction
α_3	return line inlet void fraction
$\overline{\alpha_6}$	average return line void fraction
α_7	return line outlet void fraction
θ	angle with horizontal
ρ	density
τ_w	wall shear stress

INTRODUCTION

A simulation of the Two-Phase Absorber Control (TOPAC) System [1], to study normal and abnormal operational transients and postulated accident conditions, has been performed on the Dynamic Analysis Facility in the Reactor Control Branch at CRNL. The conceptual design of the TOPAC System for the PHW-1250 reactor is described elsewhere [1], and a brief description of the system is presented in a companion paper [2].

The simulation consists of lumped-parameter models of each major component in the system, shown schematically in Figure 1. Liquid and gas flow separately from the high-pressure (HP) tank to a mixer situated roughly at the core edge. From the mixer, a two-phase mixture flows through a U-tube in the reactor core and then to the low-pressure (LP) tank. Compressors and pumps move the gas and liquid from the LP tank to the HP tank. In the PHW-1250 system, it was proposed to have 32 U-tubes,

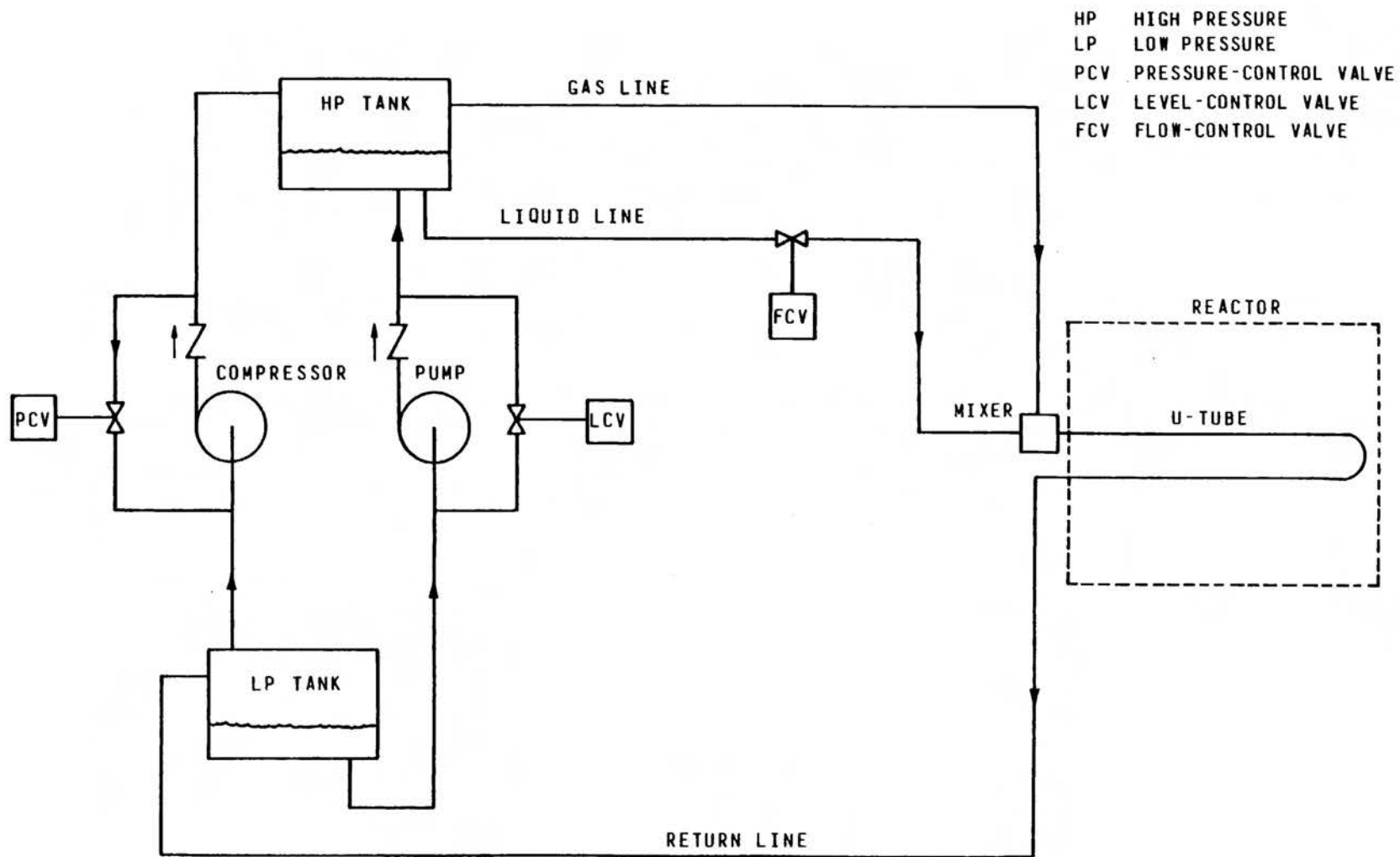


FIGURE 1 DYNAMIC SIMULATION OF TOPAC SYSTEM

each with its own gas and liquid supply lines fed from a single HP tank, and discharging the two-phase mixture to one LP tank. Five continuously operating compressors and one pump, with a second on standby, are proposed for pumping the gas and liquid from the LP to the HP tank.

The simulation of the TOPAC System consists of the following models

- the HP and LP tanks
- a compressor and pressure-control valve
- a pump and level-control valve
- a gas line
- a liquid line and flow-control valve
- a mixer
- the two-phase pressure drop in the U-tube and return line
- the void propagation in the U-tube and return line
- reactor kinetics
- discharge of gas from a tank
- discharge of liquid from a tank

In the TOPAC System, a change in reactivity is obtained by changing the density of the two-phase mixture flowing through the U-tube in the reactor core. As the interaction of the various TOPAC sub-systems is quite complex, a complete simulation is required to calculate the response to a perturbation. We are interested in both normal operational perturbations and postulated accident conditions.

The next section describes the models and the following section presents some simulation results.

THEORETICAL MODELS

A brief description of each component model is given below.

High- and Low-Pressure Tanks

The model of the high- or low-pressure tank consists of a fixed volume occupied by both gas and liquid. The model determines liquid level and gas pressure from a calculation of the net flow of gas and liquid into the tank. The ideal gas laws are used with isentropic expansion/compression.

Compressor and Pressure-Control Valve

The compressor model takes into account the pressure/flow characteristic of the compressor. No allowance is made for friction effects, gas storage or inertia, i.e. all responses are instantaneous. It is assumed that when inlet pressure is higher than outlet pressure, there is a very small pressure drop across the compressor. Reverse flow through the compressors is not permitted (because of a check valve at the compressor outlet).

The pressure-control valve bypasses gas flow from the compressor outlet back to the inlet. The model consists of

- a proportional plus integral controller,
- a second-order, velocity-limited valve, relating demanded valve lift to actual lift,
- the valve C_v characteristic, and
- the Bernoulli (orifice) equation for compressible gas flow.

The controller maintains a constant differential pressure between the HP and LP tanks. Neither frictional pressure drop nor inertia in connecting lines is considered. Reverse flow is allowed to occur through the bypass valve.

Pump and Liquid-Level Control

The pump model takes into account the head versus flow characteristic of the pump, the pressure difference between the tanks and gravity effects. The pump model does not take account of inertial or frictional effects. Reverse flow is not permitted through the pump because of a check valve at its outlet.

The level-control valve bypasses liquid from the pump outlet, back to the inlet. The model contains

- a proportional plus integral controller,
- a second-order, velocity-limited valve, relating demanded valve lift to actual lift,

- the valve C_v characteristic, and
- the Bernoulli (orifice) equation for incompressible flow.

The controller maintains a constant liquid level in the HP tank. Inertia and friction in the interconnecting lines are not considered, and reverse flow through the bypass valve is permitted.

Gas Line

The gas line feeds oxygen from the HP tank to the mixer. Only one of the 32 lines in the system is modelled, but the gas outflow from the HP tank is scaled to be 32 times the flow in one line. The model consists of one isentropic lump and takes into account the frictional pressure drop, the effect of the mixer and the inertia of the gas. The pressure drop is assumed to occur at a single point, i.e. the density along the pipe is assumed constant.

Liquid Line and Flow-Control Valve

The liquid line feeds borated water from the HP tank to the mixer. Only one of the 32 lines is modelled, but liquid out-flow from the tank is scaled to 32 times the flow in one line. The flow-control valve controls the liquid flow in the line, hence the density and reactivity of the two-phase mixture in the U-tube. The hydrodynamic part of the model takes into account

- fluid friction,
- gravity,
- valve characteristic, and
- water inertia.

The momentum equation, describing incompressible flow in the liquid line, is

$$- b_1 \frac{dQ_l}{dt} + \left\{ b_2 + b_3 F(L) \right\} Q_l^2 + b_4 H + p = 0 \quad (1)$$

where the first term is due to the inertia of the water, the second is the fluid friction due to the pipe and the flow control valve, the third is the gravity head and the last is the pressure head.

Thus, given the valve lift, L , and the pressure head, p , equation (1) can be solved for the liquid flow, Q_L . The implementation of equation (1) on the hybrid computer is shown in Figure 2. The fluid friction term is stored in the digital computer as a function of valve lift, L , and output as a coefficient that varies with L . The valve and controller comprise

- a second-order, velocity-limited valve, and
- a proportional plus integral controller that maintains neutron flux at a fixed value.

Mixer

The mixer model accepts flows of gas and liquid and generates a two-phase outflow. The outflow is characterized by a void fraction and pressure at the mixer.

Two-Phase Pressure Drop in U-Tube and Return Line

This model simulates the non-linear relation between two-phase flow and pressure drop in the U-tube and return line. It takes into account the effects of friction, inertia, gravity, changes in momentum and discontinuities in tube diameter. The model is based primarily on two previous formulations. The frictional effects are based on a wall shear-stress formula for adiabatic, two-phase flow [3], while the propagation velocity of the two-phase mixture is based on a void-fraction correlation. Some of the effects are treated using spatially-averaged quantities.

The pressure drop for a line of constant cross section is given by the momentum equation

$$\frac{\partial P}{\partial z} + \frac{\partial G}{\partial t} + \frac{\partial M}{\partial z} + \frac{P_w \tau_w}{A} + \rho g \sin \theta = 0 \quad (2)$$

Equation (2) is solved by integrating each term over the length of lines and making approximations to turn it into an ordinary non-linear differential equation. Before being implemented on the hybrid computer, equation (2) was re-arranged in a manner similar to that described in [4]. Also, we used the equations given in [5] to take into account the effects of discontinuities in pipe diameter.

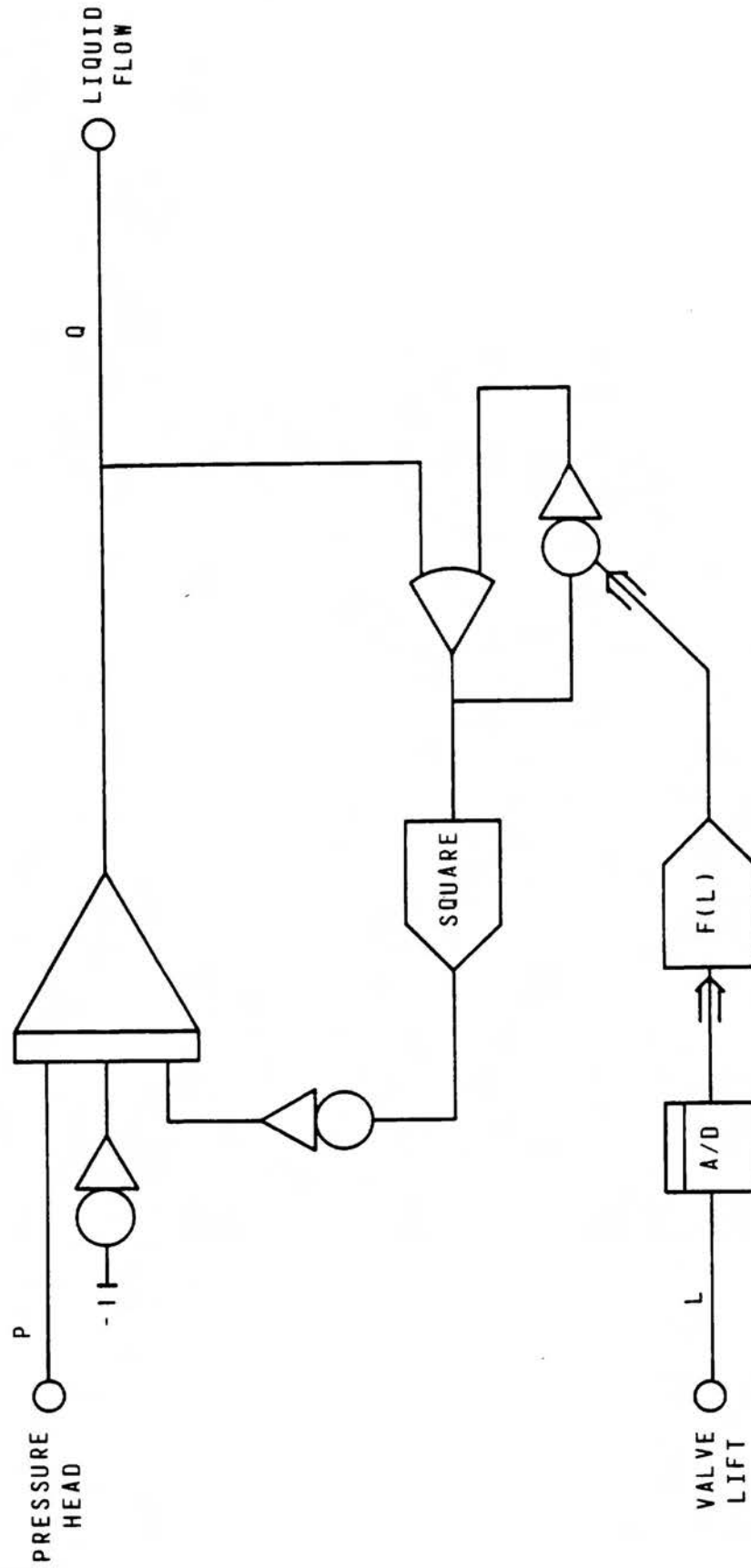


FIGURE 2 LIQUID LINE SIMULATION

The final equation is

$$\dot{u} \left(1 - a_1 \bar{\alpha}_2 - a_2 \bar{\alpha}_6 \right) + p + a_3 \bar{\alpha}_6 + u^2 \left\{ F_{10} (\alpha_1) + F_9 (\alpha_3) + F_8 (\alpha_7) + F_{11} (\bar{\alpha}_2) + F_{12} (\bar{\alpha}_6) \right\} = 0 \quad (3)$$

In equation (3), the coefficient of $\dot{u}$ is due to the inertia of the fluid, p is the pressure head and $a_3 \bar{\alpha}_6$ is the gravity head. The coefficient of u^2 contains 5 terms:

- $F_{10} (\alpha_1)$ results from the fluid momentum at the U-tube entrance,
- $F_9 (\alpha_3)$ represents the momentum plus discontinuity effects at the return line entrance,
- $F_8 (\alpha_7)$ is the momentum at the end of the return line,
- $F_{11} (\bar{\alpha}_2)$ represents the two-phase friction in the U-tube, and
- $F_{12} (\bar{\alpha}_6)$ represents the two-phase friction in the return line.

To reduce the momentum equation to equation (3), we made the following assumptions:

- (i) inertia-weighted and volume-weighted averages of the void are equal,
- (ii) orientation-weighted and volume-weighted averages of the void in the return line are equal,
- (iii) functions representing two-phase friction, which are a strong function of void and a weak function of velocity, are calculated as a function of void only,
- (iv) friction-weighted and volume-weighted averages of two-phase friction are equal,
- (v) the void fraction at all discontinuities is the same as the void fraction at the U-tube/return line junction.

The implementation of equation (3) is shown in Figure 3. All the non-linear functions are stored in the digital computer and output as coefficients that vary with the appropriate void fraction.

Void Propagation in U-Tube and Return Line

The mixture void fraction is used to determine the reactivity of the device. The void-fraction propagation is modelled to travel at a velocity that is a function of the mixture velocity and the void fraction itself [6]. This non-linear behaviour has been linearized and the model resembles a transport delay, with a variable delay time. The reactivity of the mixture is assumed to be directly related to the average mixture density in the U-tube. By assuming adiabatic flow of gas and liquid, the densities of which remain spatially and temporally invariant, and also assuming that at any point the gas and liquid velocities are equal, the following equations can be derived [7]

$$\frac{\partial}{\partial t} \langle u \rangle + \frac{\partial}{\partial z} \langle \alpha u \rangle = 0 \quad (4)$$

$$\frac{\partial \langle u \rangle}{\partial z} = 0 \quad (5)$$

where $\langle \rangle$ denotes the average over the cross-sectional flow area.

Following the development in [6], we introduce the distribution parameter C_o to obtain the well known void-propagation equation

$$\frac{\partial \langle \alpha \rangle}{\partial t} + U \frac{\partial \langle \alpha \rangle}{\partial z} = 0 \quad (6)$$

where

$$U = \left(C_o + \langle \alpha \rangle \frac{\partial C_o}{\partial \langle \alpha \rangle} \right) \langle u \rangle \quad (7)$$

If U is constant, the solution to equation (9) is given by a fixed transport delay of time τ ,

$$L = \int_{t-\tau}^t U dt \quad (8)$$

where L is the pipe length.

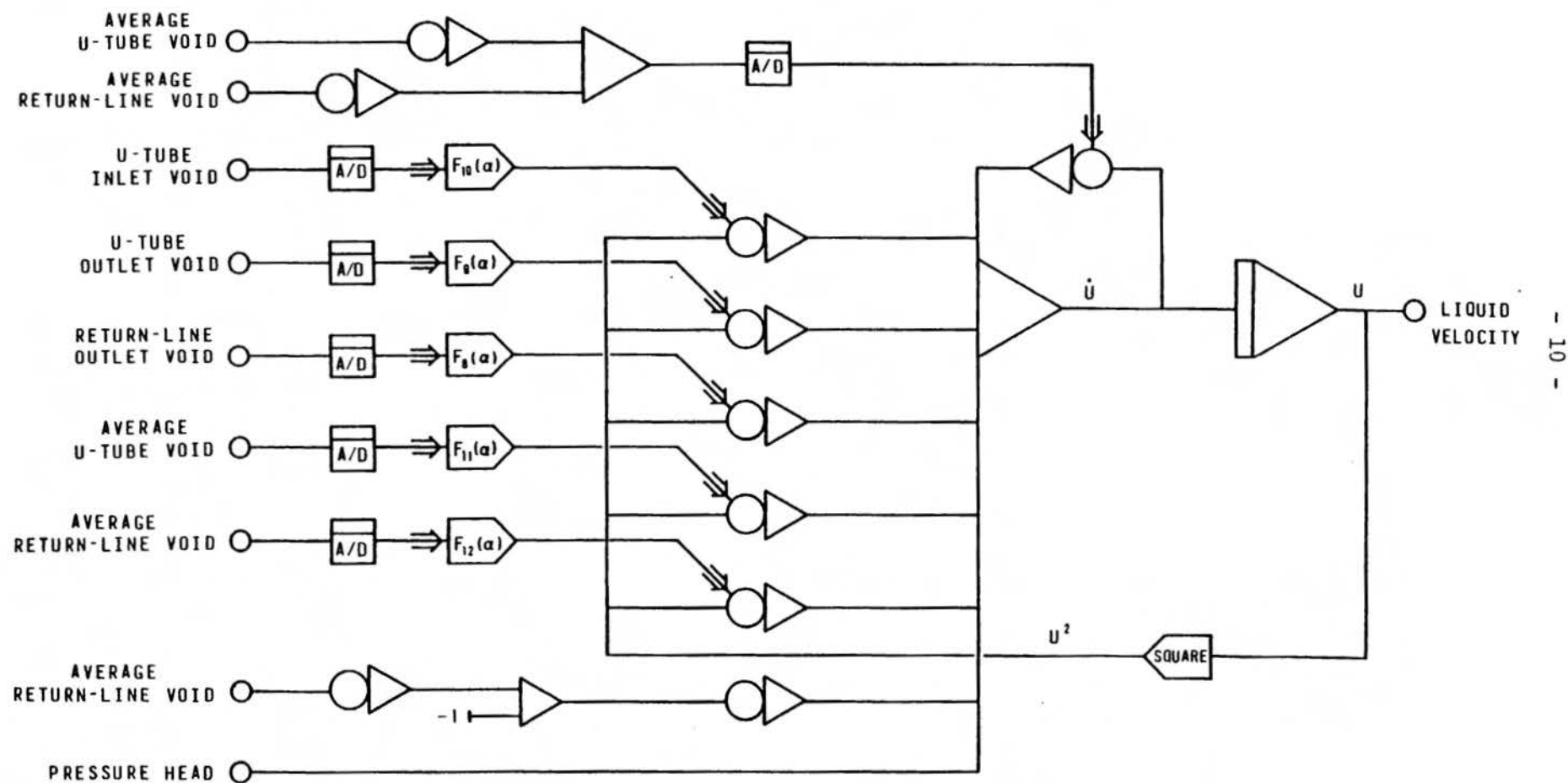


FIGURE 3 TWO-PHASE PRESSURE DROP SIMULATION

We have solved equation (6) by using a variable transport delay of time τ to satisfy equation (8). In our implementation of the solution, we recognize that

$$\alpha(t,z) = \bar{\alpha}(t) + \Delta\alpha(t,z) \quad (9)$$

and then set $\Delta\alpha(t,z) = 0$.

This permits quite a simple solution to equation (6). The approximation gives the following properties to the solution:

- (i) in steady state, i.e. when $\Delta\alpha = 0$, there is no error,
- (ii) when $\Delta\alpha$ is very small, the error is negligibly small, thus yielding the correct small-signal response.

When $\Delta\alpha$ is sufficiently small that $\Delta\alpha^2$ and higher powers are negligible, then we can state that:

- (i) $\bar{\alpha}$ is the average void fraction,
- (ii) the volume integral of the error is zero, i.e. the velocity is correct on average.

The implementation, on the hybrid computer, of equation (6) via equation (8) is shown in Figure 4.

The transport delays are obtained by converting values to digital form and storing them in delay tables of fixed length. The input of a new value and the output of the oldest is controlled by the two parts of equation (7): u , the fluid velocity, and the non-linear function of α given by equation (7). Separate delay tables and input/output control are used for the U-tube and return line.

Reactor Kinetics

The reactor is represented by a point-reactor model, with six groups of delayed neutrons. The reactor is initially critical with the U-tube containing a two-phase mixture at mid-density. Changes in the average mixture density in the U-tube are assumed to result in a proportional change in reactivity. For this study, the reactivity of the absorber,

representing the 32 U-tubes, was assumed to change by ~ 11.5 mk, as mixture density varied from 0 to 1000 kg/m³.

Discharge of Gas from a Tank

The gas-discharge model simulates a sudden rupture of a line connected to the gas portion of the HP or LP tank. The model is based on gas discharge to atmosphere through a nozzle, at tank pressures above the critical pressure [8]. The only initial input parameter to the model is the break area.

Discharge of Liquid from a Tank

The liquid-discharge model simulates liquid discharging from the HP or LP tank to atmosphere, through a line that has suddenly been sheared off. The model is derived from the Bernoulli equation for incompressible flow. The entrance to the opening was assumed to be well-rounded [9]. The area of the opening is the only initial input parameter.

SIMULATION RESULTS

Transients

The TOPAC simulation has been used to study system upsets as well as hypothetical pipe breaks and subsequent loss of gas or liquid from the HP or LP tank. In these studies, one of the key properties of the TOPAC System was found to be its ability to withstand sudden pressure changes without major disturbances to the reactivity in the U-tubes.

To study the system's tolerance to pressure disturbances, we held the LP tank pressure constant and introduced a step change in differential tank pressure of 25%, by changing the HP tank pressure by 25 kPa. The results for a decrease and an increase in differential tank pressure are shown in Figures 5 and 6, respectively. In Figure 5, the sudden drop in pressure (top trace) causes gas flow (2nd trace) to drop and a slug of water to enter the U-tube and thus decrease reactivity (5th trace). This causes reactor power to drop. When the slug of water is swept out of the U-tube, the reactivity (5th trace) returns to near its initial level.

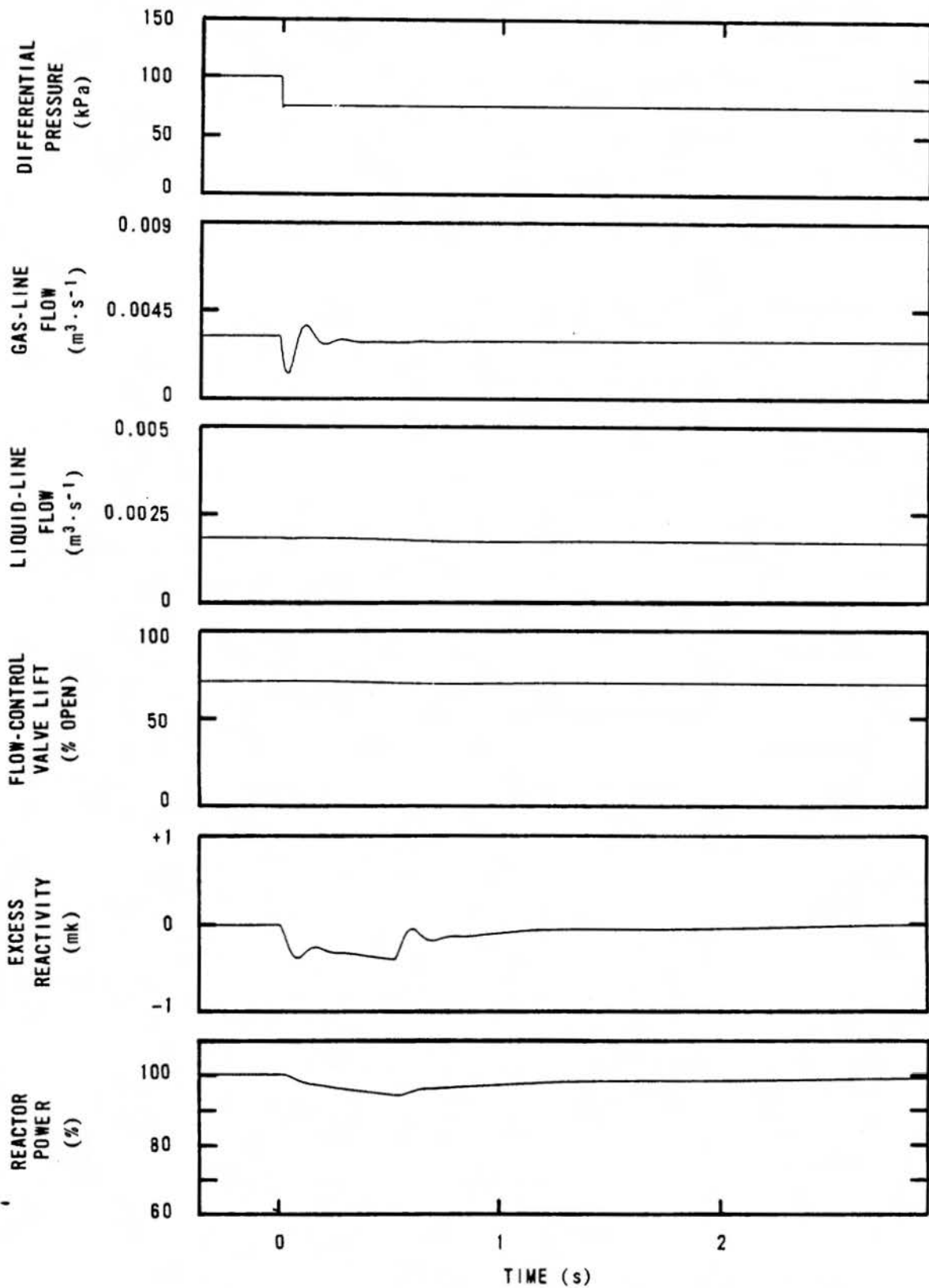


FIGURE 5 SIMULATION OF A NEGATIVE STEP IN DIFFERENTIAL TANK PRESSURE

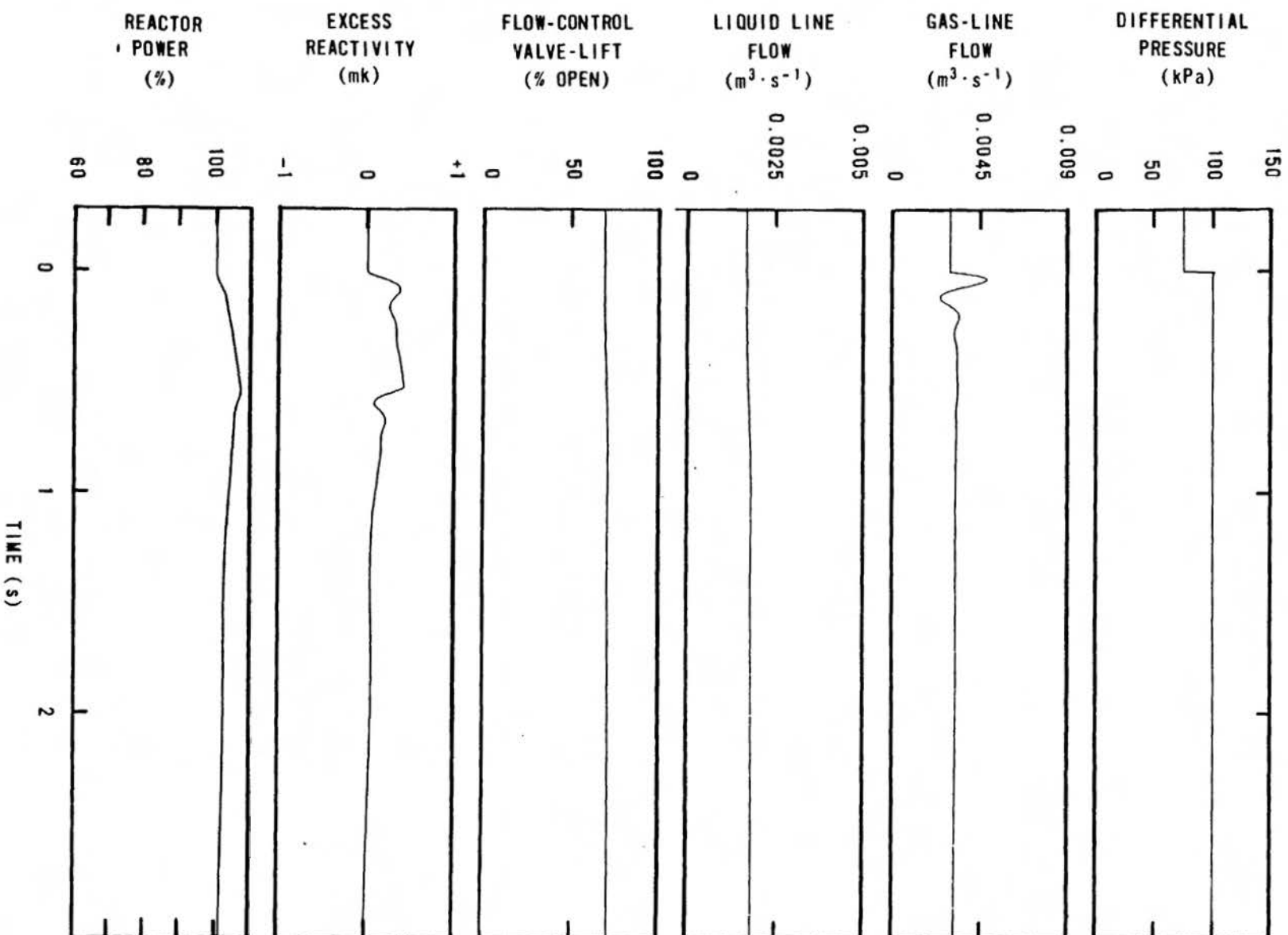


FIGURE 6 SIMULATION OF A POSITIVE STEP IN DIFFERENTIAL TANK PRESSURE

The reactor control system then acts to restore power to the correct level.

When the differential pressure is increased, as shown in Figure 6, the opposite occurs. The sudden pressure increase (top trace) causes a bubble of gas to enter the U-tube, reactivity (5th trace) to increase and power (bottom trace) to rise. When the bubble is swept from the U-tube, reactivity returns to near its initial level, and the reactor control system restores power to the correct level. These results show the system to tolerate a step disturbance in pressure even though step changes in pressure are difficult to achieve in practice.

The most severe hypothetical pressure disturbance we could envisage is the sudden rupture of a "6 in." pipe connected to the LP tank. The simulation results for the U-tube with an initial void fraction of 0.55 are shown in Figure 7. The simulation shows that:

- (i) Gas discharge (top trace) from the break causes the LP tank pressure to fall rapidly.
- (ii) The differential pressure between the HP and LP tanks rises (2nd trace) with falling LP tank pressure. This causes an increase in gas flow through the U-tubes and consequently a sharp positive reactivity transient (5th trace). The liquid flow also rises, but at a slower rate.
- (iii) The positive reactivity transient causes the power (bottom trace) to rise at a high rate. This would trip the safety system and shut the reactor down.

The safety system was not modelled, and thus a reactor trip is not shown in Figure 7. However, even without the trip, reactor power increases to only ~110% of nominal power.

Another pressure disturbance studied was the simultaneous trip of all five gas compressors. The results for an initial void fraction of 0.55 are shown in Figure 8. The sequence of events leading to reactor shutdown is as follows:

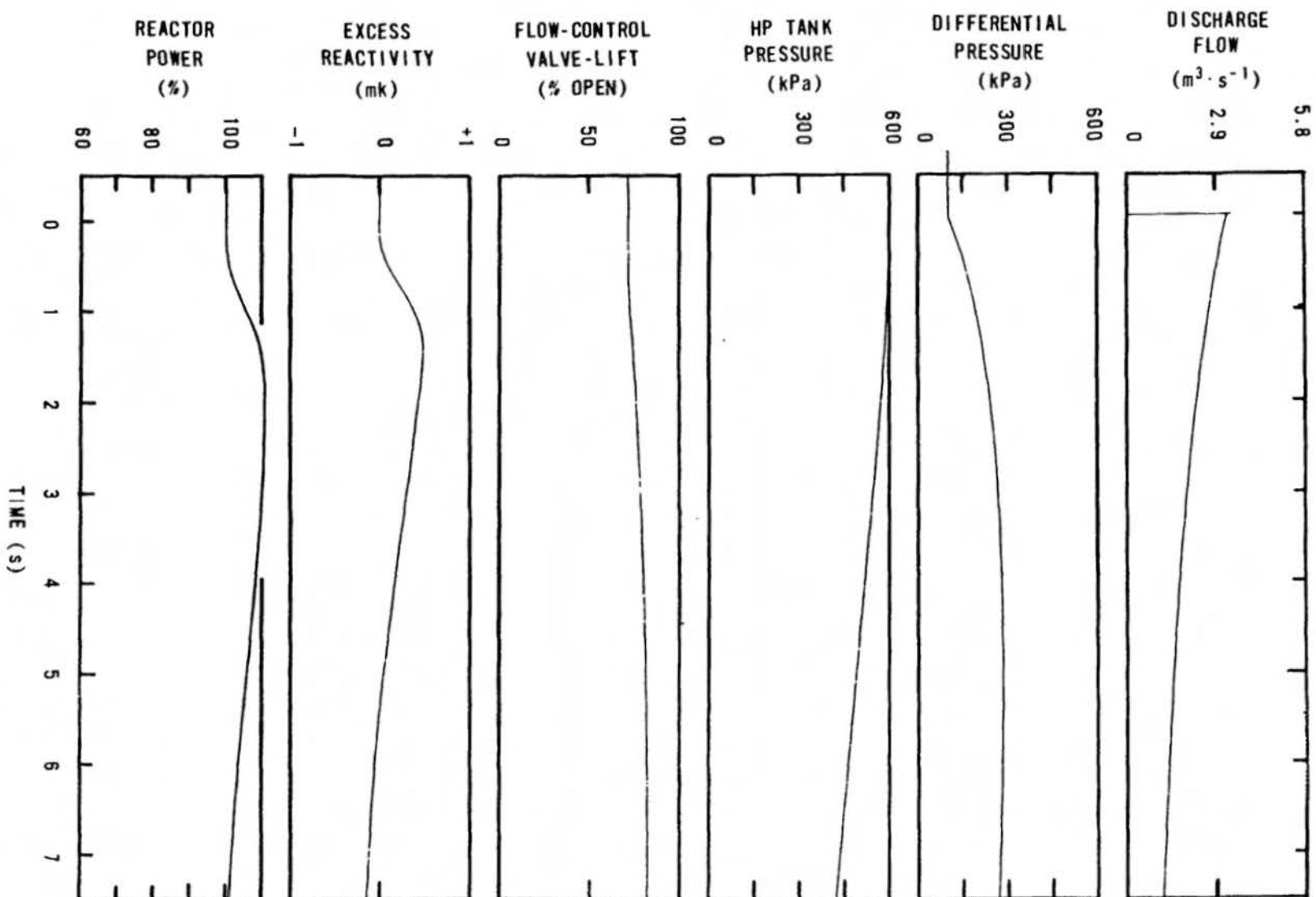


FIGURE 7 SIMULATION OF GAS DISCHARGE FROM LOW-PRESSURE TANK

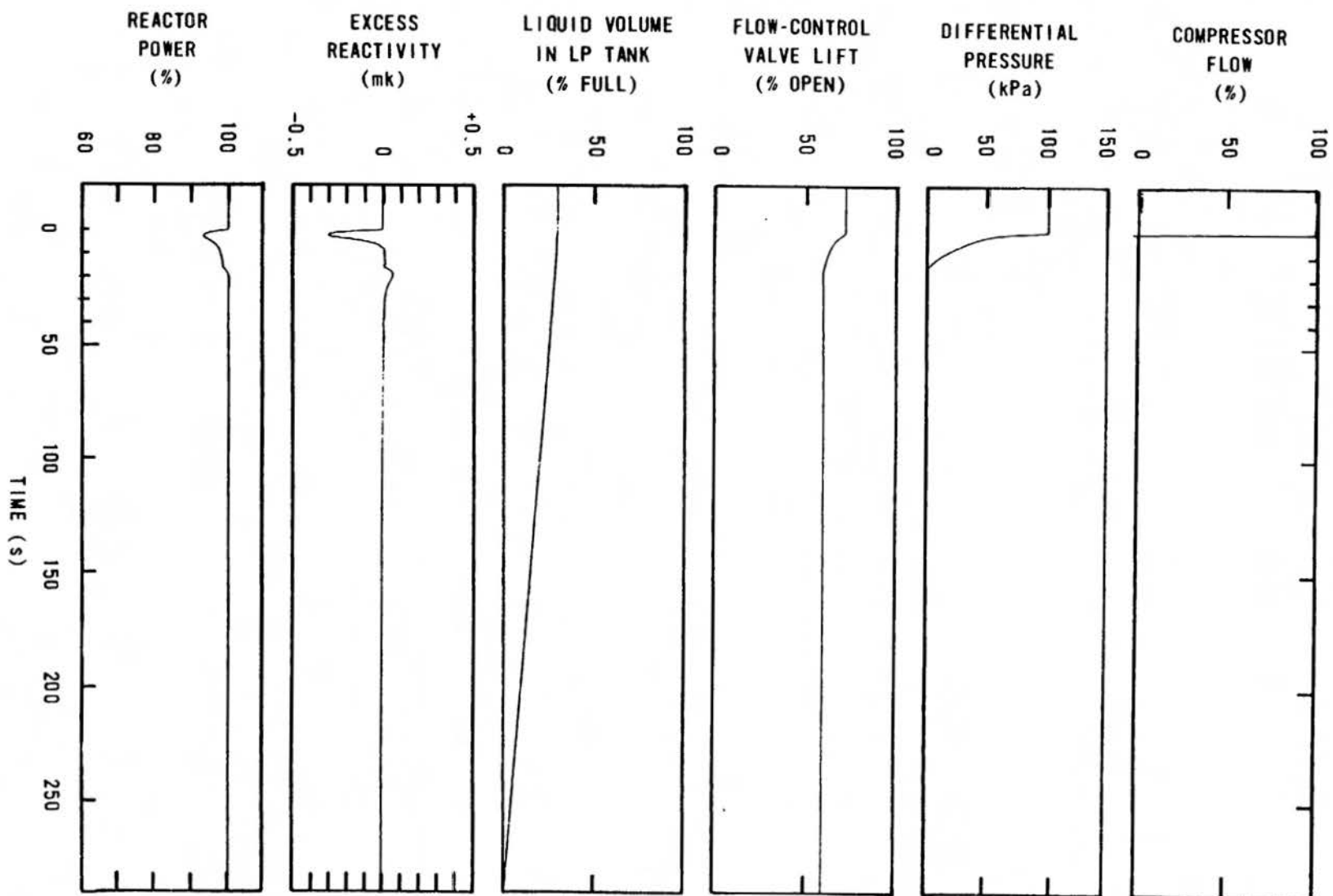


FIGURE 8 SIMULATION OF A TRIP OF ALL FIVE COMPRESSORS

- (i) With all conditions normal, all compressors cease operation, shown in the top trace of Figure 8.
- (ii) The differential pressure between the HP and LP tanks starts to drop very rapidly (2nd trace). Gas is flowing from the HP tank to the LP tank via both the U-tubes and the pressure-control valve in the gas by-pass line. After a short time, the pressure-control valve closes, in an attempt to maintain differential pressure.
- (iii) The drop in differential pressure causes the gas flow to the absorbers to decrease, and results in a reactivity dip (5th trace), with a consequent dip in reactor power (6th trace). The flow-control valve (3rd trace) moves to correct reactivity and power level.
- (iv) When the differential pressure falls below the low-level setpoint, a reactor stepback would be initiated, ~ 2 s after the compressor trip.
- (v) Water flow from the LP to the HP tank increases, because of the low differential pressure across the pump.
- (vi) If the level-control valve cannot bypass sufficient flow, the water level in the HP tank rises until the LP tank is empty (4th trace) and the pump cavitates. However, water continues to flow through the absorbers.

A reactor stepback is not shown in Figure 8, as we wanted to study the TOPAC System performance without the intervention of the stepback or safety systems. The simulation showed that the TOPAC System will continue to operate with low differential pressure, but its performance is poor and may be unstable. A low differential pressure causes the void-transit time of the absorber to increase, with a consequent decrease in phase margin of the overall control system, which results in an unstable, or oscillatory, response. Thus, an automatic stepback on low differential pressure is required to shut the reactor down.

Another case studied was the loss of both pumps, a condition that requires a reactor stepback. The sequence of events, shown in Figure 9, is as follows:

- (i) With liquid level and gas pressures at their normal setpoints, the operating pump stops and the standby is unavailable (top trace).
- (ii) The liquid level in the HP tank (3rd trace) begins to fall rapidly. The level-control valve (4th trace) closes, in an attempt to maintain liquid level, but the level continues to fall at a rate determined by liquid flow to the U-tubes.
- (iii) The initial sudden drop in water level causes a small drop in differential pressure (2nd trace) that is corrected by the pressure-control valve.
- (iv) The dip in differential pressure causes a small negative reactivity transient (5th trace) and consequent dip in reactor power (6th power). The power level is re-established by the TOPAC System.
- (v) Liquid level in the HP tank continues to fall. When the low-level setpoint is reached (from 40 to 120 s after the pump trip) a stepback in reactor power would be initiated.
- (vi) The TOPAC System continues to operate until the liquid in the HP tank is used up. Gas then flows down the liquid lines and the U-tubes void, resulting in a positive reactivity insertion.

Again, we did not include the reactor stepback in the simulation as we wished to study the performance of the TOPAC System under unusual conditions. The results show that, by itself, a pump stoppage does not upset the reactor sufficiently to cause a stepback or trip. If the pump can be restarted before the low-level setpoint is reached, there would be no upset in normal reactor operation.

The final case, shown in Figure 10, simulates liquid discharge from an area equivalent to an "8 in." pipe connected to the HP tank, with the

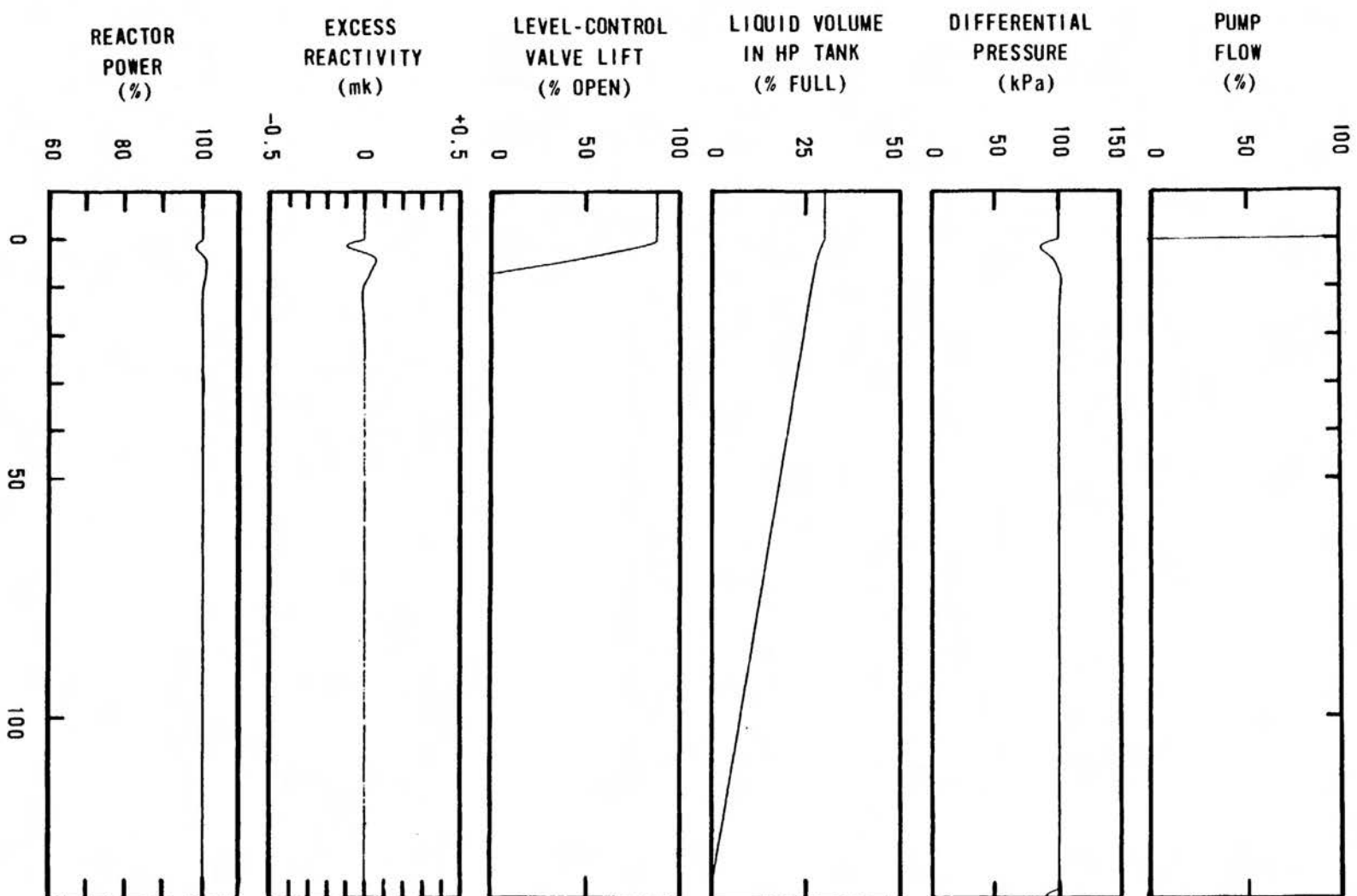


FIGURE 9 SIMULATION OF A PUMP TRIP

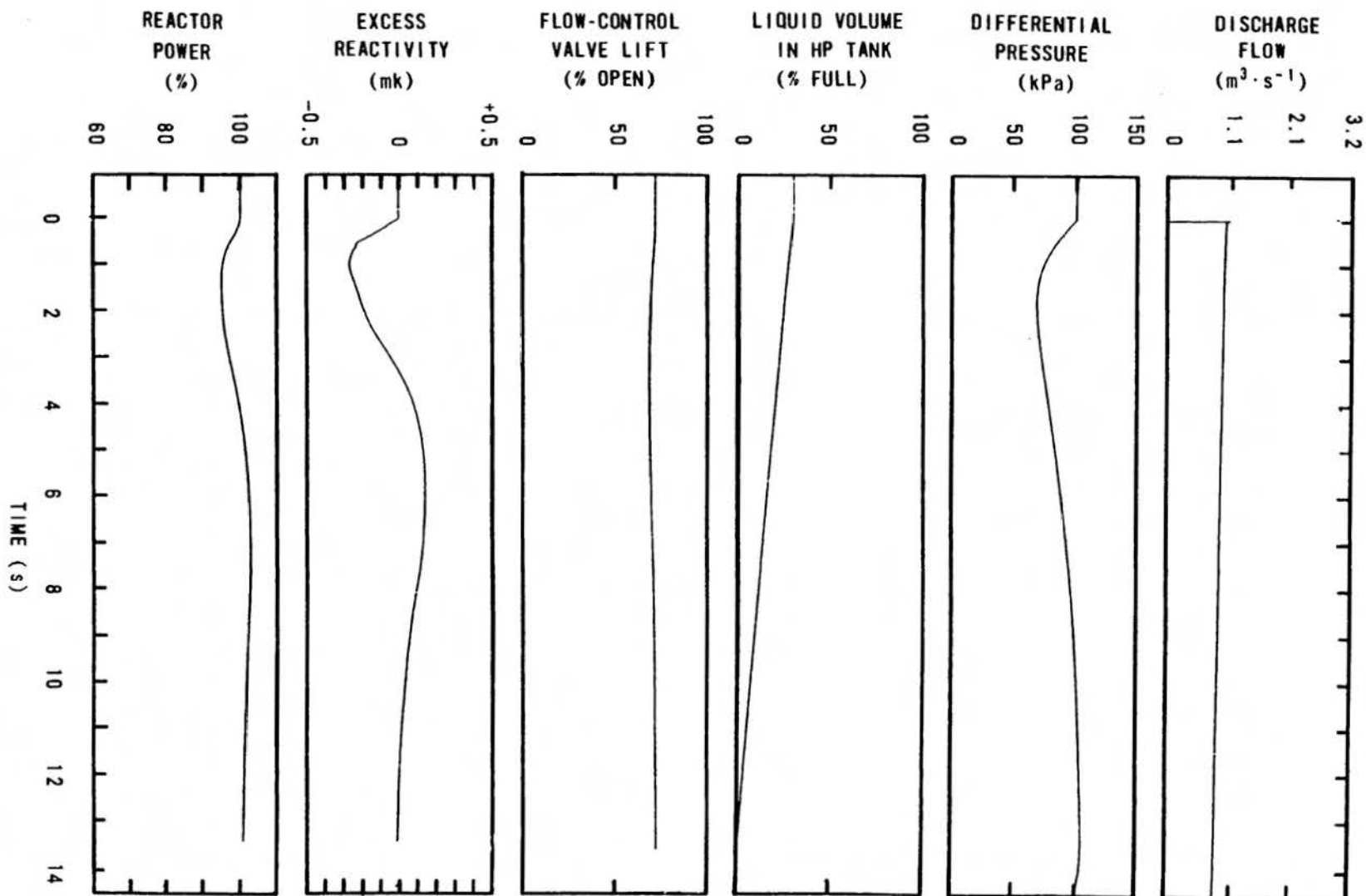


FIGURE 10 SIMULATION OF LIQUID DISCHARGE FROM THE HP TANK

absorber void initially at 0.55. The sequence of events is as follows:

- (i) The liquid level (3rd trace) and pressure in the HP tank begin to fall simultaneously.
- (ii) Gas flow to the U-tubes drops more rapidly than liquid flow, resulting in a negative reactivity (5th trace) insertion. The reactor power (6th trace) dips, but is corrected by the TOPAC System.
- (iii) The HP tank low liquid level setpoint is reached in about 5 to 10 s and would initiate a stepback in reactor power.
- (iv) Discharge continues until the liquid is exhausted from the HP tank (~ 13 s) and passes through the liquid feeders (~ 20 to 30 s). The liquid then drains from the U-tubes, inserting positive reactivity into the reactor.
- (v) If the negative reactivity associated with the reactor stepback were insufficient to cover the positive reactivity due to U-tube voiding, reactor power would rise until the safety system trips and shuts the reactor down.

Reactor power does not exceed 110% until the U-tubes void (i.e. ~ 30 to 40 s after occurrence of the break). As before, we did not simulate a reactor stepback or trip.

Frequency Response

To calculate the small-signal frequency response, transfer functions of the modules were derived by linearizing the non-linear equations and taking Laplace transforms. The frequency responses were then computed and compared with measurements on the simulation. The responses by the two methods showed excellent agreement.

One of the more complicated frequency responses, the two-phase pressure drop/inlet void, with fluid velocity held constant, is shown in Figure 11. This frequency response includes momentum, discontinuity, gravity, and two-phase friction effects in the U-tube and return line. Figure 11 was calculated for an average void fraction of 0.55.

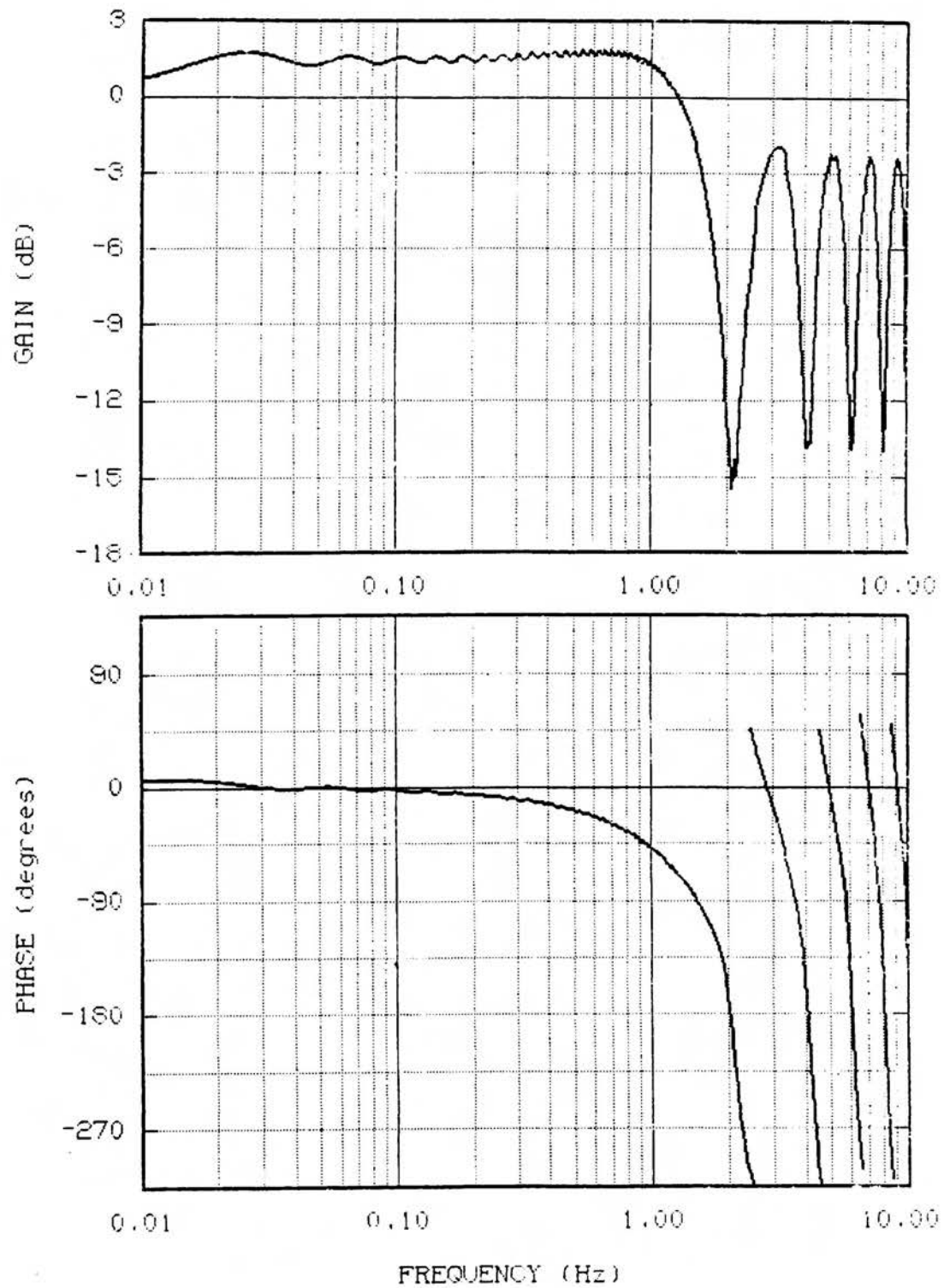


FIGURE 11 NORMALIZED FREQUENCY RESPONSE OF
TWO-PHASE PRESSURE DROP / INLET VOID

Figure 12 shows the frequency response of U-tube inlet void/flow-control valve lift. The only parameters held constant are the HP and LP tank pressures. This response includes the effects of Figure 11 as well as the inertia of the two-phase mixture and all the effects included in the gas and liquid lines. This response is also for a void fraction of 0.55.

Figure 13 is the frequency response of reactivity/flow-control valve lift. It includes all the effects from Figure 12 plus the void-transit time effect. From this response, it can be seen that the void transit time dominates the phase response of the system. The gain of the system is affected by both the inertia of the fluids and the U-tube transit time effects.

CONCLUSION

The simulation of the TOPAC System has provided not only a method of studying the transient response of the system, but also a small-signal model for use in studying the reactor control system. By using the same equation set in both, the implications in altering a system parameter are apparent from the point of view of large-signal transient and reactor control.

REFERENCES

- [1] J.S. Glen, R.M. Lepp, F.R.N. McDonnell, C.B. Lawrence and E.O. Moeck, "Conceptual Design of a Two-Phase Control Absorber for the CANDU-PHW-1250 MWe Reactor, CRNL-1705, Chalk River, in preparation.
- [2] R.M. Lepp and E.O. Moeck, "Conceptual Design of a Two-Phase Flow Absorber System for Neutron Flux Regulation in a CANDU-PHW-1250 Reactor", paper presented at the 1979 Simulation Symposium on Reactor Dynamics and Plant Control, Orangeville, 1979 April.
- [3] W.T. Hancox and W.B. Nicoll, "A Wall Shear Stress Formula for Adiabatic Two-Phase Flow", unpublished internal report CWAPD-210, Westinghouse Canada Limited, Hamilton, 1972 November.
- [4] R.M. Lepp and J.A. Plourde, "Dynamic Simulation of the Two-Phase Control Absorber", paper in Proceeding of the 5th Simulation

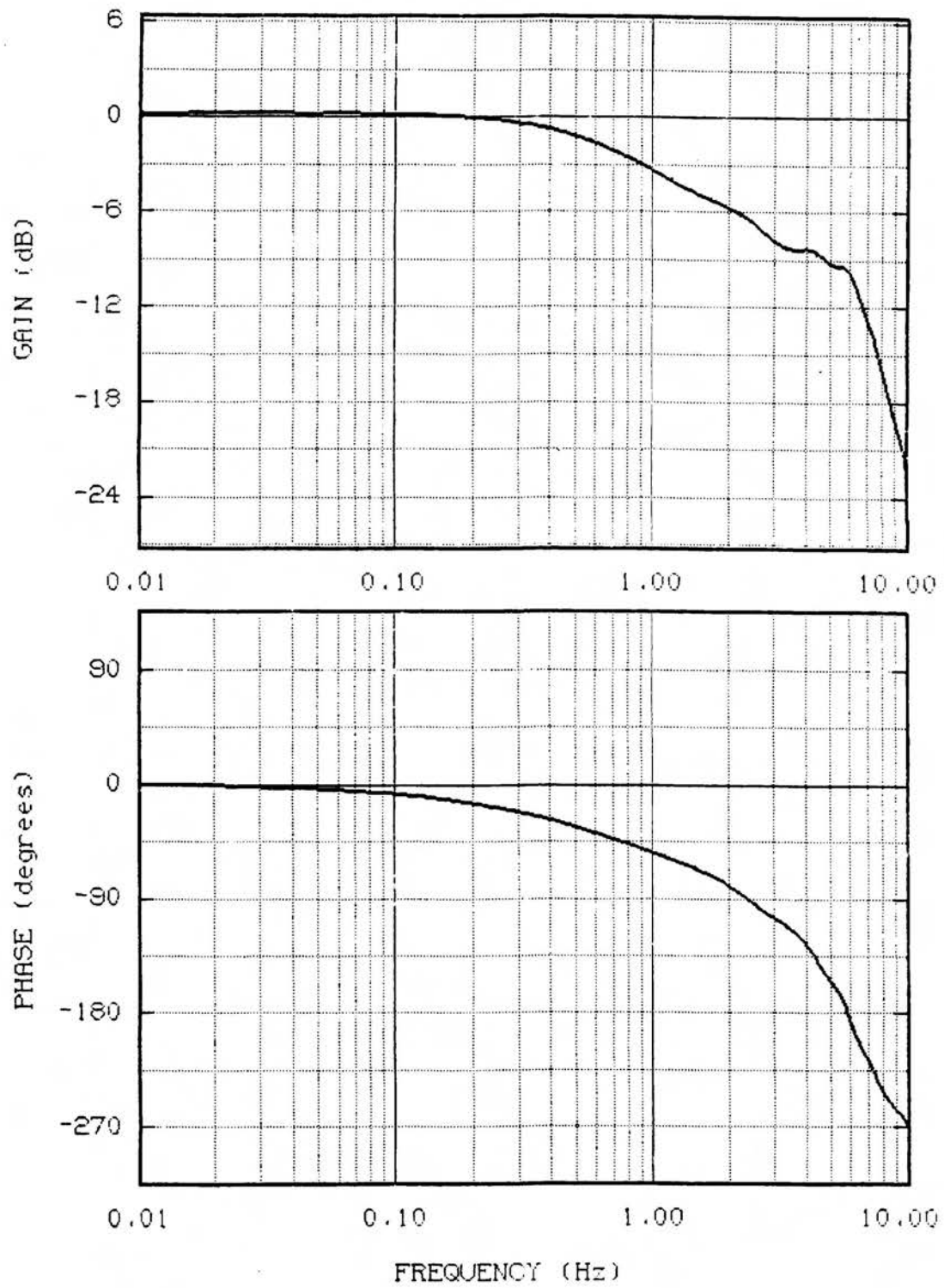


FIGURE 12 NORMALIZED FREQUENCY RESPONSE OF
U-TUBE INLET VOID / VALVE LIFT

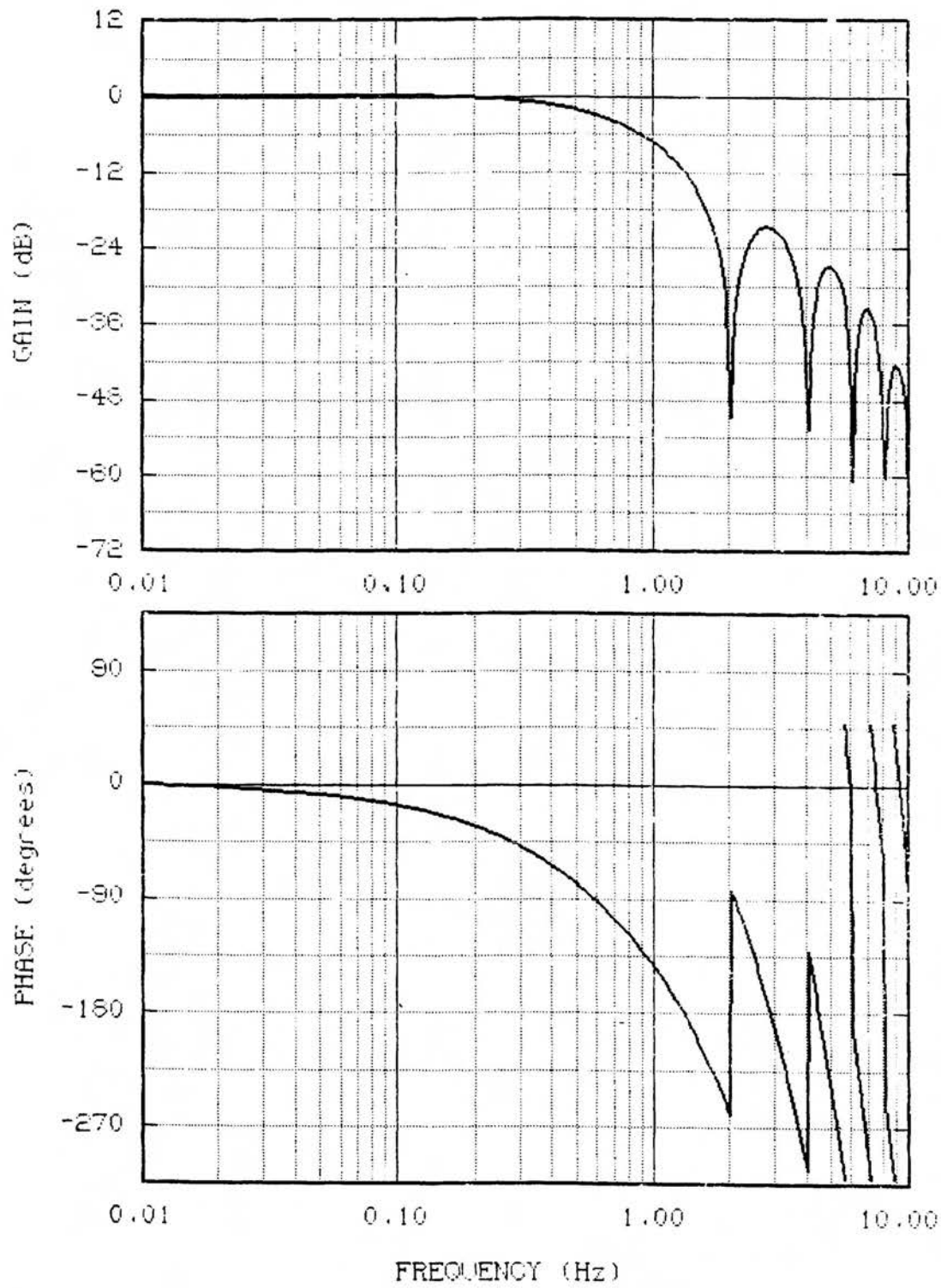


FIGURE 13 NORMALIZED FREQUENCY RESPONSE OF
REACTIVITY / VALVE LIFT

Symposium on Reactor Dynamics and Plant Control, WNRE-408, 1978
April.

- [5] J.G. Collier, "Convective Boiling and Condensation", p. 87 McGraw Hill Book Company (UK) Limited, London, 1972.
- [6] W.T. Hancox, "Predictions of Oscillating, Diabatic Steam-Water Flows", unpublished internal report, CWAPD-168, Westinghouse Canada Limited, Hamilton, 1971 March.
- [7] E.O. Moeck, R.M. Lepp and G. Frketich, "Two-Phase Control Absorber Development Program: First Results from Out-Reactor Static Tests", AECL-6077, 1977 December.
- [8] R.B. Bird, W.E. Stewart and E.N. Lightfoot, "Transport Phenomena", p. 482, John Wiley and Sons Inc., New York, 1960.
- [9] "Flow of Fluids Through Valves, Fittings, and Pipe", p. A-26, Crane Technical Paper No. 410, Crane Co., Chicago, 1957.