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CONCEPTUAL DESIGN OF A TWO-PHASE FLOW ABSORBER SYSTEM FOR NEUTRON FLUX REGULATION IN A CANDU-PHW-1250 REACTOR

Etude conceptuelle d'un système absorbeur de courant à deux phases pour le contrôle des flux de neutrons dans un réacteur CANDU-PHW-1250

R.M. LEPP and E.O. MOECK

Reprint of paper presented at the 1979 Canadian Conference on Automatic Control,
Montreal, 23-25 May 1979

Chalk River Nuclear Laboratories   Laboratoires nucléaires de Chalk River

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Résumé

Il est de plus en plus important d'améliorer le contrôle spatial des flux de neutrons des futurs réacteurs de puissance CANDU. Pour répondre à ce besoin, on développe à Chalk River depuis cinq ans un système de contrôle par absorbeur à deux phases appelé TOPAC.

On ne présente dans le rapport ci-joint que certains aspects de cette étude conceptuelle, tels que;

- la contrôlabilité du système;
- sa sensibilité aux bruits en réacteur;
- l'effet du mauvais fonctionnement de l'équipement sur la performance de la centrale, et
- le résultat d'une comparaison faite avec des systèmes concurrentiels.

On montre que le système TOPAC est une solution de rechange viable pour les systèmes actuels et futurs de contrôle des flux neutroniques faisant appel à des compartiments zonaux d'H_2O liquide.

*Rapport présenté au Congrès canadien 1979 sur le contrôle automatique tenu à Montréal du 23 au 25 mai 1979. Tiré à part autorisé par le Congrès canadien sur le contrôle automatique.

L'Energie Atomique du Canada, Limitée
Laboratoires nucléaires de Chalk River
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ABSTRACT

Improved spatial neutron flux control, for future CANDU power reactors, is becoming increasingly important. During the past five years, a Two-Phase Absorber Control (TOPAC) System has been under development at the Chalk River Nuclear Laboratories to meet these needs.

Only certain aspects of this conceptual design study are presented in the paper, such as

- system controllability
- in-reactor noise sensitivity
- effect of equipment malfunctions on plant operation, and
- a comparison with competing systems.

The TOPAC System is shown to be a viable alternative to existing and future neutron flux regulating systems based on liquid H_2O zone compartments.

*Paper presented at the 1979 Canadian Conference on Automatic Control, Montreal, May 23-25, 1979. Reprinted by permission from the Canadian Conference on Automatic Control.

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ABSTRACT

Improved spatial neutron flux control for future CANDU power reactors is becoming increasingly important. During the past five years, a Two-Phase Absorber Control (TOPAC) System has been under development at the Chalk River Nuclear Laboratories to meet these needs.

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- system controllability
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The TOPAC System is shown to be a viable alternative to existing and future neutron flux regulating systems based on liquid H_2O zone compartments.

NOMENCLATURE

C_v	control valve flow coefficient	
f	function	
$G_1(s)$, $G_2(s)$	absorber and controller transfer functions	
K	absorber gain	$k \cdot A^{-1}$
K_P	proportional sensitivity	$mA \cdot \%^{-1}$
K_I	reset rate	s^{-1}
δk	reactivity	k
L	valve position	%
L_D	valve demand	mA
M	neutron migration length	m
N	number of control absorbers in core	

Q_ℓ	liquid volumetric flow	$m^3 \cdot s^{-1}$
s	Laplace transform variable	s^{-1}
T	transport delay	s
x	distance between noise source and flux detector	m
Δ	small deviation from steady-state value	-
$\rho, \bar{\rho}$	density, average density	$kg \cdot m^{-3}$
τ	time constant	s
$\phi_1, \ldots \phi_5$	measured local neutron fluxes	$n \cdot m^{-2} \cdot s^{-1}$
$\bar{\phi}$	mean neutron flux	$n \cdot m^{-2} \cdot s^{-1}$
ϕ_g	measured global neutron flux	$n \cdot m^{-2} \cdot s^{-1}$
σ	noise standard deviation	%
σ_ℓ, σ_g	local and global noise standard deviations	%

INTRODUCTION

The power generated in nuclear stations is obtained from the heat produced by neutron-induced fission in the reactor core. The power output can be regulated by varying the fission rate (i.e. neutron flux), and this is usually done by changing the amount of neutron-absorbing material in the core. During normal plant operation, the neutron-flux regulating system automatically adjusts the positions of control absorbers which changes their neutron absorption and hence the core reactivity, to maintain the desired neutron flux.

As the size and power density of nuclear reactors increases, the need for improved spatial neutron-flux/power control becomes paramount. This implies more control absorbers, with uniform absorption along their length, to minimize local flux/power perturbations.

During the past five years, a Two-Phase Absorber Control (TOPAC) System has been under development at the Chalk River Nuclear Laboratories (CRNL) to satisfy the neutron-flux regulating requirements of future CANDU* power reactors. The basic concept was invented in Italy [1], and

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* CANada Deuterium Uranium

works on the principle that the absorption of neutrons can be regulated by varying the density of a liquid/gas mixture which flows continuously through U-tubes located in the reactor core.

Both out- and in-reactor experiments were carried out on the Two-Phase Control Absorber Experimental (TOPAX) Rig at CRNL, to determine the static and dynamic characteristics of the absorber element [2-5]. The data obtained from this program formed the basis for the conceptual design, developed to satisfy the needs of our power reactors.

The design study covered many facets, including

- piping arrangement
- system chemistry and radioactivity
- selection of materials
- reactor physics
- safety aspects
- system controllability
- in-reactor noise sensitivity
- effects of equipment malfunctions on plant operation
- a comparison with competing systems.

Only the last four items are described in this paper.

BASIC FEATURES OF TOPAC SYSTEM

A simplified schematic of the TOPAC System is shown in Figure 1. Its principle of operation is as follows: neutron flux is controlled by changing the density of a two-phase mixture of oxygen and borated light water that flows through U-tubes in the reactor core. The external circuitry contains a high-pressure (HP) tank, a low-pressure (LP) tank and suitable equipment to keep the pressure difference between the tanks constant. Transfer of liquid and gas from the low-pressure tank to the high-pressure tank is achieved by a pump and compressors.

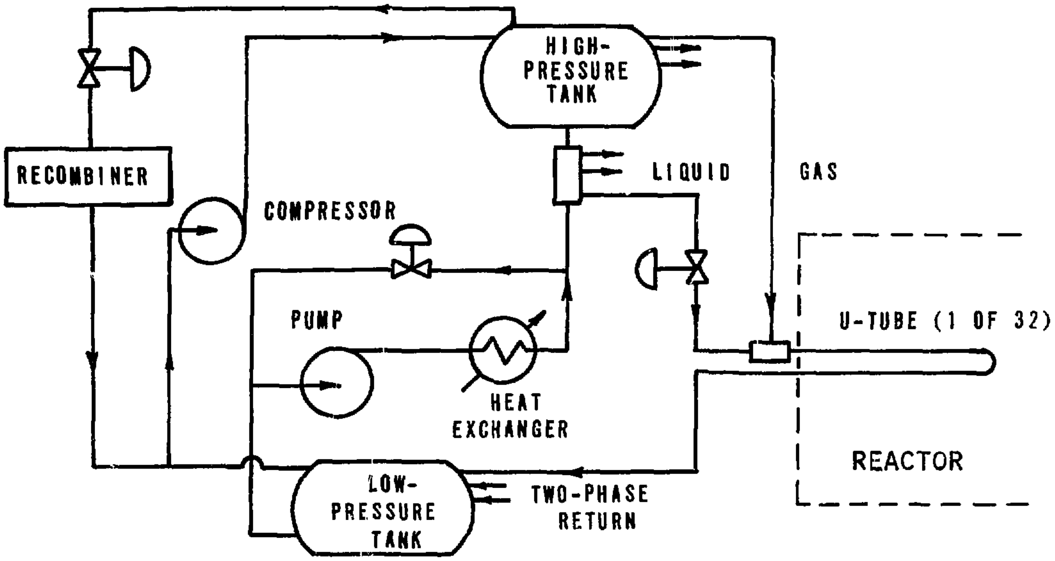

FIGURE 1 SIMPLIFIED SCHEMATIC OF TWO-PHASE ABSORBER CONTROL CIRCUIT FOR CANDU-PHW REACTORS

Several attractive features make the TOPAC System a strong candidate for future CANDU power reactors. This concept

- has uniform absorption of neutrons along the full length of the control elements
- is simple and reliable
- is easy to maintain because all moving equipment is located remote from the reactor

- has U-tubes that can be oriented horizontally or vertically
- was initially developed in Italy and has been adopted for the CIRENE reactor
- has good dynamic response which meets our controllability requirements.

SYSTEM CONTROLLABILITY

The controllability of the TOPAC System was examined by carrying out small-signal stability analyses of the neutron-flux regulating loop at different absorber densities. As well, the installed flow-characteristic of the TOPAC valve, required to obtain constant loop gain, was calculated.

Absorber Small-Signal Frequency Response

The analysis procedure used to examine the stability of the neutron-flux regulating loop comprised three steps:

(i) calculation of the absorber small-signal frequency responses at various U-tube densities, for different operating conditions,

(ii) fitting simple transfer functions to these frequency responses, and

(iii) carrying out open-loop stability analyses for these different operating conditions.

In the open-loop stability analysis, the effects of different

- void-transit time through the U-tube
- controller sampling frequency and
- controller gain settings

were examined.

A block diagram showing the small-signal dynamics of the two-phase absorber, between valve demand and reactivity, is given in Figure 2.

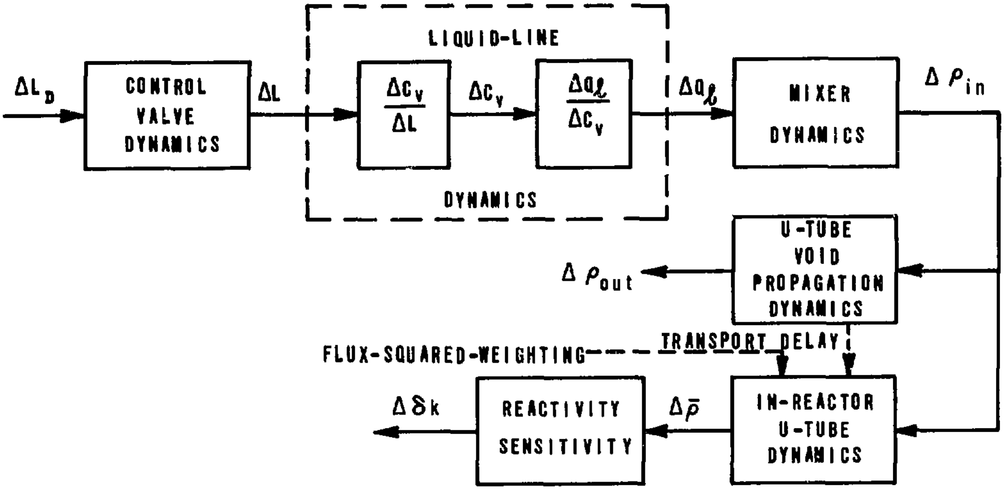

FIGURE 2 CONTROL ABSORBER BLOCK DIAGRAM

Transfer functions for these blocks were obtained from both experimental measurements and calculations [4]. The dc gains for several of the blocks were obtained from static calculations with the two-phase absorber thermohydraulic code, BIBI/CRNL [3]. The resulting transfer functions were combined in a Bode/Nyquist program [6] to obtain the complete absorber frequency response, from the valve demand signal to reactivity change in the core. A good fit to these data was obtained with a transfer function of the form

$$\frac{\Delta\delta k}{\Delta L_D} = G_1(s) = \frac{Ke^{-sT}}{1 + s\tau} \qquad (1)$$

The variables K, T and τ in this transfer function change with changes in valve position and absorber system operating pressures. An equal-percentage valve characteristic was chosen for the analysis described below.

Open-Loop Stability Analysis

The absorber transfer function, given in equation (1), was used along with transfer functions for the other blocks of Figure 3 to determine the open-loop frequency responses of the flux regulating loop at different operating conditions.

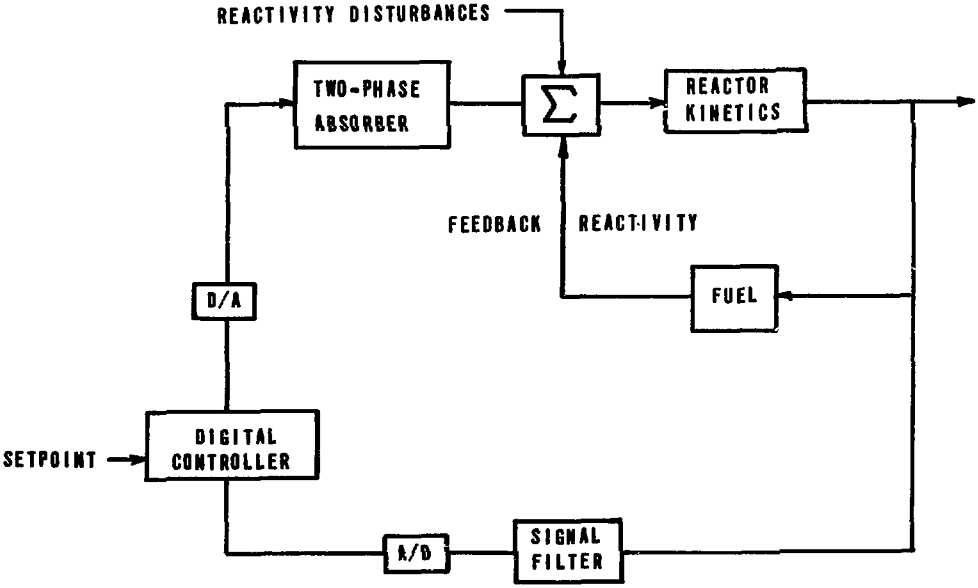

FIGURE 3 FLUX REGULATING LOOP FOR THE PHW-1250 REACTOR

The controller shown in Figure 3 has proportional plus integral action, given by

$$G_2(s) = K_P + \frac{K_P K_I}{s} \tag{2}$$

The best values for K_P and K_I were determined from the open-loop stability analysis.

The transfer function for the reactor kinetics was derived from reactor physics data, while the parameters describing the reactivity feedback through the fuel were obtained from earlier work on the controllability of future CANDU power reactors.

A typical open-loop frequency response, obtained from the Bode/Nyquist program, is shown in Figure 4.

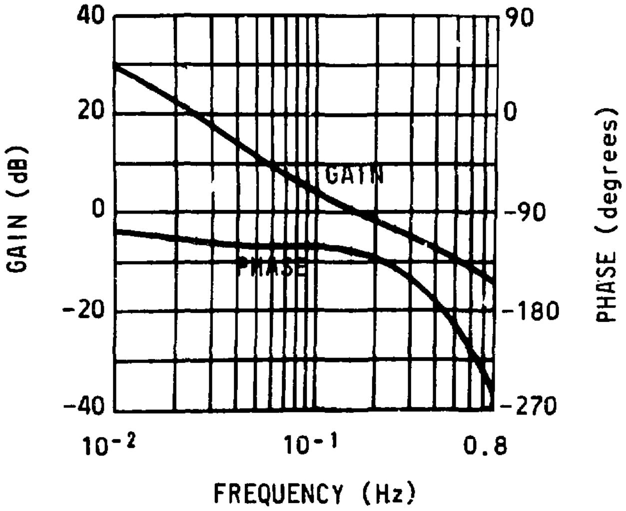

FIGURE 4 OPEN-LOOP FREQUENCY RESPONSE OF THE PHW-1250 FLUX REGULATING LOOP WITH A TWO-PHASE ABSORBER AT MID-DENSITY AND A SYSTEM SAMPLING PERIOD OF 0.128 SECONDS

The information obtained from this figure, the relative stability of the loop, indicates a

phase margin ≃ 55°
gain margin ≃ 7.7 dB

Also, the system crossover frequency, a measure of speed of response, is ∿0.155 Hz.

The loop gain, and hence the relative stability, change over the density operating range of the absorber. The possible techniques for obtaining constant loop gain are discussed in the next section. System stability is also sensitive to the sampling period for A/D and D/A conversion, as well as the void propagation time in the U-tube. Both were examined in detail in the conceptual design study, and it was found that

- sampling periods of 0.128 or 0.256 s are acceptable, however,
- the decrease in stability is substantial when the sampling period is increased to 0.512 s
- there is an ∿1 dB decrease in gain margin and a 1° to 4° decrease in phase margin when the time for the void to propagate through the U-tube is increased by 25%. This would be acceptable.

Selection of Control-Valve Characteristic

The water flow-control valve used in the analysis had an inherent "equal-percentage" flow characteristic. This results in a flux-control loop with good speed of response (i.e. crossover frequency $\simeq$ 0.155 Hz) at mid-density, but slower speed of response at low and high densities. Consequently, the ability of such a system to cope with reactivity disturbances would depend on the mean density in the U-tubes at the time of a disturbance.

There are techniques for obtaining the same speed of response over the entire density operating range of the absorber. One is to design a control algorithm whose proportional gain changes with valve-stem position, i.e. absorber density. Another method would be to select the control-valve characteristic to maintain constant loop gain over the entire density operating range of the absorber. Since the process gain (i.e. reactor kinetics) is a function of reactor power only, the absorber gain would have to be constant over its density operating range. Referring to Figure 2, this means that

$$\frac{\Delta\delta k}{\Delta L_D} = \left(\frac{\Delta L}{\Delta L_D}\right)\left(\frac{\Delta Q_\ell}{\Delta L}\right)\left(\frac{\Delta\bar{\rho}}{\Delta Q_\ell}\right)\left(\frac{\Delta\delta k}{\Delta\bar{\rho}}\right) \tag{3}$$

$$= \text{constant}$$

Since $Q_\ell = f(C_v)$, equation (3) can be expressed as

$$\frac{\Delta\delta k}{\Delta L_D} = \left(\frac{\Delta L}{\Delta L_D}\right)\left(\frac{\Delta C_v}{\Delta L}\right)\left(\frac{\Delta\bar{\rho}}{\Delta C_v}\right)\left(\frac{\Delta\delta k}{\Delta\bar{\rho}}\right) \tag{4}$$

$$= \text{constant}$$

This equation, when rearranged, gives the expression used to determine the installed flow characteristic of the valve for constant loop gain, i.e.

$$\frac{\Delta C_v}{\Delta L} = \frac{\text{constant}}{(\Delta L/\Delta L_D)\quad(\Delta\bar{\rho}/\Delta C_v)\quad(\Delta\delta k/\Delta\bar{\rho})} \tag{5}$$

A computer program, based on curve fitting of cubic polynomials to static data, was written to solve this equation. A typical result for one of the absorbers in the proposed system is shown in Figure 5. Since it is very close to being an equal-percentage characteristic, we conclude that valves with such characteristics would give reasonably constant loop gains.

In the stability analysis presented earlier, the valve characteristic used was, in fact, equal percentage. This resulted in a factor of two variation in loop gain which is considered acceptable.

IN-REACTOR NOISE SENSITIVITY

Small variations in flow of the two-phase fluid through the absorber elements will appear as neutron flux noise in the reactor core. Noise measurements were carried out in the ZED-2 test reactor as part of the experimental program. These results were then extrapolated to a CANDU power reactor to determine whether or not two-phase flow noise could be a problem.

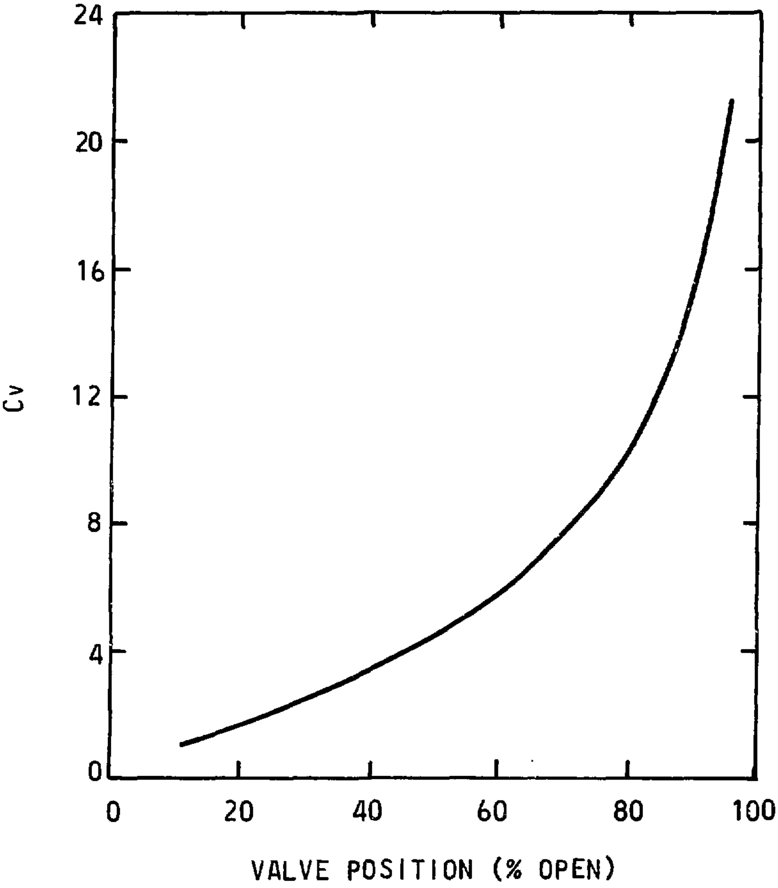

FIGURE 5 VALVE INSTALLED FLOW CHARACTERISTIC DESIRED FOR CONSTANT LOOP GAIN IN A TYPICAL CIRCUIT OF THE TOPAC SYSTEM

Noise Measurements

Five neutron fission chambers, positioned axially between the legs of the U-tube installed in the ZED-2 test reactor, were used to measure the neutron flux noise at different absorber mean densities and different boron concentrations [5]. The global flux noise was also measured with a fission chamber located near the edge of the core. As shown in Figure 6, the noise signals were recorded with an FM tape recorder for subsequent analysis.

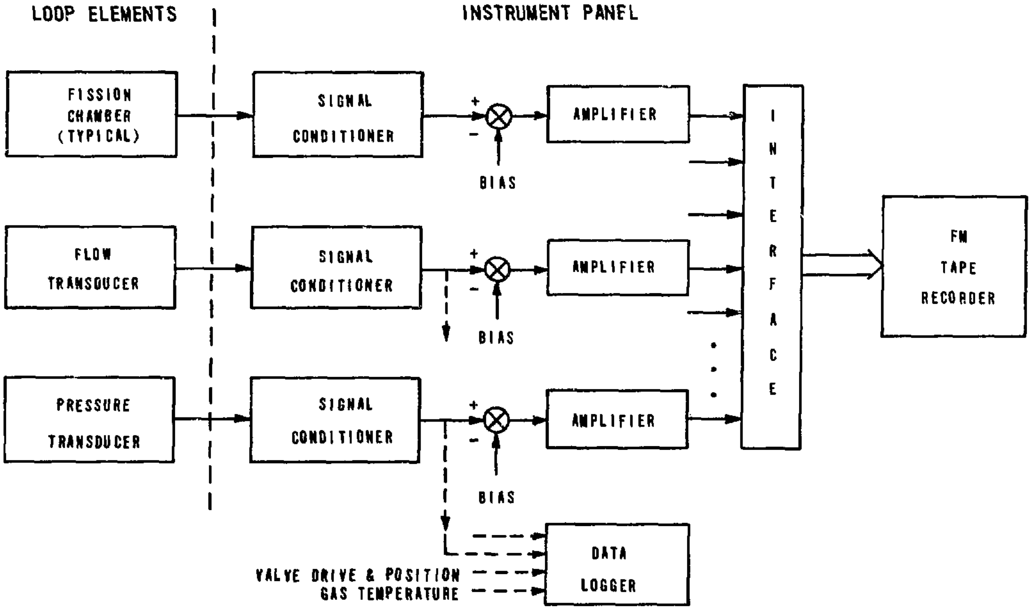

FIGURE 6 BLOCK DIAGRAM OF NOISE MEASUREMENTS SETUP FOR IN-REACTOR OPEN LOOP TESTS

The analysis procedure was one of digitizing the noise data and then determining the standard deviations of the noise-signal amplitudes, as well as their frequency spectra. The signal processing arrangement used is shown in Figure 7.

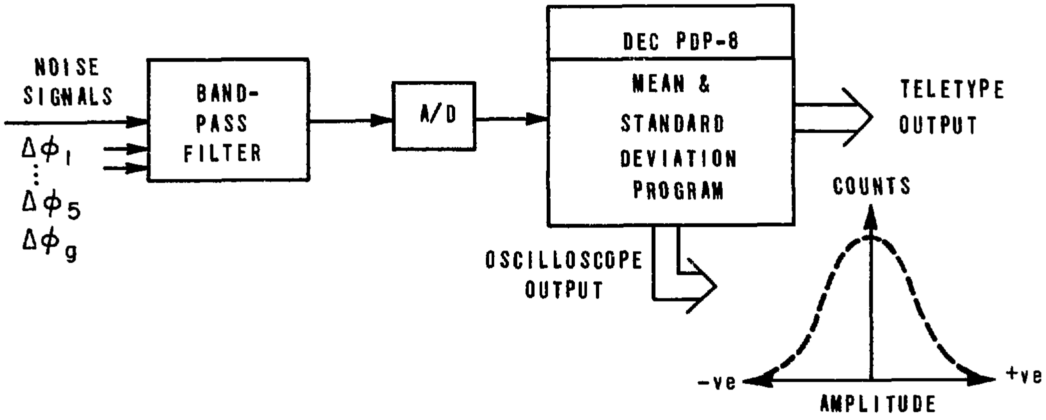

FIGURE 7 SIGNAL PROCESSING ARRANGEMENT FOR NOISE DATA

The standard deviations, expressed as percentages of the steady-state signals from the corresponding fission chambers, were plotted against fluid density. A plot of data from a typical fission chamber between the legs of the U-tube is shown in Figure 8.

The standard deviations in the noise measured at the edge of the core are approximately a factor of 2.5 less than the values given in Figure 8. These lower values are a good representation of the global noise in the reactor [5]. Since the global noise and the total noise measured at the U-tube are correlated, the difference between the two represents the local noise resulting from two-phase flow fluctuations. Separation of the two is desirable to facilitate the calculation of the expected two-phase control absorber noise in a power reactor.

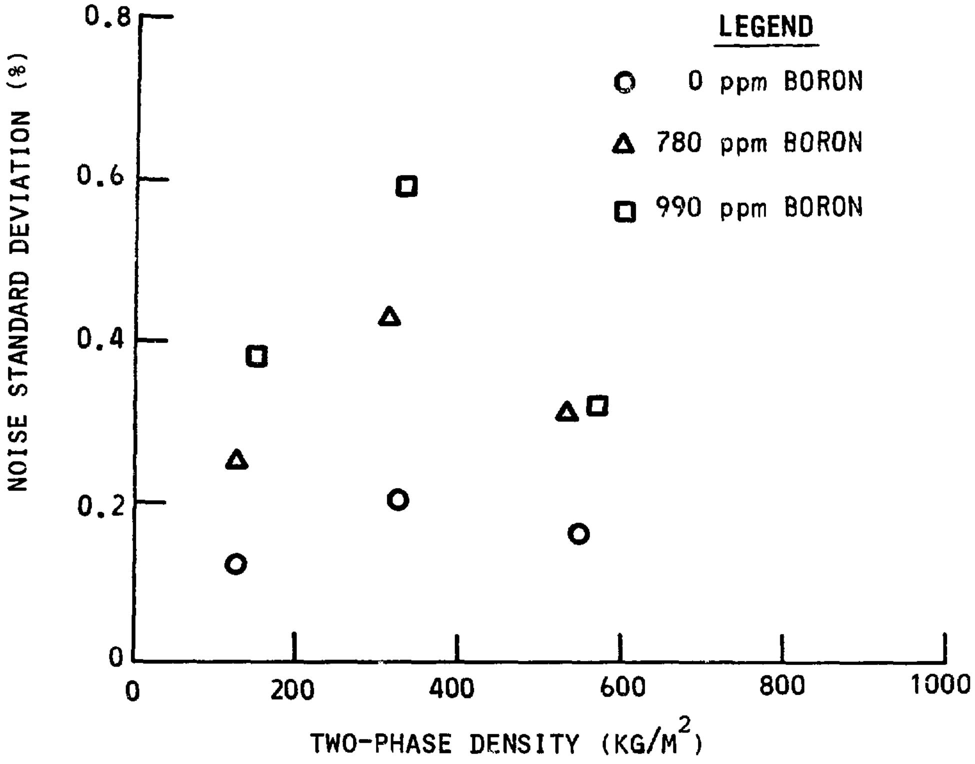

FIGURE 8 NEUTRON FLUX NOISE MEASURED AT THE ABSORBER U-TUBE IN THE ZED-2 REACTOR AS A FUNCTION OF ABSORBER MEAN DENSITY AND BORON CONCENTRATION

The sensitivity of the neutron-flux regulating loop to noise varies with the frequency of the noise. This sensitivity is given by the frequency response of neutron-flux-to-reactivity disturbances, when the regulating loop is closed. This disturbance transfer function, measured on the experimental facility with a large fission chamber at the edge of the core, shows that [5]

- noise below ∿0.06 Hz is attenuated by the neutron-flux regulating system,

- noise above ∿0.80 Hz is attenuated by the rolloff in the reactor kinetics response, and
- for some part of the frequency range between 0.06 Hz and 0.08 Hz, the noise is amplified somewhat by the neutron-flux regulating loop.

The noise density within each of the three frequency ranges of inter-t can be obtained from the neutron-flux noise spectrum for the case ing studied. The spectrum for the highest noise signal, measured tween the legs of the U-tube, is shown in Figure 9.

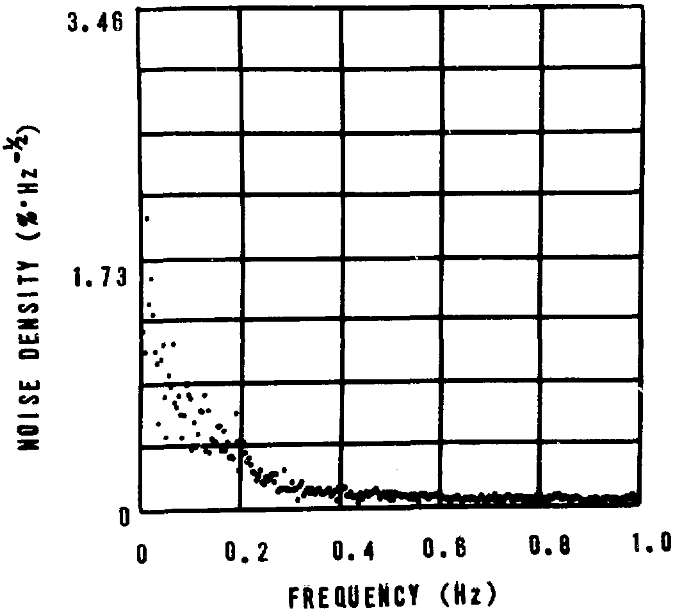

FIGURE 9 NEUTRON-FLUX NOISE SPECTRUM MEASURED AT THE ABSORBER U-TUBE AT MID-DENSITY AND 990 PPM BORON

It shows that the highest noise density is at low frequencies, where the flux regulating system is most effective. The noise density decreases rapidly within the frequency range of highest sensitivity to noise. Consequently, in the closed-loop, the neutron flux fluctuations in ZED-2 will be different from the values measured in the open-loop and given in Figure 8. The analysis shows that the noise standard deviation increases by ∿20% when the loop is closed [5].

Predicting Noise in a Power Reactor

The noise standard deviation measured in the ZED-2 reactor, at a particular absorber density, is used to predict the open-loop neutron flux noise in a power reactor resulting from a TOPAC system operating at the same density. This is done by separately scaling up the measured local and global noise. In scaling up the local noise, $\sigma_{\ell 1}$, we include the effects of

- the change in local neutron absorption resulting from the change in boron concentration, and
- the noise attenuation due to the distance between the absorber and the closest flux detector.

Consequently, the local noise, $\sigma_{\ell 2}$, in the power reactor is [5]

$$\sigma_{\ell 2} = \sigma_{\ell 1} \left(e^{-\frac{x}{m}} \right) \frac{\delta k_2}{\delta k_1} \Bigg|_{\rho} \tag{6}$$

In scaling up the global noise, σ_{g1}, we include the effects of

- the change in reactivity worth of a single absorber, and
- the noise from the other absorbers in the core.

Consequently the global noise, σ_{g2}, in the power reactor is [5]

$$\sigma_{g2} = \sigma_{g1} \frac{\Delta k_{\text{worth } 2}}{\Delta k_{\text{worth } 1}} \sqrt{N} \tag{7}$$

Adding the local and global effects gave an open-loop noise standard deviation of 0.22% from the TOPAC System.

Analysis of ZED-2 data shows that the closed loop noise is ∿20% greater than the measured open-loop noise. Assuming that the same holds true for the power reactor, its total absorber noise, σ_2, at the flux detectors would be

$$\sigma_2 = (\sigma_{\ell 2} + \sigma_{g2})\,1.2 \qquad (8)$$

$$\simeq 0..$$

To determine the expected peak value of the noise, we take the 3σ point, i.e.

$$\text{Peak noise at flux detectors} = 3\sigma_2 \qquad (9)$$

$$\simeq 0.78\%$$

This is within the range of acceptability for a power reactor.

SYSTEM UPSETS

The safety aspects of the TOPAC System were examined using a dynamic simulation as well as hand calculations. Typical malfunctions which have been examined in this phase of the work include

- compressor trips
- pump trip
- gas line breaks, and
- liquid line breaks

Results from the dynamic simulation have led to the conclusion that the TOPAC System can tolerate a short-term loss of a pump or the loss of some of the compressors. If the operating pump stops and its standby is unavailable, the system will operate normally for ∿40 to 120 s, until the water level in the high-pressure tank falls below the low-level setpoint, necessitating a reactor shutdown. The loss of one or more compressors is inconsequential, as long as bypass flow can be reduced to maintain the correct differential pressure between the HP and LP tanks. If the differential pressure cannot be maintained, the performance of the reactor-control system will deteriorate and the reactor must be shut down.

Simulation results for the loss of all five compressors are presented in Figure 10. The sequence of events leading to a reactor shutdown are as follows:

(i) With all conditions normal, all compressors cease operation, shown in the top trace.

(ii) The differential pressure between the HP and LP tanks starts to drop very rapidly (2nd trace), since gas is flowing from the HP tank to the LP tank via both the U-tubes and the pressure-control valve in the gas bypass line. After a short time, the pressure-control valve closes (3rd trace), 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 (4th trace), with a consequent dip in reactor power (5th trace).

(iv) Water flow from the LP to the HP tank increases, because of the low differential pressure across the water pump.

(v) If the level-control valve cannot bypass sufficient flow, the water level in the LP tank falls until the LP tank is empty (6th trace) and the pump cavitates. However, water continues to flow through the absorbers.

The simulation showed that the system will continue to operate with low differential pressure, but performance of the reactor-control system 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. For this reason, the conceptual design of the TOPAC System provides for automatic power decreases, initiated by a low differential pressure between the tanks.

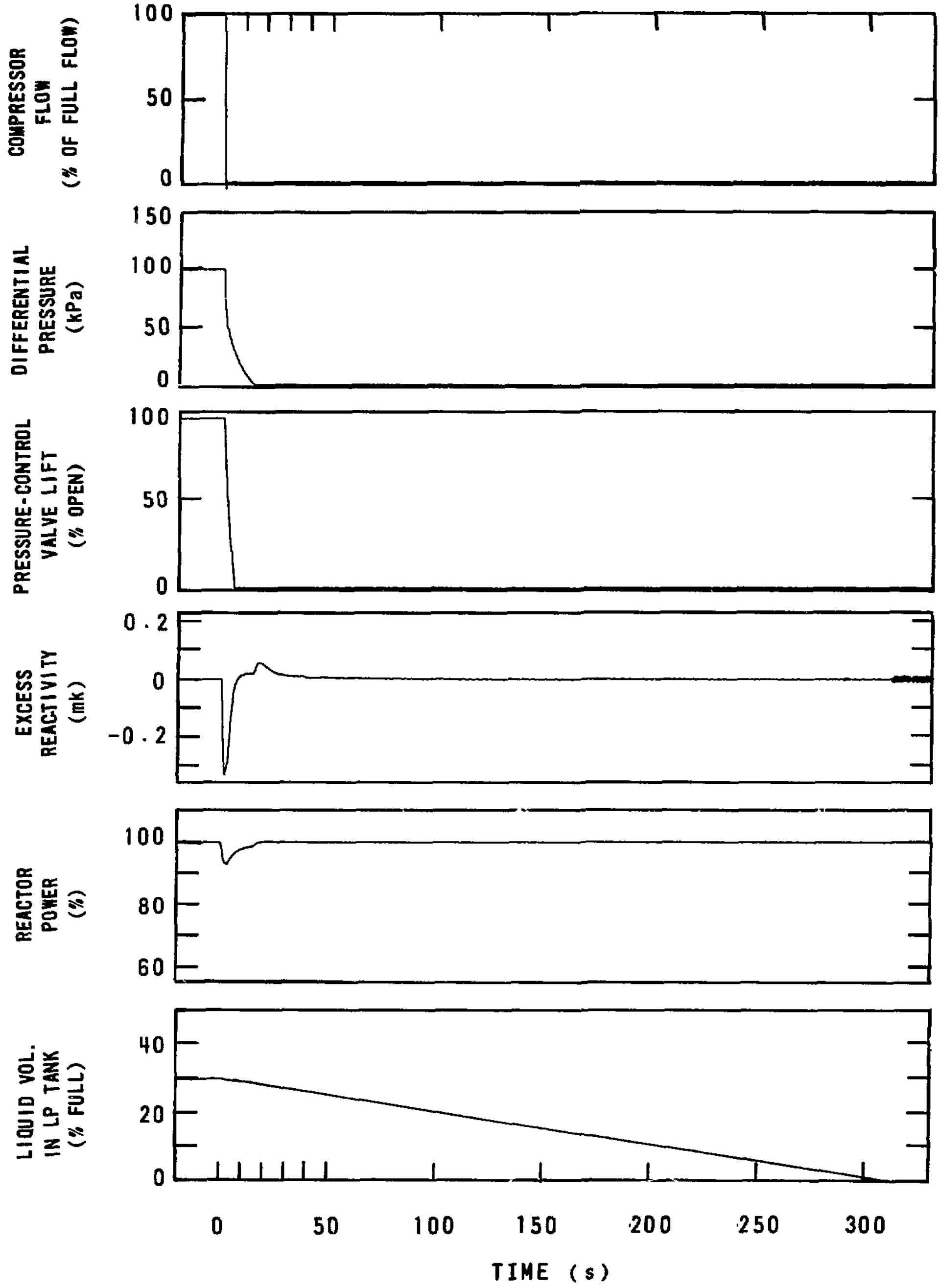

FIGURE 10 SIMULATION OF A TRIP OF ALL FIVE COMPRESSORS ($\bar{\rho} \simeq 445$ KG/M^3)

COMPARISON WITH COMPETING SYSTEMS

Beginning with the Pickering Nuclear Generating Station, all CANDU power reactors are controlled by varying the amount of H_2O liquid in an array of compartments (typically 14) in the core. This is called the Vertical Liquid Zone Control (VLZC) System. While these systems are quite satisfactory for the current generation of reactors, they are not necessarily the best for future large reactors. An alternative, called the Horizontal Liquid Zone Control (HLZC) System, is being developed because it is superior with respect to

- top-to-bottom flux tilt, due to partially-filled, vertical absorber compartments,
- power cycling of fuel adjacent to the absorbers, and
- avoiding congestion on the reactivity-mechanisms deck.

The TOPAC System is equivalent to the HLZC System in the above three respects and is therefore also superior to the VLZC System.

We compared the HLZC and TOPAC Systems on the basis of

- reactivity worth
- bulk and spatial flux control
- reactor safety
- engineering complexity
- reactivity-range adjustment
- cover gas
- absorber position indication
- potential for tube leaks
- pipe sizes
- process system complexity
- radiation fields
- costs.

This point-by-point comparison revealed pluses and minuses on both sides which, on average, balanced out. The one exception was that 'absorber position', i.e. the density of the two-phase mixture in a TOPAC System U-tube can be easily inferred from the position of the corresponding liquid flow-control valve, whereas the liquid level in a HLZC System compartment is more difficult to measure remotely with the required precision.

CONCLUSIONS

The two-phase control-absorber concept has been studied, both analytically and experimentally, and found to be a viable alternative to the Horizontal Liquid Zonal Control (HLZC) System for future CANDU reactors. Only certain aspects of this study, namely

- system controllability
- in-reactor noise sensitivity
- system malfunctions, and
- comparison with competing systems

are described in this paper.

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Only a small part of the work on the conceptual design study, involving many individuals, is presented in this paper. We would like to thank them all, and notably J.S. Glen, C.B. Lawrence, F.N. McDonnell and R.E. Green, for their contributions to the work reported in this paper. Also, we would like to thank G. Frketich for carrying out the required calculations.

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