CANDU 600 HEAT TRANSPORT SYSTEM

FLOW STABILITY

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ABSTRACT

The investigation of CANDU-600 Heat Transport System Stability, when the system is operating with net quality at the reactor outlet, is discussed. The possible instability modes are reviewed and the nature of the Heat Transport System flow stability phenomenon is investigated. Details covered in the paper include a description of the phenomena, the computer codes used, sources of perturbations, predictions, criteria for evaluation, code verification and commissioning tests.

Commissioning tests have proved that the CANDU-600 Heat Transport System is stable under all conditions with the interconnect line in service as designed. Tests performed with significant void in the outlet header and the interconnect line out of service confirmed the instability phenomena.

INTRODUCTION

Overview

The topic to be discussed here is the stability of the CANDU 600 Heat Transport System, that is, the dynamic characteristics of the major process variables such as pressure and flow. By way of introduction, the CANDU Nuclear Power System is briefly presented, emphasizing those features pertinent to the stability issue. Then an overview of oscillatory modes and mechanisms permits a more lucid discussion of details. The remaining sections deal with the details of the investigation into stability and the hardware installed to ensure Heat Transport System stability.

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CANDU 600 Heat Transport System

Figure 1 gives an overview of the CANDU Nuclear Power System. The pressure tube forms the pressure boundary of the Heat Transport System (HTS) in the core (Figure 2); the heavy water coolant passes through and around the bundles of natural uranium fuel located within the pressure tube.

The portions of the fuel channel assemblies external to the calandria (Figure 2) are known as the end fittings; the end fittings are connected to the feeder pipes (feeders) which feed coolant into and out of the fuel channels.

The CANDU 600 reactor has 380 fuel channels arranged in a square lattice within the calandria. The Heat Transport System (HTS) is arranged into two circuits, one on each side of the vertical centre line of the reactor core, with 190 fuel channels in each circuit. Figure 3 shows an end view of the arrangement of the main components of the HTS.

The HTS circuit schematic is shown in Figure 4; each circuit contains 2 pumps, 2 steam generators, 2 inlet headers and 2 outlet headers in a "figure-of-eight" arrangement. Feeders connect the inlet and outlet of the fuel channels to the inlet and outlet headers respectively.

The flow through the fuel channels is bidirectional (i.e. opposite directions in adjacent channels). The feeders are sized such that the coolant flow to each channel is approximately proportional to channel power. The enthalpy increase of the coolant is therefore approximately the same for each fuel channel assembly.

The operating pressure of the CANDU 600 reactor (outlet header) is 10 MPa. In order to increase unit efficiency, boiling in the core at high power is utilized, leading to an outlet header quality of up to approximately 4% at full power. Other typical Heat Transport System parameters are given in Figure 1.

To enhance Heat Transport System stability, the reactor outlet interconnect (a small pipe - 150mm I.D.) has been installed in each circuit and is now an integral part of the total design. This pipe connects the reactor outlet on one side of the core to the reactor outlet on the other side of the core, as shown in Figures 1, 3 and 4. Additional views are given in Figures 5 and 6 as clarification since the effect of the interconnects on the stability performance of the Heat Transport System is part of the focus of this paper.

OSCILLATORY MODES AND MECHANISMS - AN OVERVIEW

Oscillatory behaviour of two-phase systems is a well recognized phenomenon. Many general classifications of two-phase oscillations have been reported in the open literature (Reference 1). In the Heat Transport System, oscillations can arise from a number of areas.

Single and parallel channel instabilities have been addressed at length in the past. The main characteristic for this type of instability is the relative size of the pressure drop in the two-phase region compared to that of the single-phase region. Since two-phase resistance is higher for a given mass flow than for 'liquid only' flow, a drop in quality reduces the resistance to flow causing increased flow for a given pressure drop. The increased flow in a channel of a given power causes a reduction in exit enthalpy and quality. This causes further acceleration of flow, and so on. All CANDU designs are inherently stable for this mode of instability since the single-phase to two-phase pressure drop ratio is high for the feeder-channel-feeder flow path between the reactor inlet and outlet headers.

Localized instabilities in the steam generator inlet area or in the two-phase regions of the steam generator secondary side have not been observed in CANDU plants.

Two-phase loops are also subject to Ledinegg type instabilities. This instability occurs in loop flow for the same reason as the channel instability but on an overall loop basis, rather than just for a channel. The CANDU 600 is stable for this type of bimodal instability, since, by design, the single phase resistance dominates the total circuit resistance for all possible operational modes.

Finally, there is the possibility of an oscillation of the loop process parameters, such as flow and pressure. Following the classifications of Reference 1, the instability under consideration is a compound dynamic instability characterized by low frequency density waves. This report addresses such a possibility. Based on analyses done to date, the prerequisites for such oscillations in CANDU stations are:

a) void in both ends of the "figure-of-eight" circuit;
b) low inherent system damping;
c) the presence of an asymmetric disturbance (for example, random perturbations, valve action, etc.).

Given these prerequisites, the Heat Transport System would exhibit an oscillation with:

a) a 14 second period (related strongly to the transit time of density waves);
b) a sinusoidal flow variation in time with the maximum amplitude occurring in the single-phase regions;
c) a sinusoidal pressure variation in time with the maximum amplitude occurring in the two-phase regions.

Perturbations that can occur during normal operation of the Heat Transport System can excite oscillations. If the damping is sufficiently low, the oscillations would be divergent. For sufficiently large oscillation amplitudes (in flow, pressure, quality, void fraction, etc.), reactor trip setpoints could be exceeded, leading to frequent reactor trips. This would pose an undue operational burden. As part of the design process, this eventuality was investigated.

OUTLINE OF INVESTIGATION

Status of Plants

At the start of the investigation no CANDU station had operated with significant voiding in a figure-of-eight circuit; thus, analytical and numerical modelling, as well as laboratory testing, were used in assessing the stability of the Heat Transport System in CANDU 600 stations.

The studies indicated that the present CANDU 600 station design, with the reactor outlet interconnect, is stable to system perturbations but would exhibit divergent flow oscillations if the interconnect were removed and if more than 1 or 2% quality (but less than 8% quality) in the reactor outlet regions were to occur. The nominal design is 4% quality in the Reactor Outlet Header (ROH) but design margins led to an operating quality of about 0% at the start of plant life.

The bulk of the analysis was carried out assuming that the station would operate at the design point. Normal design practice, however, is to build in margins in pump heads, boiler areas, etc. These margins shift the onset of boiling to approximately 100% FP (from the design value of 87% FP) and the onset of instability to greater than 103% FP if there were no interconnect.

At the end of the investigation period, tests were conducted on CANDU 600 stations with the interconnect blanked off and then with orifices installed. As predicted by the computer codes, the plants proved stable with the interconnect but unstable without the interconnect if sufficient quality existed in the HTS.

Initiating Events

For the idealized case a specific perturbation is not needed in determining system stability about an operating point. However, to ensure robustness, the major perturbations must be considered to cover off non-linear effects. Significant operating events which could constitute a major perturbation to the system include:

1) Power maneuvering up and down at the maximum rate;
2) grid load changes;
3) purification flow turned on and off;
4) full steam bleed from the pressurizer as per controller demand;
5) full liquid bleed as per controller demand;
6) full liquid feed as per controller demand;
7) drum level mismatched; and
8) the above events with imbalances in pump heads, pipe sizes or circuit losses.

Other minor initiating events include refuelling, pressure, temperature, flow and power fluctuations.

Of all these events, the one giving the largest perturbation to the system is the pressurizer steam bleed. A larger, enveloping, perturbation is a direct extraction of mass from the ROH equivalent to the steam bleed perturbation. Thus the standard disturbance chosen for analysis purposes was a 200 kg/s bleed from the ROH for 5 seconds.

Variations on this standard disturbance were tried and it was found that the initial disturbance did not significantly alter the characteristics of the oscillation.

Performance Indicators

As previously mentioned, the main process parameters in the phenomena under investigation are the flow in the liquid regions and the pressure, void and quality in the two-phase regions. As an indication of the degree of damping of the system, the damping ratio of the flow was primarily used. This gave a measure of the peak to peak attenuation of the oscillation and the margin to stability. The damping ratios of all process parameters were similar.

Referring to Figure 7, the damping ratio, ζ, is defined as:

$$\zeta = \frac{-\ell n(x)/2\pi}{\sqrt{1 + [(\ell n(x)/2\pi]^2}}$$

Damping ratio may also be defined, for a linear system, by the location of the roots of the characteristic equation in the Laplace (complex frequency) domain; these two definitions are equivalent. A positive ζ indicates a convergent oscillation. Negative ζ indicates a divergent oscillation. Zero ζ indicates a sustained oscillation.

Other parameters such as levels, power, pressurizer behaviour, etc., were also monitored as appropriate.

Analysis Summary

Analysis included comparisons of the computer simulation codes (HYDNA, SOPHT and FIREBIRD*), test loop results (RD12**) and analytical formulations. Fundamental investigations were directed at the potential sources of instability, the sources of damping and the stability criteria. Code analysis included a parametric survey and an investigation of the various means of achieving stability. These analyses indicated that damping of the PHT system as modelled with no interconnect is sufficiently low to give divergent oscillations. However, these pretest predictions indicated that the actual damping of the Heat Transport System could be sufficient to assure stable operation since the simulation codes underestimate many of the processes which provide damping. Thus the damping of the real system might have been sufficient to assure stability without system modification but this could not be established without plant testing.

Several practical options were available to enhance the stability of the Heat Transport System. The most promising was a reactor outlet interconnect, a passive installation. The interconnect pipe is between the steam generator inlet pipes at opposite ends of each circuit as previously discussed. Under the category of active options, the option showing the most promise was flow control. A controlled recirculation flow from the Heat Transport pump discharge to the pump suction could provide sufficient flow control to suppress flow oscillations. Experiments in the RD12 loop at WNRE showed that the RD12 loop could simulate divergent oscillations in a figure-of-eight circuit similar to the Heat Transport System and that stability could be regained by pump flow control or by an outlet header interconnection. Because it was effective, relatively simple, passive and, hence, reliable, the interconnect was chosen as the most appropriate means to enhance system stability in stations that were in the final phases of construction. Future stations, as well, will likely employ the interconnect because of its simplicity and proven performance, or alternatively, in a new design, the quality can be eliminated by changing the process conditions. This implies larger steam generators, larger reactor cores, larger core flows, lower temperatures or higher primary side pressures or some combination of these. Whether these can, or will, be considered depends on the very market factors which have set the present design.

* SOPHT, HYDNA & FIREBIRD are computer codes for the simulation of the Heat Transport System.

** RD12 is a semi-scale CANDU test loop using electrical heaters. The loop is located at the Atomic Energy of Canada Ltd. laboratory (Whiteshell Nuclear Research Establishment) in Manitoba, Canada.

CIRCUIT OSCILLATIONS - THE PHENOMENA

As is the case for two-phase flow oscillations in general, the "figure-of-eight" circuit oscillations, to whatever extent they exist, are a result of the interaction between numerous effects. In this section, the major characteristics are discussed individually and then combined to develop an understanding of the phenomena. To aid in the discussion, a schematic of the Heat Transport System, showing the single and two-phase regions, is given in Figure 8. Figure 9 is a greatly simplified representation of the HTS, but it is sufficient for explanation of the oscillatory phenomena. The interconnect is omitted for the moment for discussion purposes.

The Spring-Mass Effect

The two-phase region (see Figure 9) is compressible and, in this regard, acts like a spring. The single phase liquid region acts predominantly as an incompressible mass, giving substantial inertia to the system. Although this is a gross simplification, this illustrates one essential characteristic: the spring-mass effect. Given a perturbation, say a small pressure reduction in one of the two-phase regions (point 2 of Figure 9), the fluid in the upstream liquid region is accelerated and the fluid in the downstream liquid region is decelerated. The mass flow into the two-phase region is, thus, increased, compressing the region and causing the pressure to rise (the other two-phase region undergoes an expansion). The inertia of the system causes the increased inflow into the perturbed region to continue even after the pressure has returned back to normal. An overpressure will result, causing a rebound effect. The upstream liquid now decelerates and the downstream liquid accelerates. With no losses or gains, this oscillation will continue undiminished. The characteristic period associated with this effect is approximately 14 seconds (roughly twice the transit time of density wave transport in a two-phase region). It is important to note that when one of the voided regions is pressurizing, the other voided region is depressurizing and vice versa. The phase shift is 180°. Similarly, when one liquid region is accelerating, the other is decelerating; again, the phase shift is 180°.

The Positive Feedback (Flow-Enthalpy-Pressure) Effect

A positive feedback occurs through the interaction of the flow and channel power. For small perturbations, the reactor and channel power remain constant. Ignoring the secondary effect of flow rate on heat transfer for the sake of discussion, the power transferred to the coolant is, therefore, essentially constant. If the flow is perturbed, the main result is that the enthalpy rise per unit mass of coolant is perturbed. Through the equation of state, there is a pressure associated with the mass and enthalpy in a volume. For the case in point, an increase in coolant velocity or flow causes a reduction in specific enthalpy of the two-phase region downstream of the reactor channel. The pressure in this region is reduced causing an acceleration of the upstream flow, all other things being equal. The flow increase gives positive feedback to the enthalpy reduction and if the gain is greater than 1, the process is divergent.

An alternative, and more intuitive, way of thinking about this effect is to replace the reference to the equation of state with reference to the quality. The perturbation in specific enthalpy of the two-phase region gives a perturbation in the quality of the region. Associated with the quality perturbation is a void fraction change. Thus, an increase in coolant flow decreases specific enthalpy, reduces quality and void fraction. This constitutes a partial void collapse and accompanying depressurization in much the same manner as depressurizing a domestic pressure-cooker by dousing it with cold water.

Thus, the positive feedback to flow constitutes an excursive phenomenon which, in the absence of other effects, would lead to void collapse at one two-phase region and an excursive increase in void to approximately twice the nominal void-fraction at the other two-phase region. This condition cannot be sustained since the collapse of one of the two-phase regions effectively joins the liquid regions and the velocities rapidly return to the nominal velocities. Consequently, the enthalpies, qualities and void fractions return to their nominal conditions.

The Negative Feedback Effects

The main stabilizing mechanism is the resistive losses in the circuit. These losses would tend to oppose increases and decreases in velocities by increasing and decreasing losses respectively. Since the HTS has been designed to have as low as practicable circuit head loss, the flow losses are not sufficient to ensure convergence, according to the analysis. Further, the HT pumps tend to counteract flow changes and the steam generators tend to counteract void changes. The piping walls also tend to exchange heat so as to dampen temperature changes, in effect acting as a heat capacitor. The many parallel channels offer a spectrum of transit times and channel exit qualities which tend to smear out any sharp moving fronts of density or energy waves. None of these additional effects is of sufficient magnitude in the CANDU 600 to ensure a stable system.

The Transport Delay Effect

None of the above effects occur instantaneously in a distributed system such as the CANDU 600. Significant delays occur in energy and density through the reactor channel, the feeders and the main piping to the steam generators. This effect and other time dependent effects already mentioned (inertia, heat transfer to pipe walls, differential transit time through the various feeders, etc.) affect the dynamics of the interaction of the above effects.

Combining the Effects

Consider again a pressure reduction perturbation at point 2 of Figure 9, caused by, say, the removal of a small amount of mass. This incites an increase in flow (velocity) upstream of the two-phase region and a decrease in flow (velocity) in the downstream liquid region. For a specified liquid region flow perturbation, w, (Figure 10), two effects occur simultaneously. The extra mass tends to compress the fluid and thereby raise the pressure. This is an accumulative or integral effect. The second effect is the lowering of enthalpy (per unit mass) by the addition of lower enthalpy fluid. This has a decompression effect as discussed above. Since the flow perturbation is sustained by the inertia, the new core flow yields a new lower enthalpy. Thus, in time, the bulk specific enthalpy moves to this new lower enthalpy and tends to stabilize there; therefore the pressure reduction due to enthalpy reduction is limited (or proportional). Since the compression effect due to adding mass is integral, after some characteristic time, the compression effect dominates causing the oscillation to reverse direction. The flow-enthalpy effect thus provides the driving energy (forcing function) and the integral action provides the spring. Simultaneous to these events at point 2, the opposite perturbation is occurring at point 5 (see Figure 9).

The precise nature of the dynamic behaviour depends on the values of the various parameters. For instance, if there were little inertia, the early drop in pressure would cause the flow perturbation to increase and the enthalpy would drop even more. This is an example of an excursive instability (void collapse). If the inertia were very large, a pressure perturbation would not accelerate or decelerate the flow and the feedback loop would be broken; no oscillation would occur.

A feedback block diagram is shown in Figure 11.

It should be noted that the boiling boundaries do not move substantially for small amplitude oscillations. Voiding starts towards the fuel channel exit and ends in the condensing region of the boiler. The boiling boundary does move as the cycle amplitude increases but the change in voided volume is small compared to the total voided volume. What does oscillate are the velocities in the liquid region, the pressures, the void fraction and the quality and these are oscillations about the nominal values.

The presence of additional compressible regions (the pressurizer and the second HTS circuit) do affect and complicate the dynamics and have, therefore, been omitted from the above discussion. The computer models include these effects.

The Phenomena with the Interconnect

With the interconnect in place (see Figures 12 and 13), a perturbation (such as a fluid extraction) at position 2 (ROH) propagate in much the same manner as described previously. However, the presence of the interconnect diminishes the effect of the perturbation by allowing fluid to move from the remote header to the perturbed header. A volume of fluid (liquid/steam) moves into the perturbed header to replace some of the fluid extracted. This directly reduces the driving force for the 'liquid pass' velocity changes. In addition, it helps to relieve the subsequent increase in void fraction (and pressure increase) at the remote header. It is important to note that the exact nature of the fluid transferred (liquid or steam) is unimportant. The nature of the fluid is important only insofar as it affects the volume moved and the timing of that movement.

For maximum effectiveness, the flow in the interconnect should be in phase with the driving force (pressure difference between headers) as much as possible. This places the fluid at the needed place at the best time. However, fluid inertia in the line causes a phase shift (delays the initial movement of the fluid and carries it on longer than required). Increasing the interconnect resistance will increase the inphase component compared to the out-of-phase component (i.e. increase the ratio of fluid arriving at the right time to fluid arriving too late to be effective). But this increased resistance lowers the amount of fluid transferred. Hence, given the fluid in the interconnect (and its inertia), the interconnect resistance can be tuned to optimize the effectiveness of the interconnect. It is more effective if the inertia is low to begin with. Hence, a steam filled interconnect is preferable to a liquid filled line. To enhance phase separation in the line and hence increase the amount of steam in the line, provision has been made to elevate the line and to provide liquid drainage.

CODES AND MODELS

The codes used in the investigation were SOPHT (references 2 and 3), FIREBIRD and HYDNA-3. Spatial and temporal convergence checks were performed on these heat transport system models. Refinement of convergence was required for all of the codes. Code sensitivities to various quality void correlations and other modelling details were investigated. Given enhanced convergence and a consistent model basis between the codes, reasonable quantitative agreement was reached.

The above codes also give good qualitative agreement with the results from the scale model test rig, RD12. Reference 4 gives a description of the RD12 loop and the tests performed. The period of oscillation agreement was excellent. Flow and pressure oscillation amplitudes agreed reasonably well. Reference 5 compares HYDNA-3 to RD12 experimental results.

Analytical models were also used in the stability evaluations. These models were compared with the above codes and the RD12 results and were found to predict the period and damping ratio accurately. One comprehensive linearized model has been reported (References 6 and 7) and a comparison of predictions to RD12 data was given. In addition, a simple analytical model was developed that proved invaluable in understanding the phenomena involved (reference 8). This simple model was the cornerstone of all subsequent work in that it guided the detailed analysis and prompted the conceptual development of the interconnect.

All of the above models and the experimental loop indicated a possible divergent HTS flow oscillation when no interconnect is used. However, there exists stabilizing features in the real CANDU 600 system that are not represented in any of the models and laboratory tests.

The RD12 loop is physically not to scale and has only one channel per pass. The multichannel aspect has been shown to enhance stability since not all channels have the same power, quality, flow or transit time. This serves to diffuse system perturbations and lower the loop gain. The different geometric scale could lead to a difference in flow regime effects, drift between phases, turbulent mixing, void holdup, etc.

The computer code models also lack details such as complete multichannel modelling, and turbulent mixing and diffusion in large pipes. In addition, conservative approximations are made. The major ones include a pressurizer (or surge tank) model that assumes adiabatic compression and equilibrium expansion for the liquid and vapour D_2O contained within the pressurizer. The adiabatic compression assumption makes the system more divergent than an equilibrium compression assumption. Reality probability lies between the two extremes. Another conservatism, stability-wise, is to assume homogeneous two-phase flow in the HTS. This gives the largest void fraction for a given quality and contibutes to instability by increasing the gain in the flow-enthalpy-pressure feed-back circuit. Other minor effects include wall heat and the effect of the second circuit in damping a perturbation in the first circuit. Both these effects were found to add a small amount of stability.

As reported in a later section, the commissioning results with the interconnected isolated confirmed the existance of the instability and overall agreement with SOPHT was readily achieved by using the adiabatic compression assumption and a twin channel model.

SYSTEM BEHAVIOUR - MODEL PREDICTIONS

No Interconnect

To illustrate the flow void and pressure distributions, Figure 14 shows a snapshot of the circuit at time t. Figure 15 illustrates the situation approximately 1/2 cycle later. This very simplistic illustration shows that maximum flow variations occur in the liquid regions and that maximum pressure and void variations occur in the ROH region. Distributions within regions are deliberately omitted for clarity.

The calculated pressure, flow and void fraction at these positions of maximum variation are plotted as a function of time in Figures 16 to 18. The initial condition is 100% reactor power with 4% quality in the headers, as designed. The initiating perturbation is an extraction of 200 kg/s of mass from an ROH for 5 seconds. The process trips have been removed from these simulations to allow a study of the oscillations as they develop.* The pressure oscillation is characterized by an initial drop at the header that is perturbed. The remote header is initially unaffected due to the physical separation by the liquid regions. It is only after some change in velocity of these liquid regions has taken place that the remote header sees the perturbation. The period of the developed oscillation is 14 seconds or roughly twice the transit time for void propagation in the two-phase region. The two halves of the circuit are approximately 180° out of phase.

The flow oscillation is characterized by an initial increase in velocity of the upstream liquid region and a decrease in velocity of the downstream liquid region. The perturbation affects both passes simultaneously and almost symmetrically as discussed previously. The period and phase relations are similar to the pressure oscillation case.

Ultimately, if the oscillations were permitted to grow undamped (i.e., in the absence of reactor power regulation and trip) the void collapse point would be reached, giving a limit cycle characterized by no void in one ROH and twice nominal void in the opposite ROH. At this limit cycle, the flow oscillations would be bounded by roughly +30% and -50% of normal flow.

Analysis indicates that divergent flow oscillations only occur over the limited quality range of 1% to 8%. At less than 0% quality oscillations are not possible since the compressible regions do not exist. At high qualities, the flow-enthalpy-pressure feedback gain decreases and convergent oscillations result.

With the Interconnect

In the present CANDU 600 design, system stability can best be assured at full power by interconnecting the two compressible regions in the figure of eight circuit. Studies were made to assess the effect of interconnecting the two compressible regions in the "figure-of-eight" circuit.

Considerable analysis with various connection configurations (length, area, resistance) between the reactor outlet headers was done. The results showed that one 150 mm pipe per circuit, each about 35 meters long with a 65 mm orifice located near each of the reactor outlet headers is effective in providing stability for all operating transients. As discussed, the orifices are provided to ensure that the flow in the interconnect will be optimally phased with the circuit flow oscillation to obtain a maximum stabilizing effect.

In the analysis, credit was not taken for the presence of more steam in the line than was present in the headers in order to be conservative. Tests at Westinghouse (Canada) Ltd. to study the flow regimes present in the interconnect indicate that phase separation occurs

* Studies have shown that the high ROH pressure relief (setpoint at 103.4% of normal operating pressure), the reactor trip on high ROH pressure (setpoint at 105.5% of normal operating pressure), and the low flow trip (setpoint at 70% of normal operating flow) ensured recovery from a divergent oscillation situation.

readily provided system embalances do not generate a unidirectional flow in the interconnect of more than 8.9 m/s. This flow can be expected if a pump head mismatch of 3% exists. Commissioning tests show that the pumps are well matched.

Figures 19 to 20 illustrate the results of the SOPHT analysis showing the stabilizing effect that is achieved as a result of the interconnect line. Figure 19 is based on a homogeneous model for two-phase flow, while Figure 20 uses a drift flux model assuming homogeneous initial conditions in the interconnect. The actual hydraulic conditions probably lie between these extremes, but in any case, the results demonstrate that the system response to a perturbation is stabilized by the presence of the interconnect. Using the homogeneous model, it is found that the oscillations dampen from a 3% initial disturbance to less than ±1% of flow in about 3 cycles. Using the drift flux model, the oscillations dampen from a 3% initial disturbance to less than ±1% flow variation in 2 cycles. A flow variation of ±1% is below the level of detectability and is therefore considered effectively stable.

The behaviour with an interconnect is characterized by an increased cross talk between the headers. The remote reactor outlet header is now affected sooner by the initial perturbation. This increased cross talk also causes the period to be reduced to about 12 seconds as the circuit approaches a figure-of-zero configuration.

The heat transport system was modified during the final design stage to enhance system stability, and an analysis of the as-built system was completed from a safety and from a design point of view. The results are summarized in the following two sections, showing that the as-built system satisfied the safety and design requirements..

Accident Analysis

This section summarizes the effect of the interconnect on accident analysis cases.

There are two general types of accidents:

1. Accidents which produce a large pressure drop across the interconnects. Examples are large loss of coolant accidents, asymmetric feedline breaks affecting only one steam generator, and loss of one pump per circuit. Such accidents have the following characteristics: they tend to be asymmetrical with respect to the two core passes; there are large uni-directional flows through the interconnect; and there are, therefore, no flow stability concerns. A key feature of the interconnect is that its resistance is much, much greater than the parallel path resistance through the steam generators and the core. The resistance to area ratio is about 3100 for the interconnect versus about 3 for the parallel path. Thus, the hydraulic effect of the interconnect on these accidents is intrinsically small.
2. Accidents with a small pressure drop across the interconnect. Examples here are a small loss of coolant, or a loss of pressure control, and a slow loss of reactivity control. These produce slow symmetrical voiding in the circuit. Their characteristics are: they are symmetrical with respect to the two passes, the interconnect acts as a flow stabilizer, and therefore, the accident analysis required an investigation of flow stability with the interconnect present. The key feature here is that the oscillations, if any, exist only over a limited quality range and over a limited range of time. The interconnect stabilizes potential oscillations for these cases.

Process Design Considerations

The presence of an interconnect between the outlet headers of an HTS circuit will, in general, tend to reduce the maximum amplitude of an asymmetric disturbance and have negligible effect on symmetric disturbances. Analysis of the major operational events (power runup and rundown, turbine trip, loss of feedwater, purification system being turned on and off, loss of Class IV power, one pump/loop trip and steam generator level deviation) confirmed that the interconnect does not adversely affect steady state or transient operations including overpressure transient operations.

The interconnect line has been insulated and shielded to ensure accessibility to the steam generator room and to the reactor deck area. A 230 mm steel shield has been installed to reduce the fields to 21 mRem/h on contact and 2.7 mRem/hr on the deck assuming the pessimistic flow conditions (such as a continuous flow) in the interconnect at full power.

COMMISSIONING PROGRAM

Philosophy

As any oscillatory system approaches a point of zero damping, accurate prediction of amplitudes becomes more and more difficult. Since the models predict near a zero damping for CANDU 600 stations, precise dynamic predictions are unachievable without some verification of the codes. Since these codes are used for station design and safety analysis, it is required to show that these codes predict performance in, at least, a conservative manner. To satisfy this requirement, a commissioning program was performed to compare station performance to code prediction and to adjust the models in a prescribed manner to lock the codes onto the station.

Briefly, the procedure was to:

1) Measure the HT flow under 0% F.P. conditions and compare to code predictions. Adjust codes to suit (frictional correlations and pump curve).
2) Measure the HT thermal performance (mainly, temperature as a function of power) and compare to code predictions. Adjust codes to suit (heat transfer correlations). The power maps from Reactor Physics are used here and may also be adjusted.
3) Predict the onset of voiding and compare to plant data. Discrepancies would require a code retuning or modified code modelling.
4) Perform dynamic predictions and tests. Adjust the void-quality relation, if necessary, or retune/remodel the code as required.

The first three parts of the procedure were summarized in reference 9. The fourth part is being reported simultaneously (reference 10) with this paper.

In summary, part one showed that the single phase pressure drops and pump heads matched well with code predictions. Only minor adjustments were made to some local entrance and exit losses, etc. All adjustments were within engineering tolerances and measurement error.

Part two revealed modelling differences between NUCIRC* and SOPHT steam generator models. Updating the NUCIRC steam generator model to include more detailed and realistic heat transfer coefficients gave agreement with site data and SOPHT predictions

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* NUCIRC is a steady state design code for the HTS.

provided the SOPHT node structure was sufficiently detailed. The major impact of modelling variations was in the prediction of the onset of void. Pretest estimate for the onset of void was 98% F.P. The plant tests gave an onset of void at approximately 100% FP. The details of the steady state NUCIRC code tuning process is an interesting study in its own right. It is hoped that this will be reported upon at later date. The "best estimate" SOPHT prediction of the dynamic tests with no interconnect is shown in Figures 21-22 (reference 10).

The test results (reference 10), are shown in Figures 21 to 23. These results are within the spectrum of the prepredictions. The SOPHT results shown in Figures 21 to 23 include minor modelling enhancements, mainly in the use of more detail in the feeder modelling. Excellent agreement between SOPHT and the plant data was achieved.

This "best estimate" post-test model was used to reaffirm the pre-test design analysis and associated analyses such as plant aging, transient performance, etc. The post-test activity was largely perfunctory since the test outcome fell within the range of the predictions upon which the design modification was based.

CONCLUSIONS

As a result of the comprehensive and thorough program of analytical studies, laboratory testing and on-power plant testing, it has been clearly demonstrated that:

- The as-built CANDU 600 primary heat transport system (with the interconnect) is not susceptible to divergent oscillations in the presence of asymmetric disturbances with steam quality in the reactor outlet headers.
- With the provision of a suitably designed 150 mm diameter interconnect between the two reactor outlet headers in each circuit, the system has been demonstrated to be convergent under the worst possible asymmetric perturbation that can be applied to the system. The instability concern in the CANDU 600 heat transport system therefore stands resolved.
- SOPHT code predictions of the stability test results based on the current "best estimate" of heat transport system conditions and using the "twin channel" core model and the adiabatic compression pressurizer model compares well with plant tests in terms of damping ratio and oscillation period.
- Minimum system damping occurs at a ROH quality of about 3% (corresponding to a ROH pressure of 9.5 MPa(a) with clean steam generators).
- The stability test has demonstrated that, under normal operating conditions (up to 100% FP), and at the present clean steam generator condition (i.e. fouling = 0) there is insufficient void in the HTS to substantiate unstable flow oscillations. Therefore, the as-built CANDU 600 is stable under these conditions even without the interconnect.
- The information collected during the commissioning test proved extremely useful for fine tuning and checking the steady state and transient computer codes which models the system behaviour. It is noteworthy that only minor changes to empirical correlations (flow resistance and heat transfer coefficients) and increased detailing of the feeder modelling were required in the fine tuning process. This confirms the relevance of models used for design and analysis.

ACKNOWLEDGEMENTS

Work of this scope could only have been accomplished by a dedicated team with the support of many people distributed throughout the various organizations of New Brunswick Power Commission, Hydro Quebec, Ontario Hydro and Atomic Energy of Canada Limited. This report is an overview of their work.

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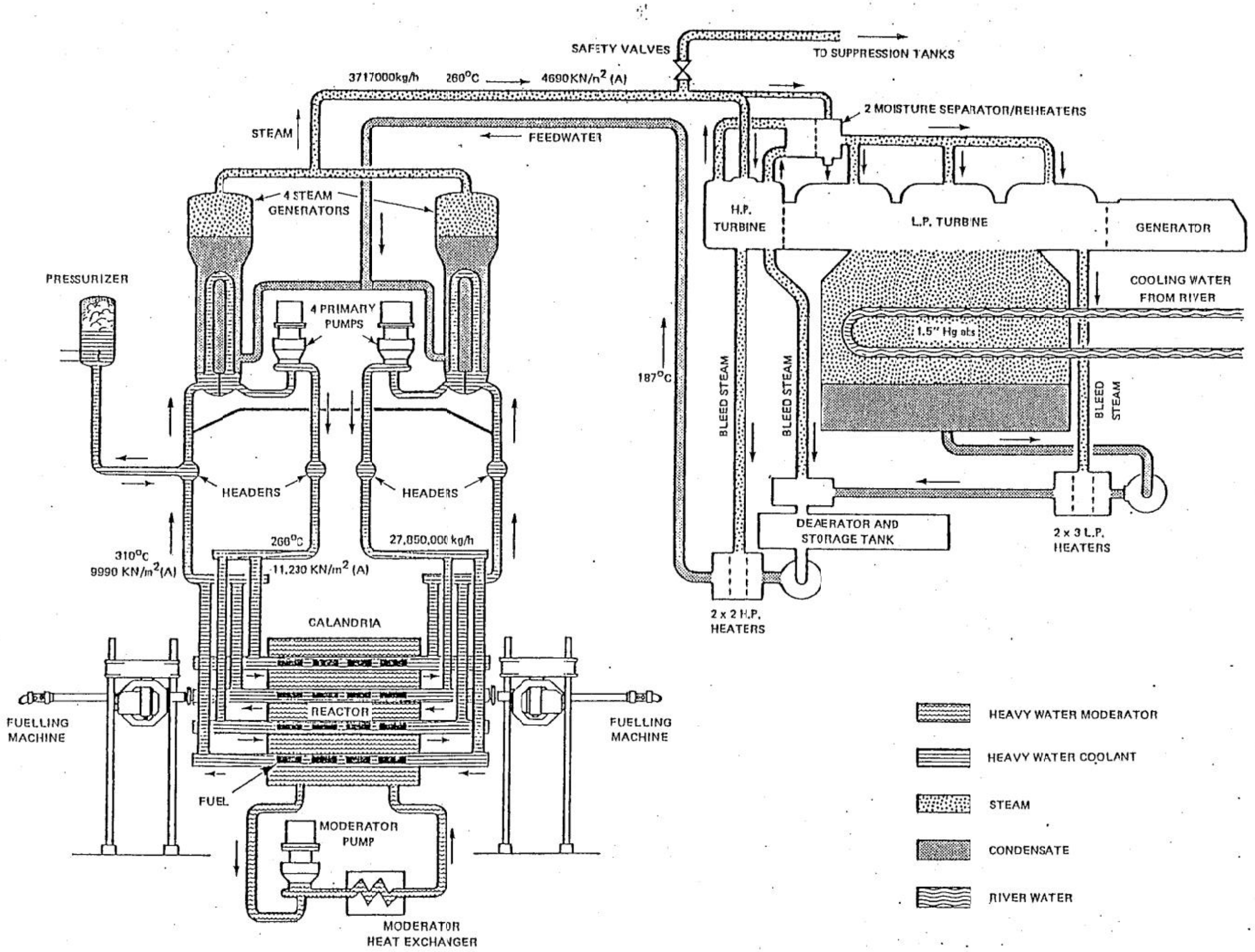


FIGURE 1 CANDU NUCLEAR POWER SYSTEM

XX 30000 2
July 79

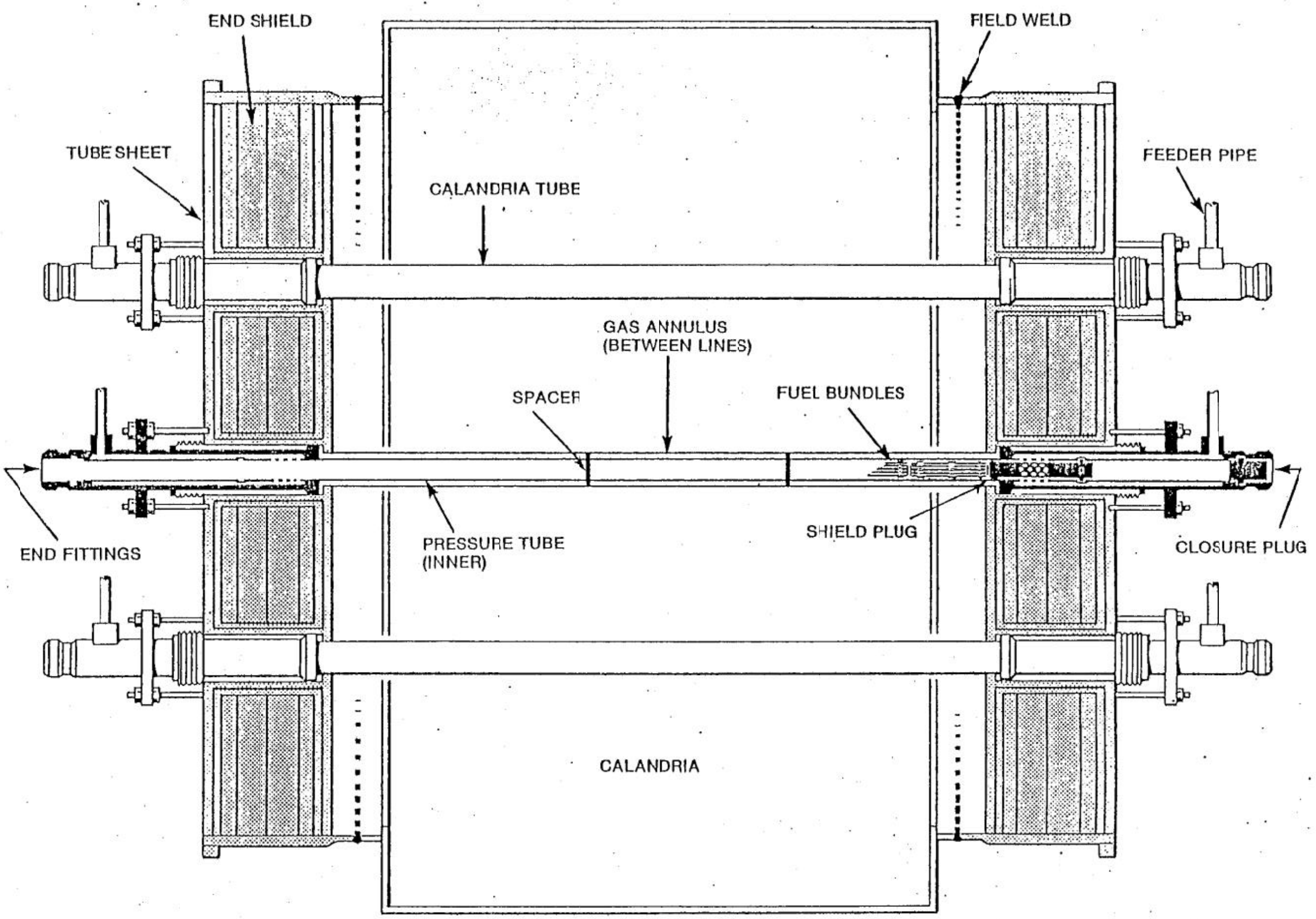
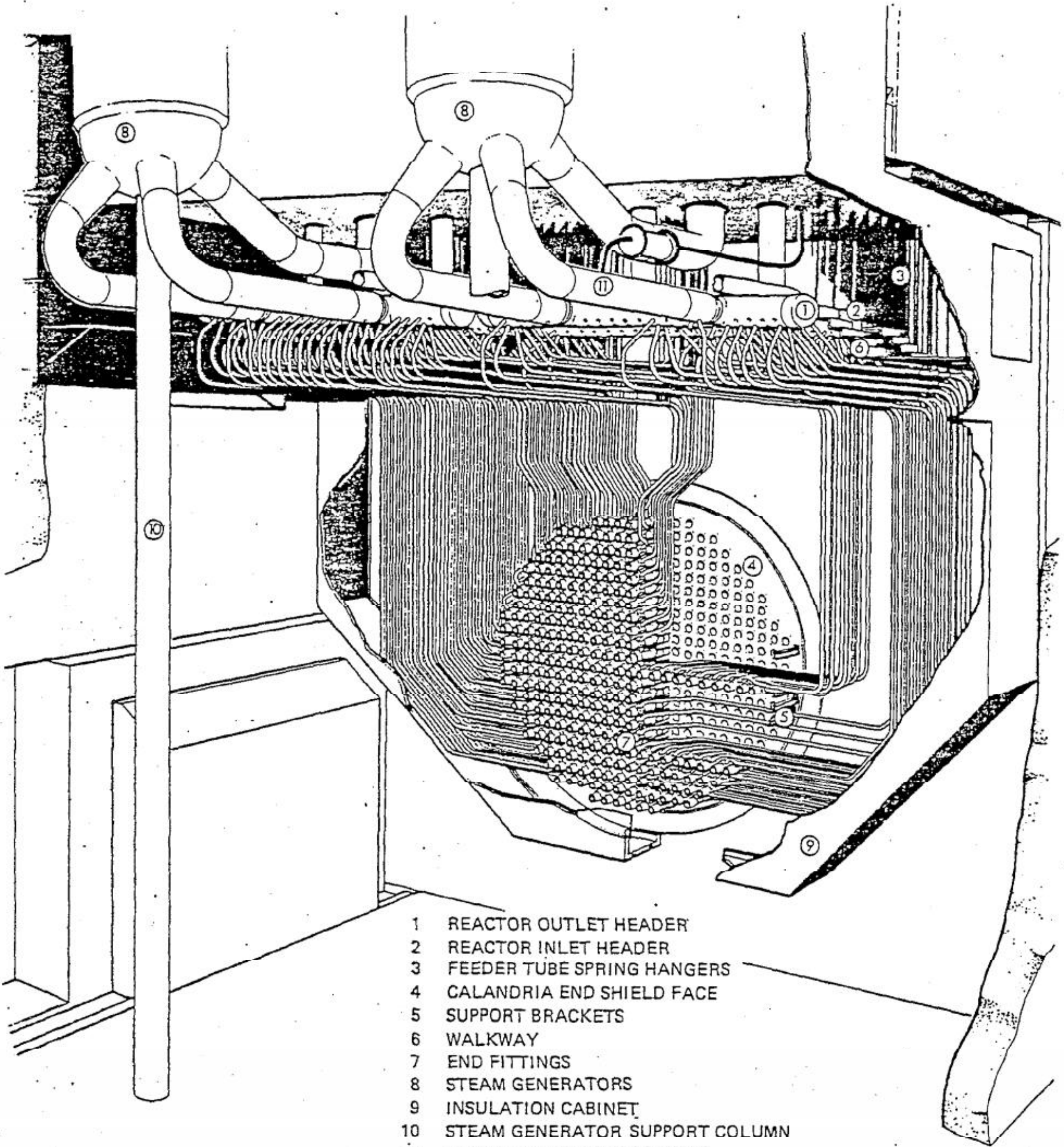


FIGURE 2 REACTOR CORE SCHEMATIC



66.33120-1
APRIL 1977
66 FSR

FIGURE 3 HEAT TRANSPORT SYSTEM TYPICAL FEEDER ARRANGEMENT

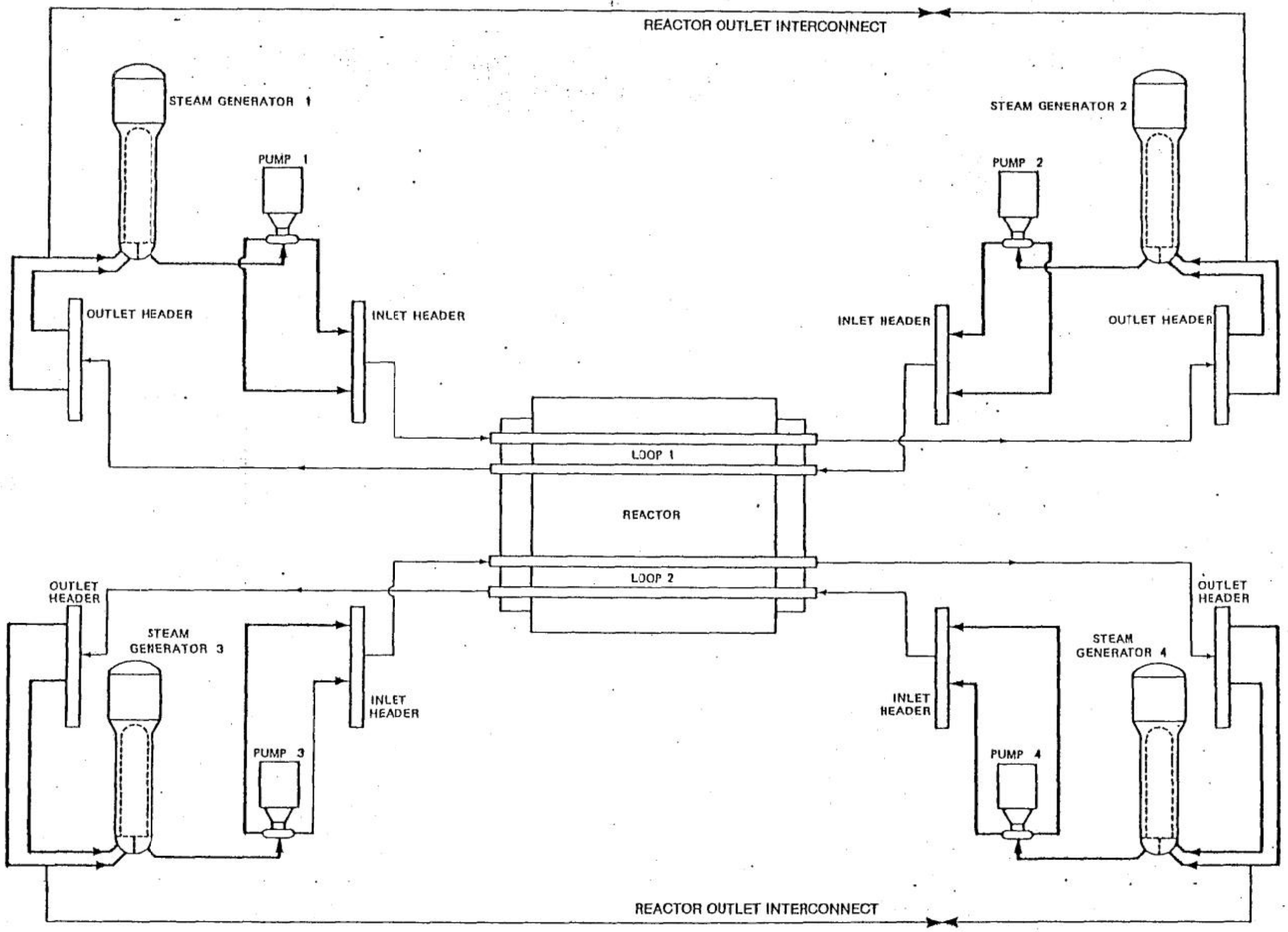


FIGURE 4 A HEAT TRANSPORT SYSTEM

66,33100-3
1973
66 FSR

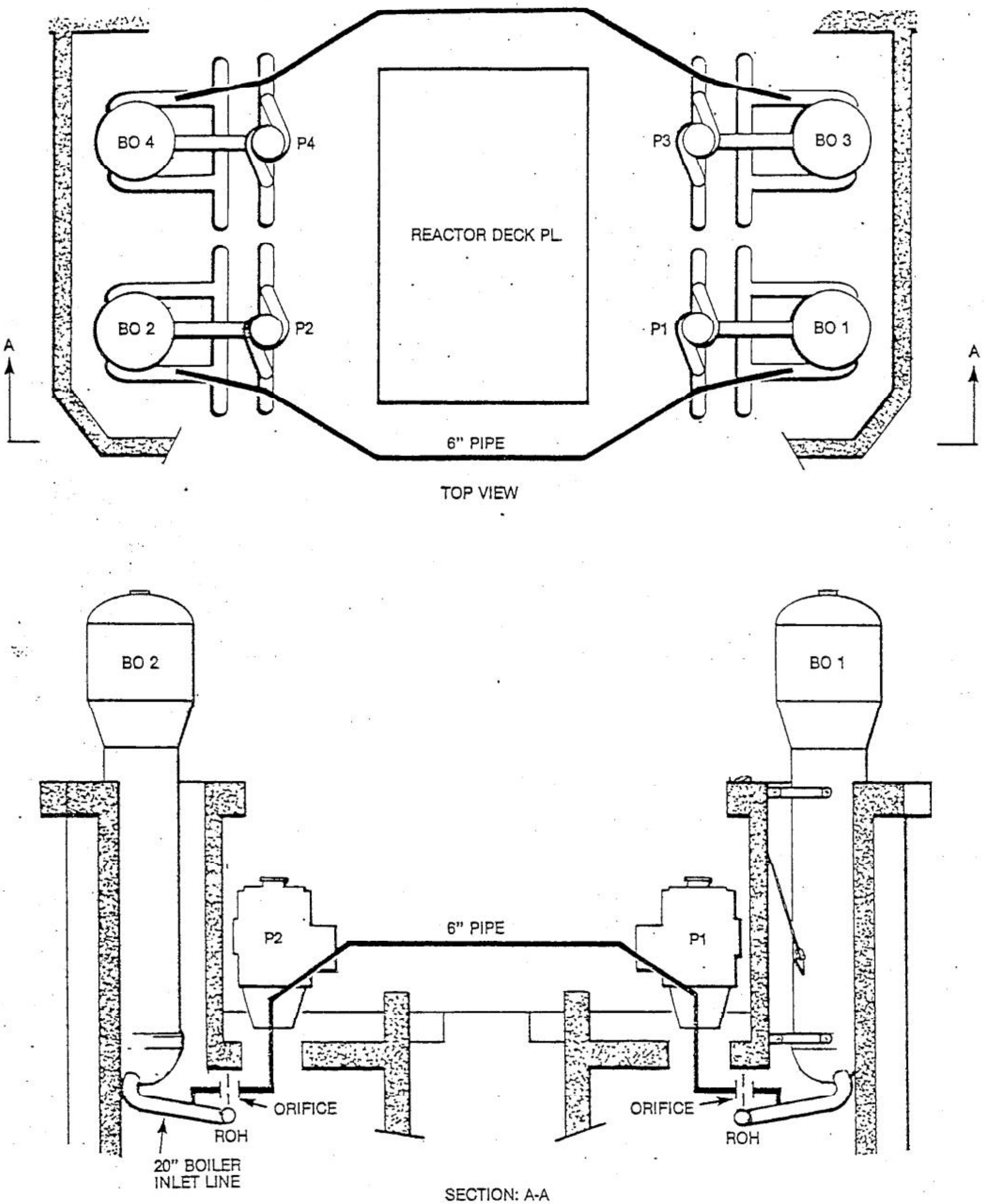


FIGURE 5 PRIMARY HEAT TRANSPORT SYSTEM

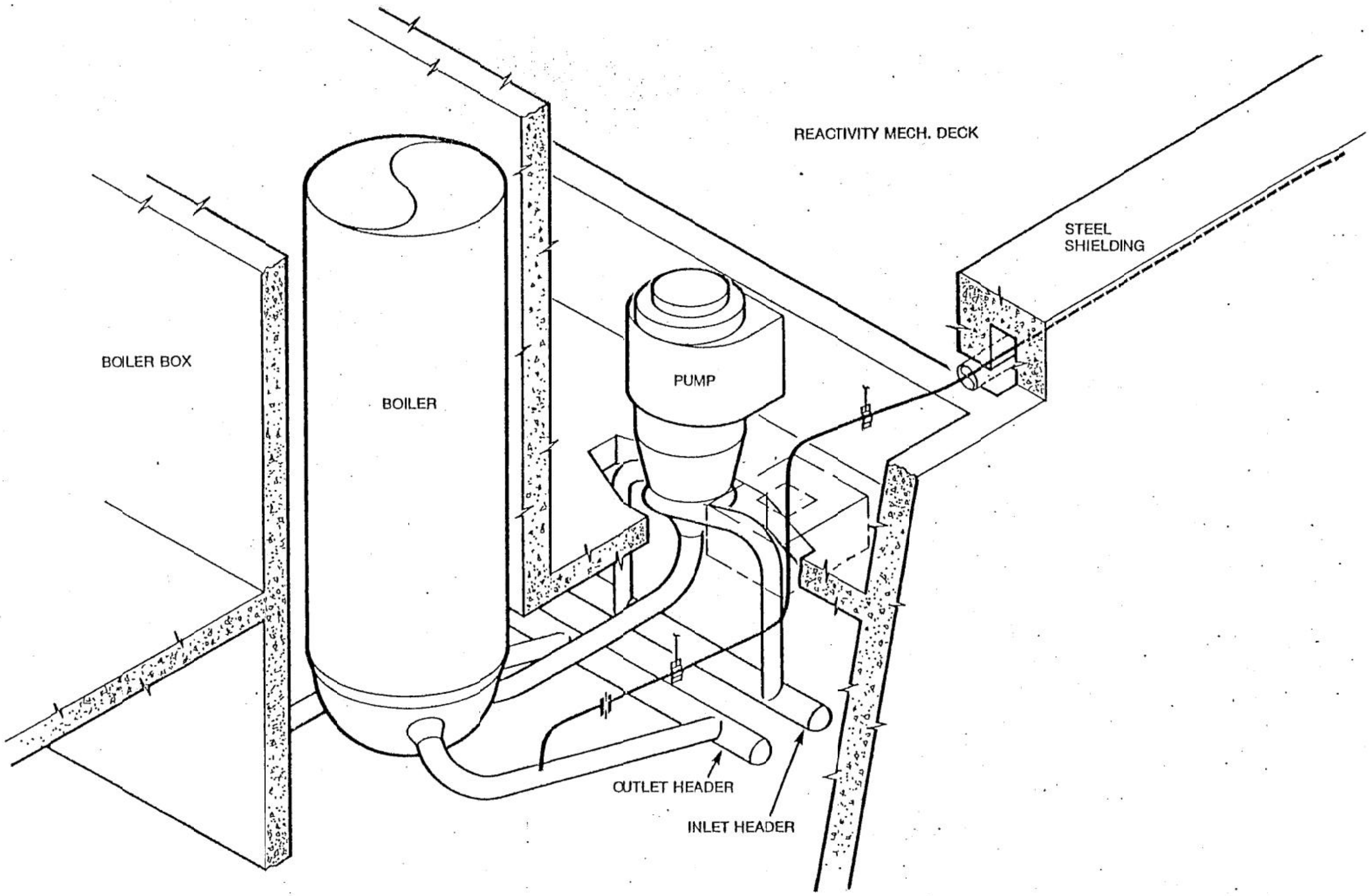
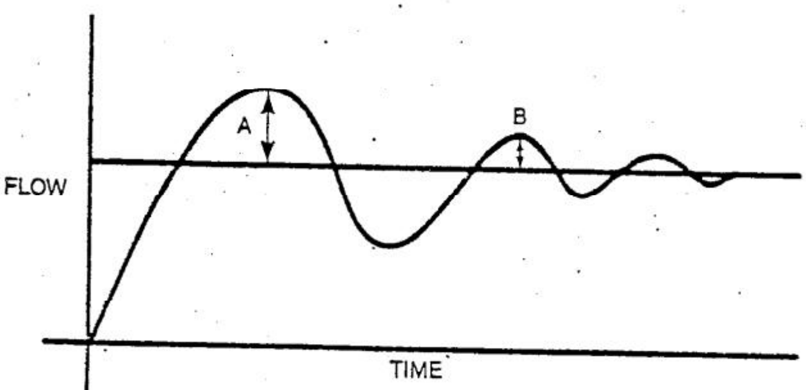


FIGURE 6 P.H.T. STABILITY INTERCONNECT



$$X \equiv \frac{B}{A}$$

$$\zeta \equiv - \frac{\frac{\ln \chi}{2\pi}}{\sqrt{1+\left(\frac{\ln \chi}{2\pi}\right)^{2}}}$$

FIGURE 7 DAMPING RATIO

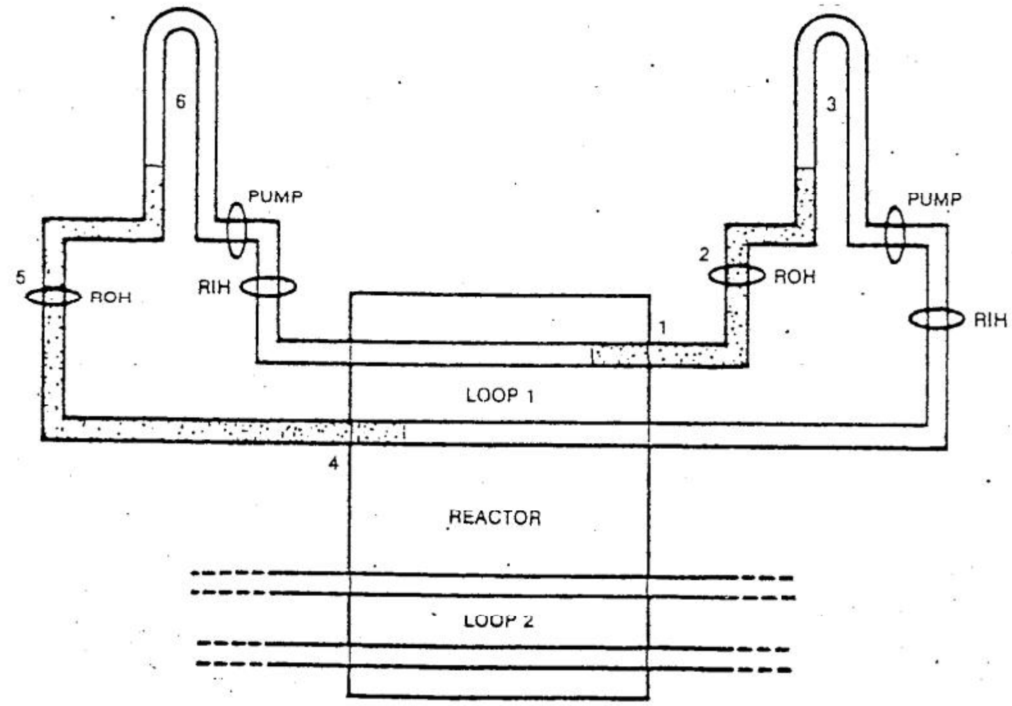


FIGURE 8 PHTS SCHEMATIC

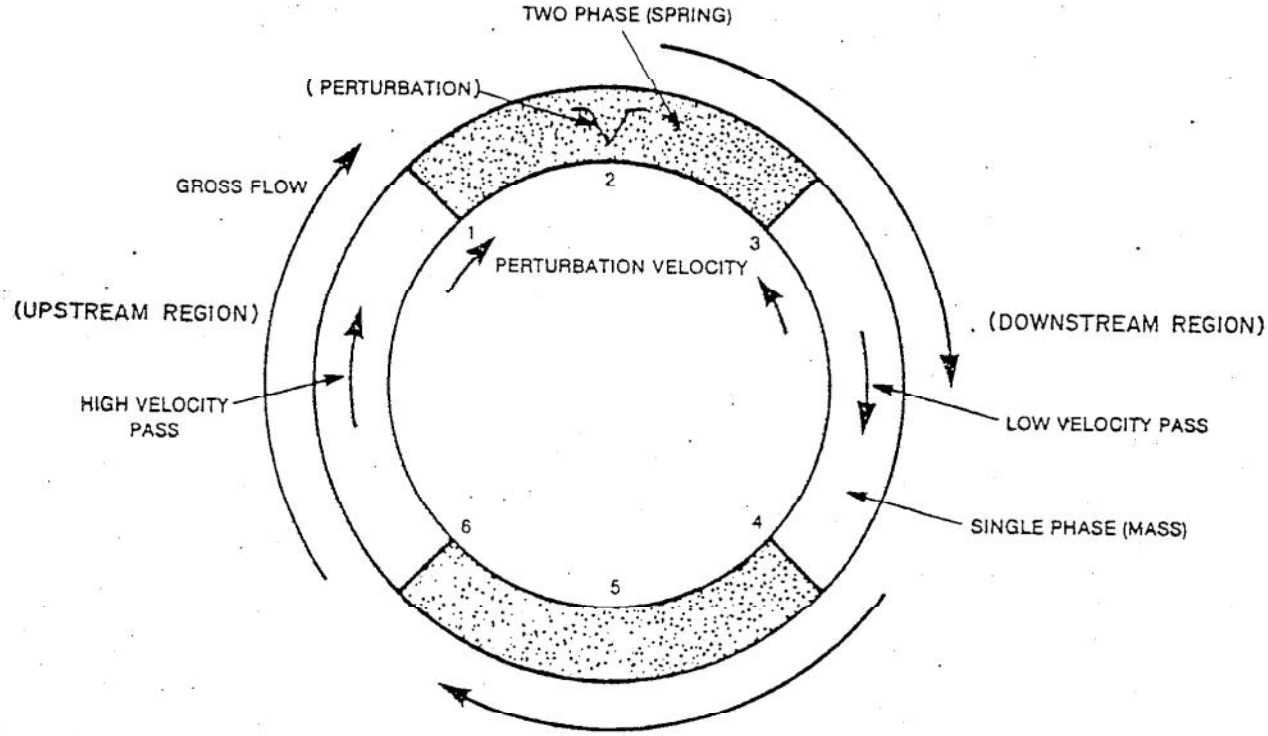


FIGURE 9 2 SPRING — 2 MASS MODEL

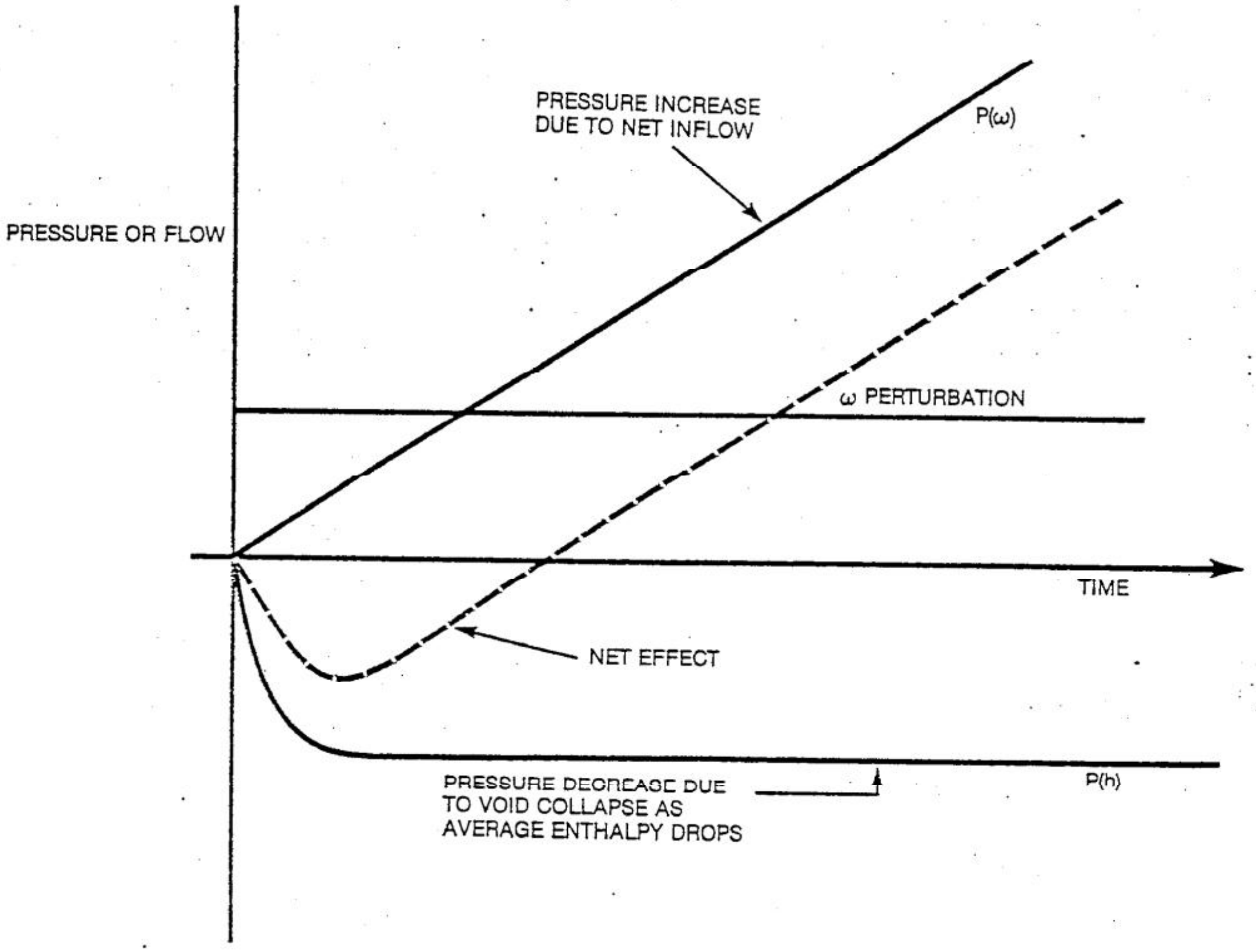


FIGURE 10 PRESSURE VARIATION FOR A CONSTANT FLOW PERTURBATION (FROM H.W. HINDS)

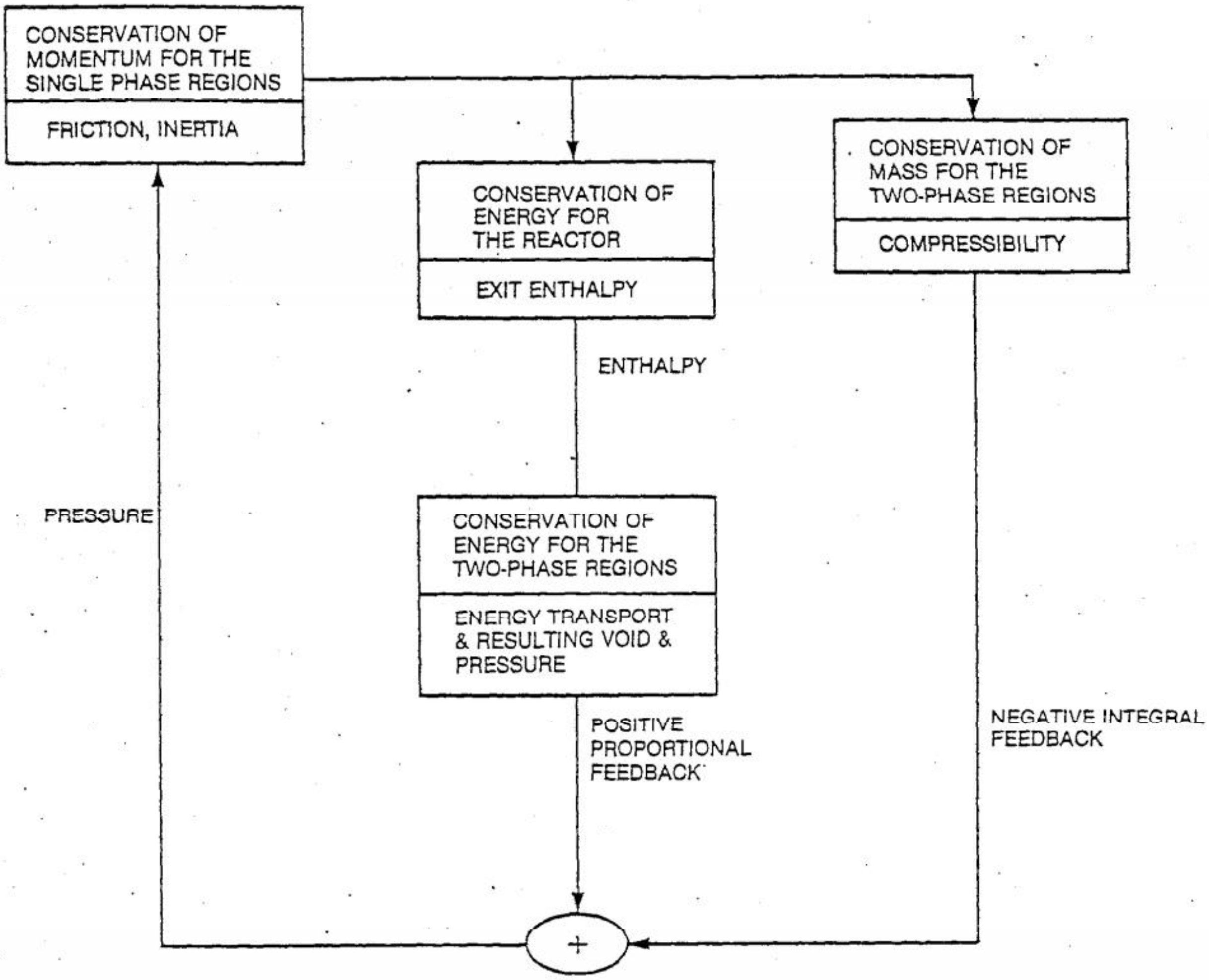


FIGURE 11 FEEDBACK BLOCK DIAGRAM

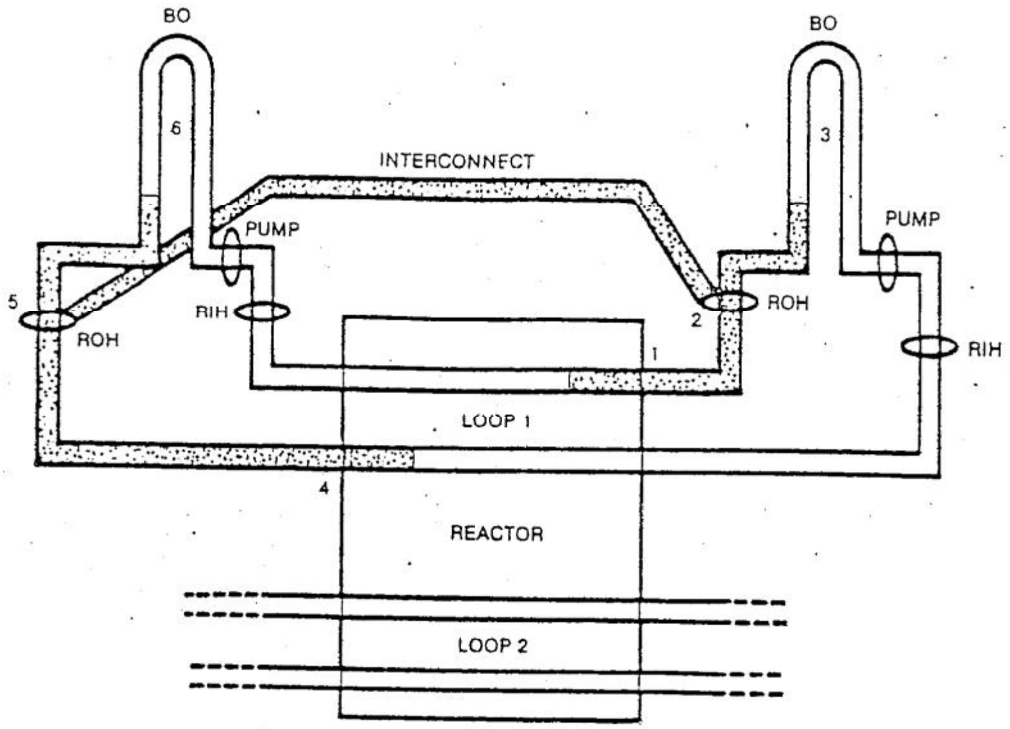


FIGURE 12 PHTS SCHEMATIC

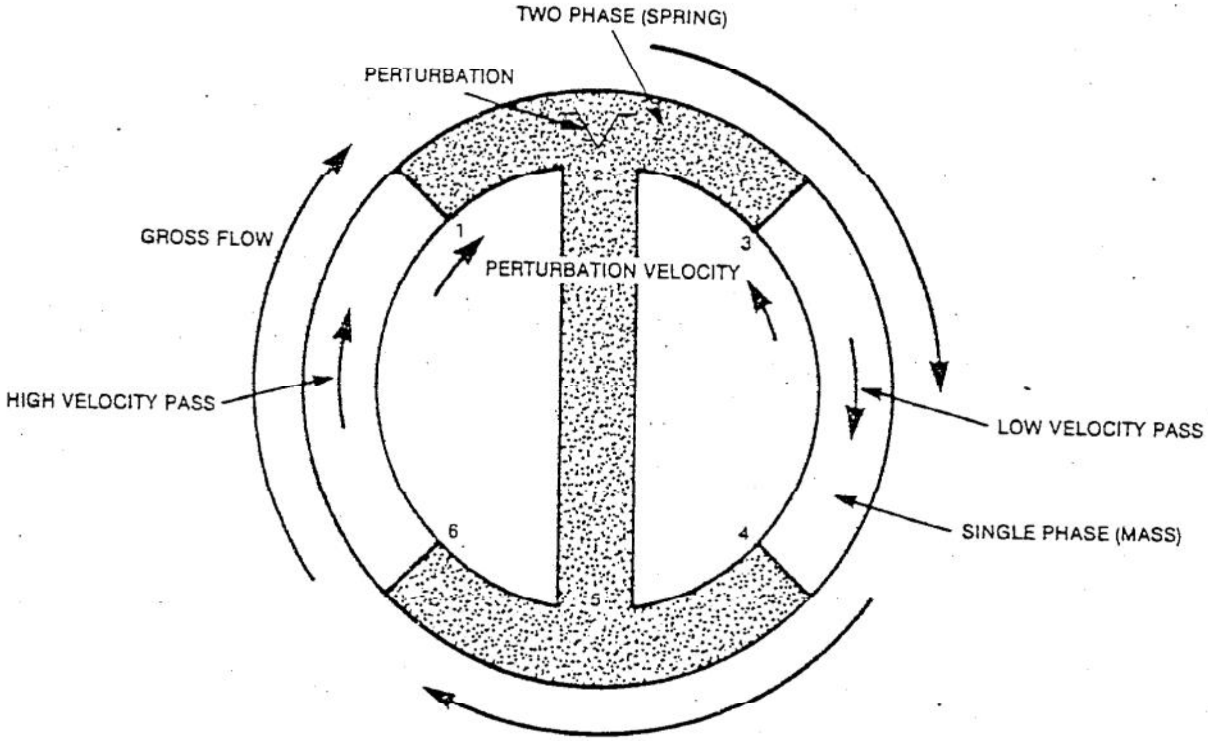


FIGURE 13 2 SPRING — 2 MASS MODEL

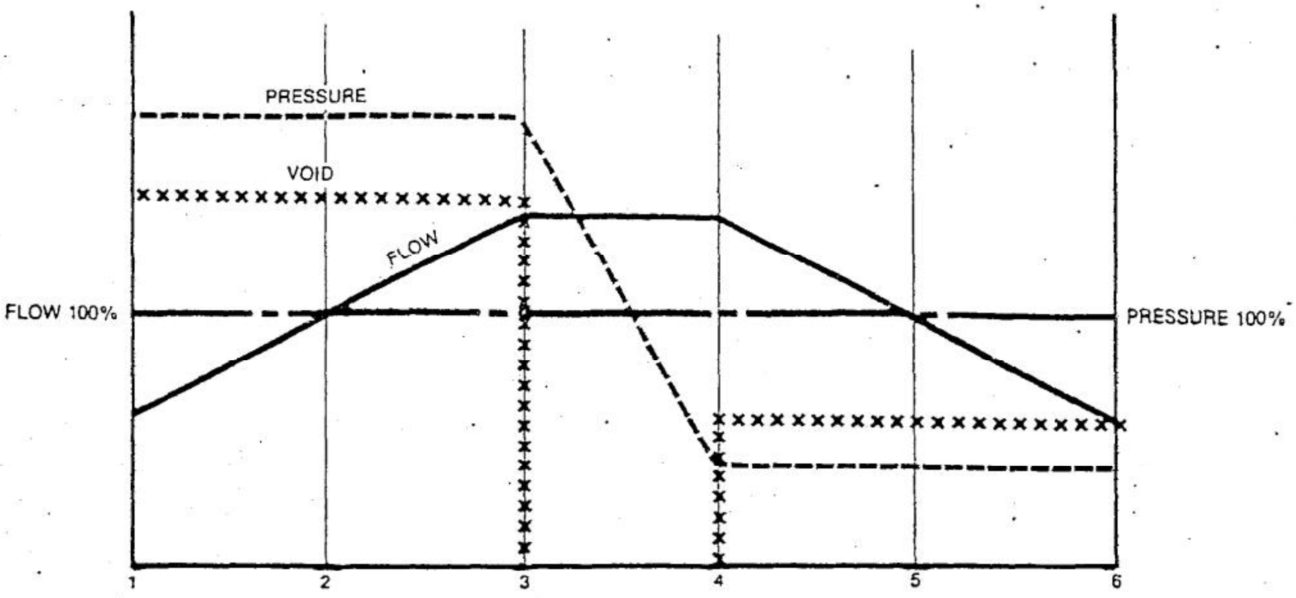


FIGURE 14 SNAPSHOT OF FLOW AND PRESSURE AT AN INSTANT IN TIME, t FOR VARIOUS POSITIONS (AS PER FIGURES 12 AND 13)

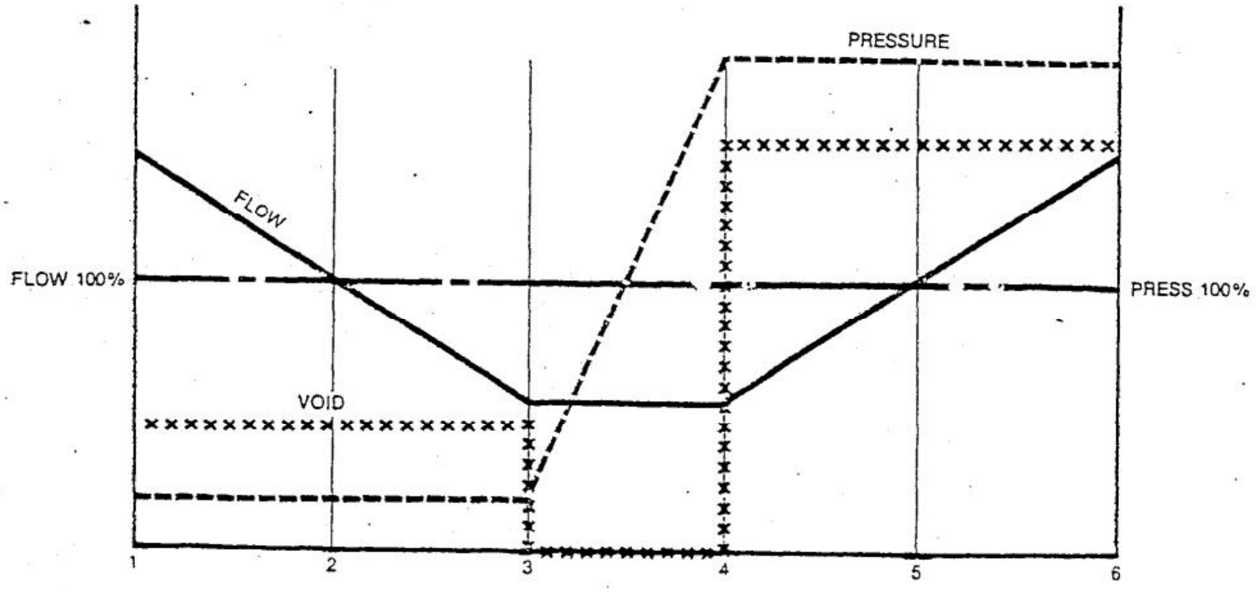


FIGURE 15 SNAPSHOT OF FLOW AND PRESSURE AT TIME (t + 1/2 CYCLE) FOR VARIOUS POSITIONS (AS PER FIGURES 12 AND 13)

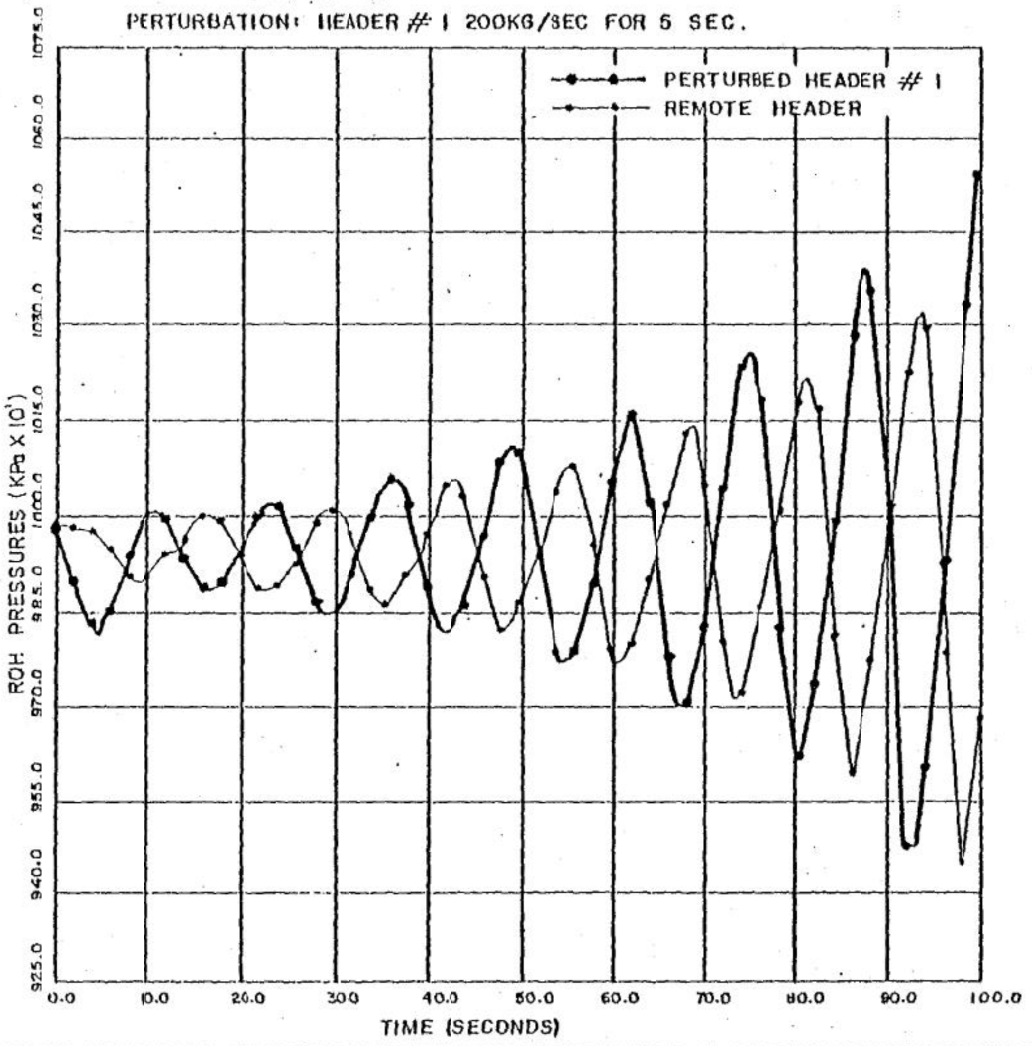


FIGURE 16 REACTOR OUTLET HEADER, PRESSURE vs. TIME
NO INTERCONNECT

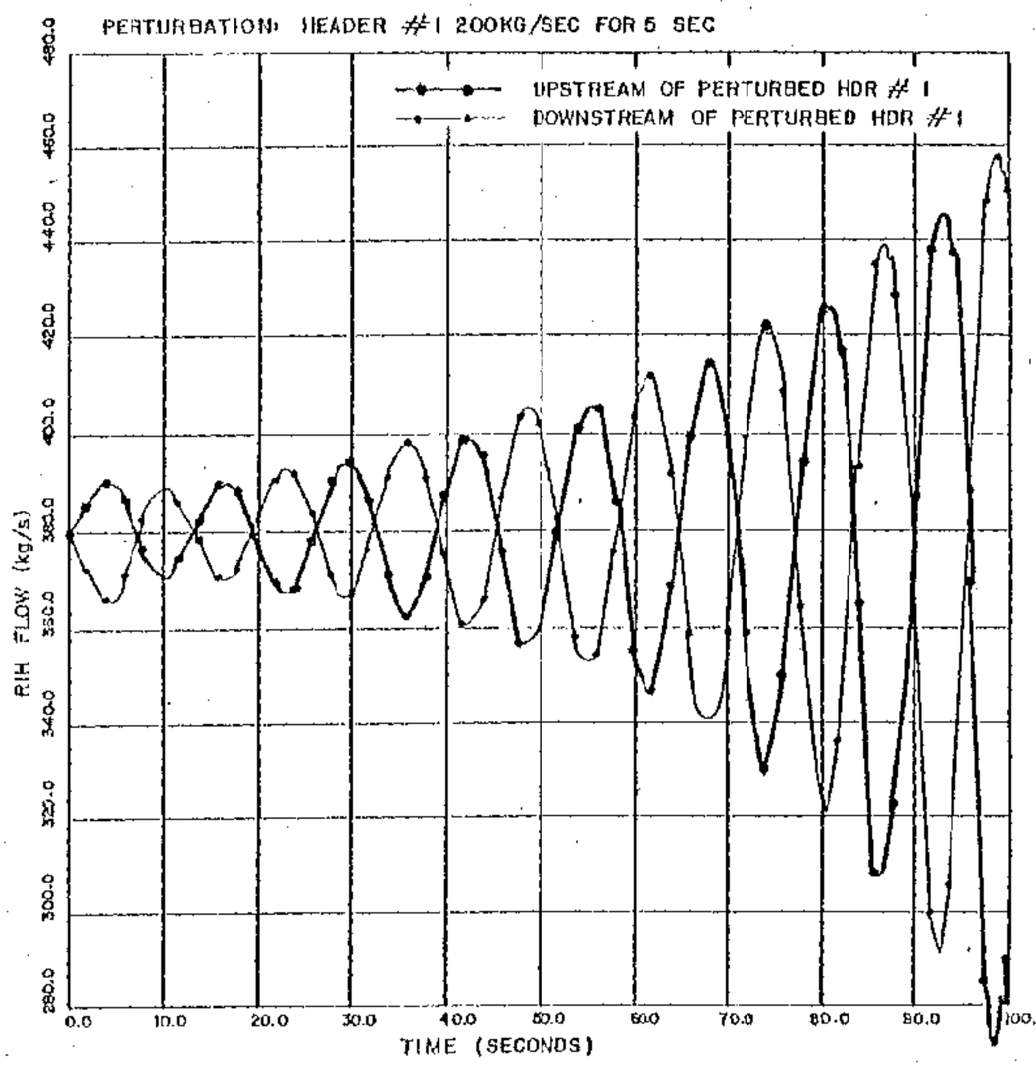


FIGURE 17 REACTOR INLET HEADER
FLOW vs. TIME, NO INTERCONNECT.

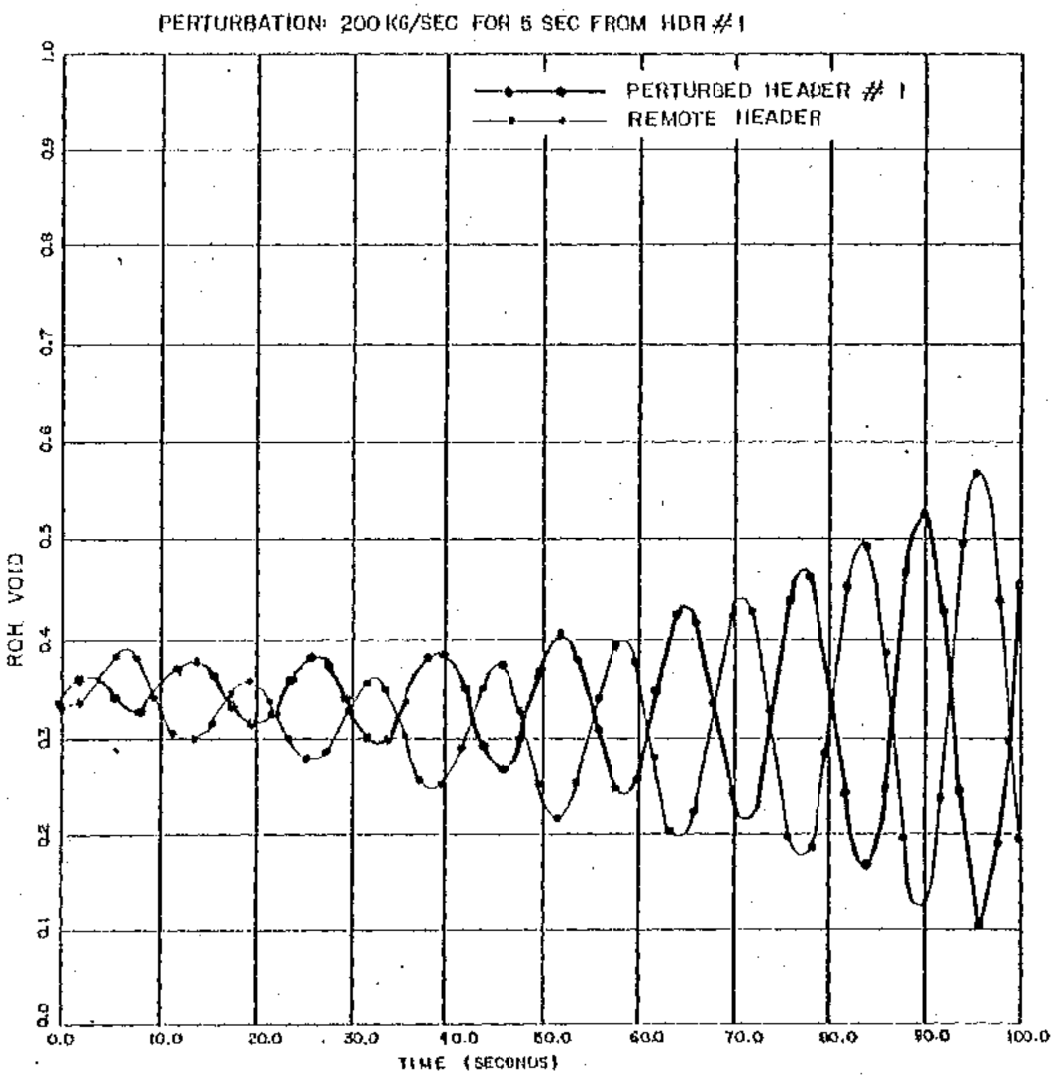


FIGURE 18 REACTOR OUTLET HEADER VOID vs TIME
NO INTERCONNECT

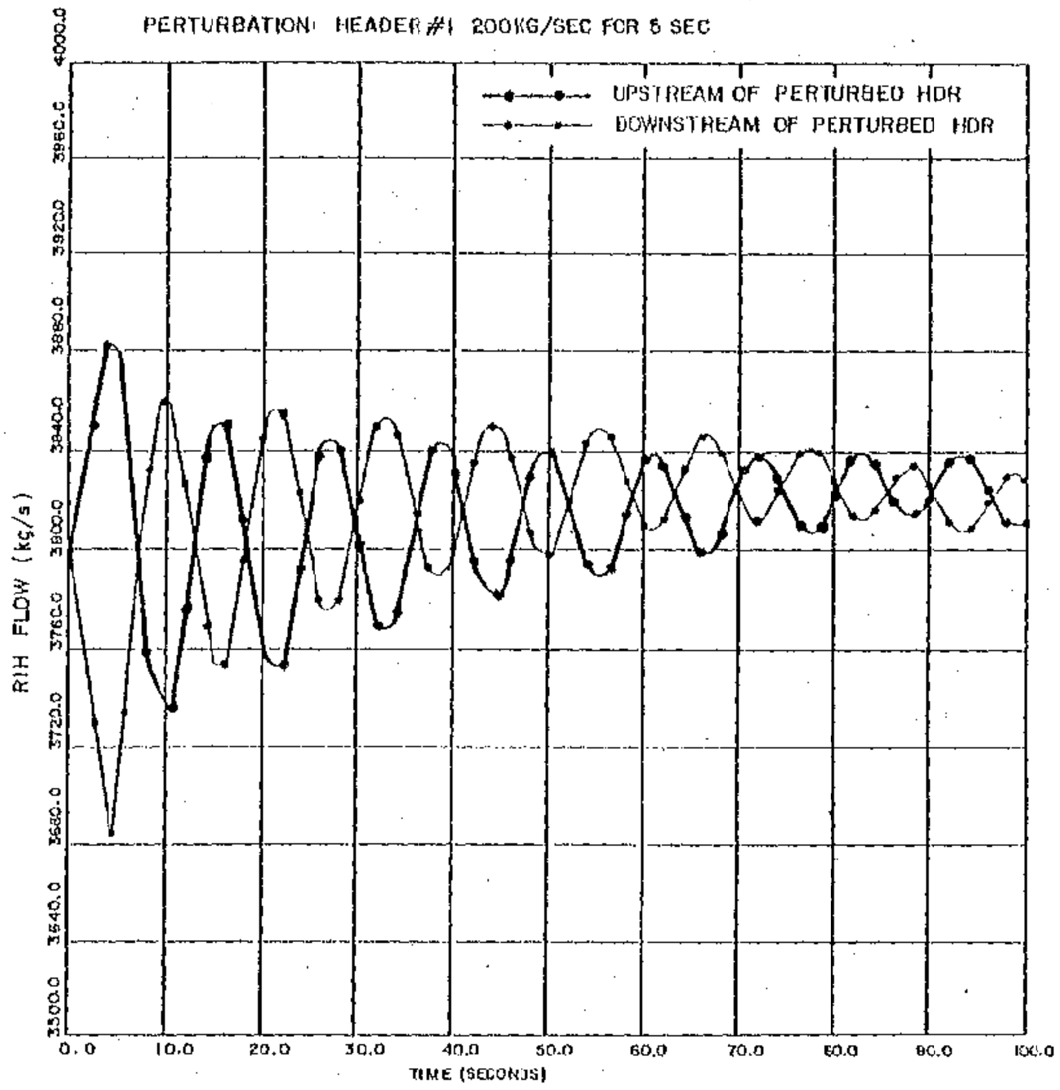


FIGURE 19 REACTOR INLET HEADER
FLOW vs. TIME, WITH INTERCONNECT, HOMOGENEOUS MODEL

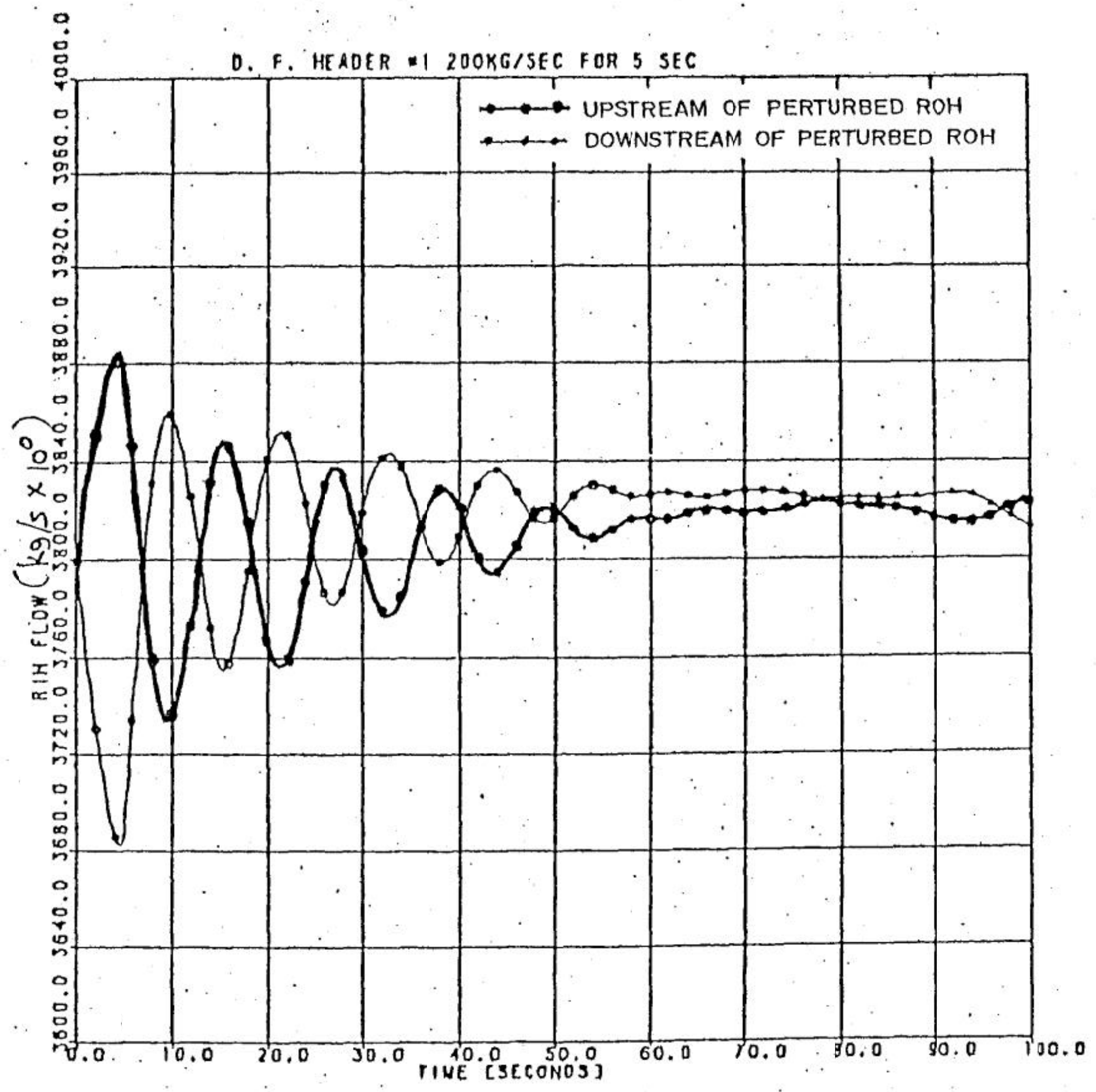


FIGURE 20 : RIH FLOW vs. TIME, WITH INTERCONNECT, DRIFT FLUX, HOMOGENEOUS START

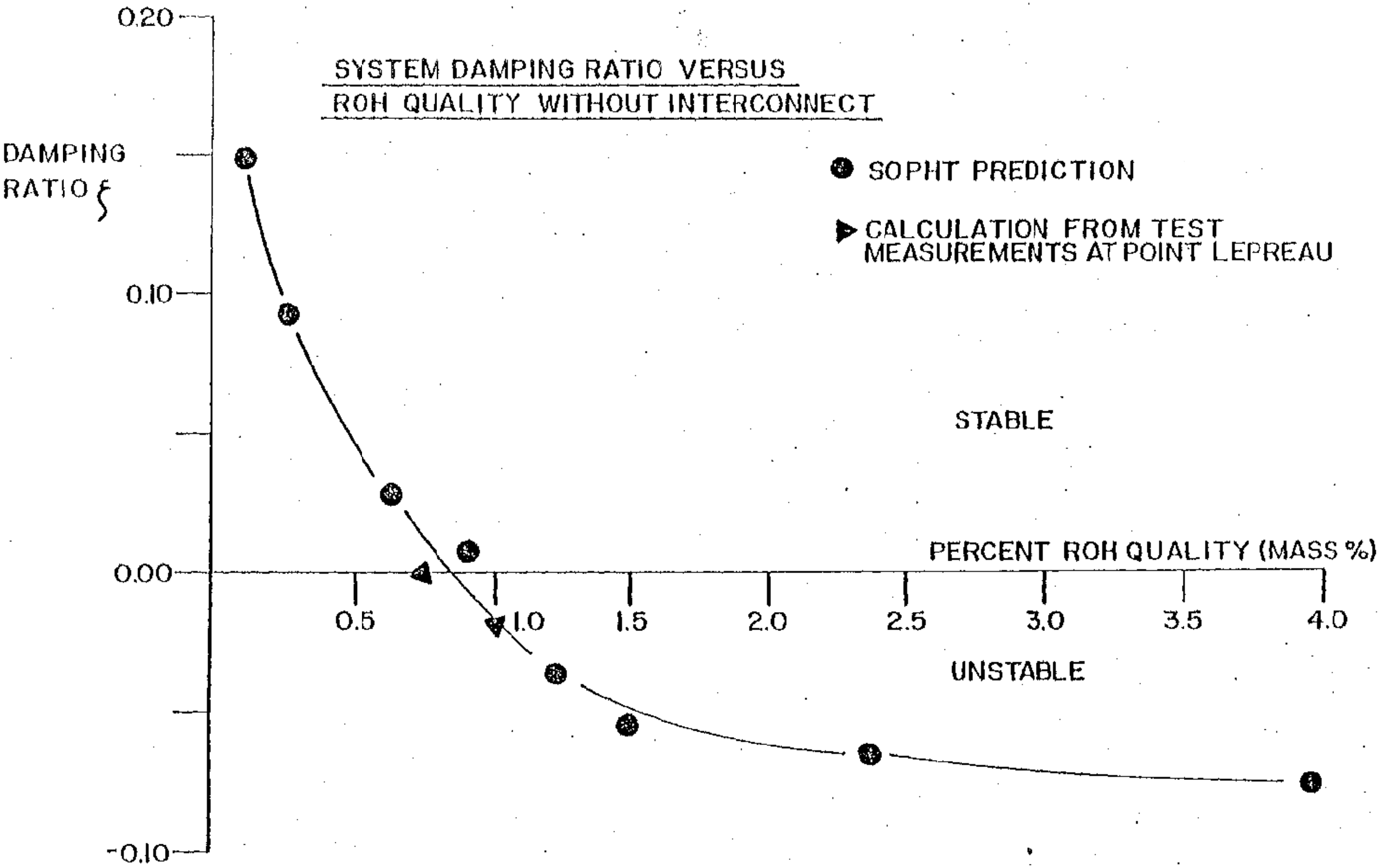


FIG. 21 : REACTOR OUTLET HEADER QUALITY ACHIEVED DURING TESTS AND SYSTEM DAMPING RATIO COMPARISON BETWEEN PREDICTION AND TEST RESULTS

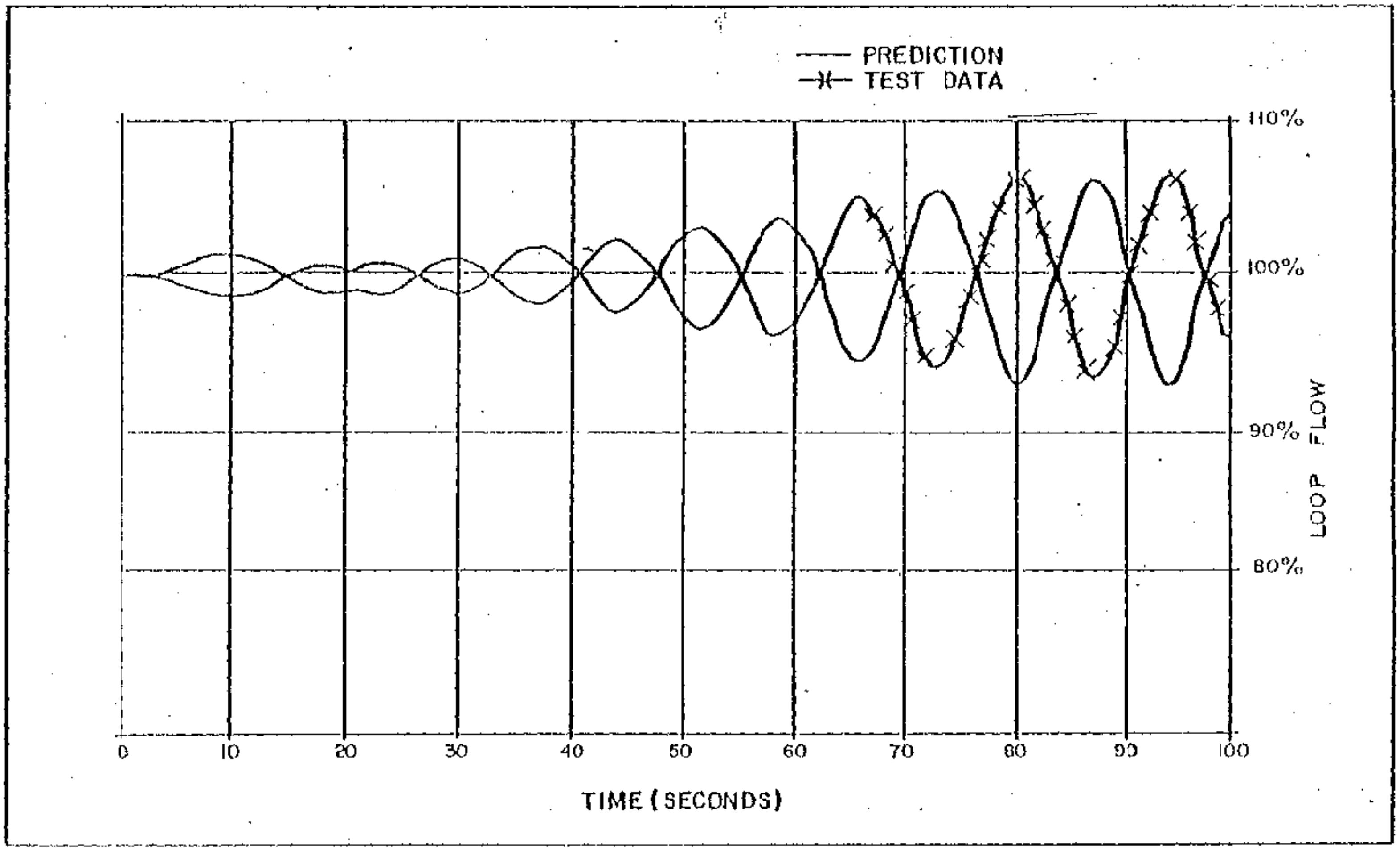


FIGURE 22: COMPARISON OF TEST DATA WITH SOPHT PREDICTION TUNED TO 65% FP DATA

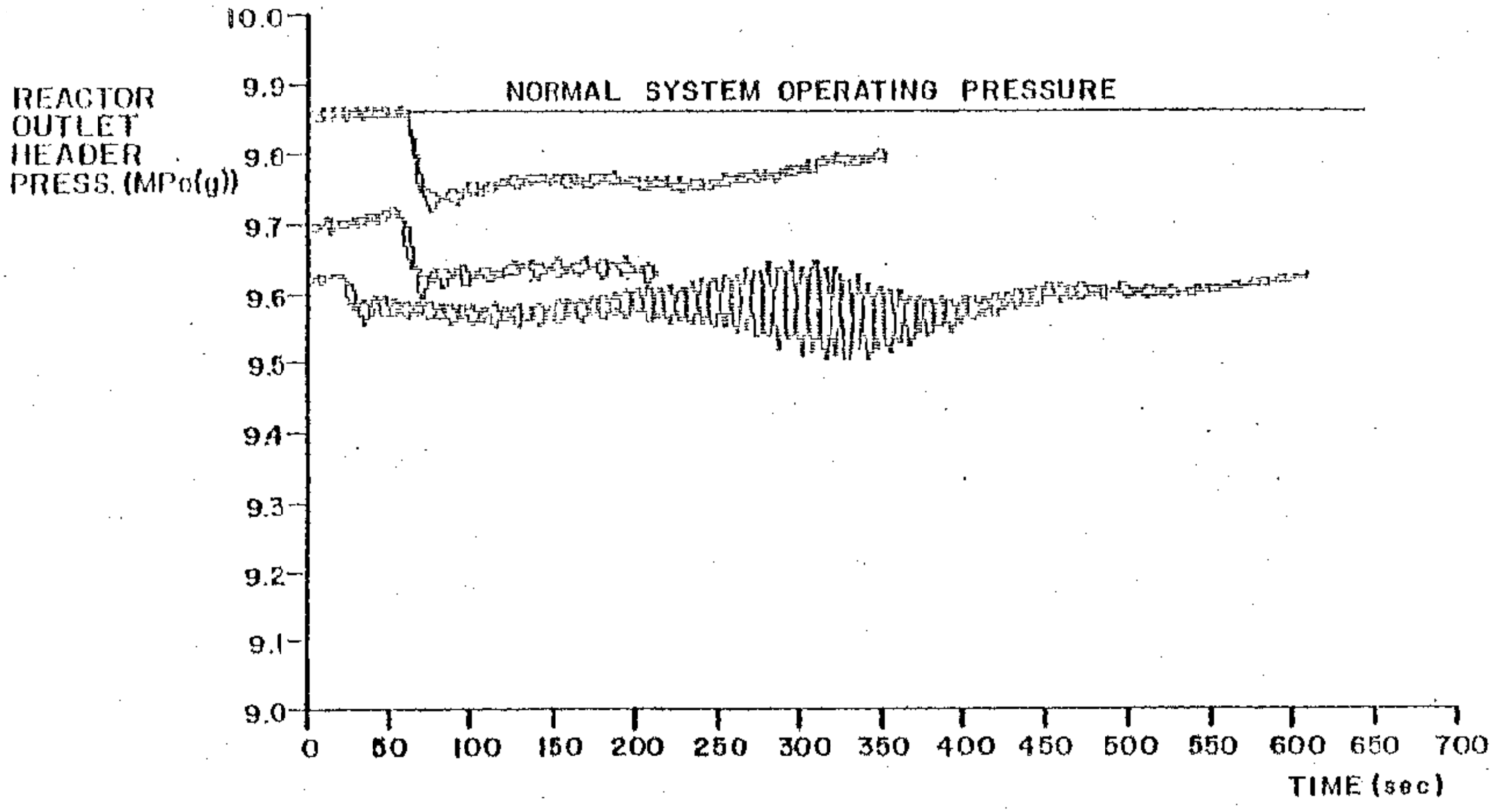


FIG.23' REACTOR OUTLET HEADER PRESS. RESPONSE TO A 10sec PRESSURIZER STEAM BLEED VALVE OPENING AT REDUCED SYSTEM OPERATING PRESS.