SIMULATION OF LOSS OF COOLANT ACCIDENTS AT THE ONTARIO HYDRO PICKERING NGS SIMULATOR

by

W.R. Bassermann and G.S. Hall

Abstract

The purpose of the Pickering Simulator is the training of key nuclear power plant operating personnel. To fulfill this role, the models must be sophisticated enough to handle a wide variety of trainee interactions and instructor initiated malfunctions. However, because the programs must run in a real time operating environment, the models must avoid time consuming calculations. In spite of these two rigorous requirements, the models developed for use on the simulator give surprisingly good results when compared with more sophisticated models and actual plant experience. In particular, the simulation of loss of coolant accidents has not only resulted in valuable training, but it brought about changes in operating procedures and safety systems at the plant itself.

Paper to be presented at
1979 Simulation Symposium on Reactor
Dynamics and Plant Control
Ontario Hydro Conference Centre
Orangeville, Ontario
April, 1979

SIMULATION OF LOCA AT PICKERING G.S. SIMULATOR

Objectives

The purpose of the Pickering Simulator is to train key nuclear power plant operating personnel such as unit first operators and shift supervisors. Prior to the construction of the simulator and implementation of a simulator training program, control room operating experience could not be acquired in an orderly fashion. Practicing such standard operating procedures as startups and shutdowns was limited by the low frequency of planned outages and the activity associated with them. Experience in handling non-standard operating procedures such as reactor or turbine trips was limited by their sporadic nature. Furthermore, the high cost of a loss of generation precluded staging such events for training purposes. Other non-standard procedures such as those associated with a loss of coolant accident could obviously not be practiced at all.

This training vacuum is the gap which the simulator fills. It allows for the implementation of a coherent and systematic training program in which startups, shutdowns, power manoeuvres, and credible equipment failures can be performed.

Model Requirements

The fundamental criterion for the simulator models is that they allow standard and non-standard operating procedures to be performed. These procedures are given in the Pickering Operating Manuals and are based on the design of the station, operating experience, the Pickering Safety Report and analysis using sophisticated models. This simply stated criterion places rather rigorous requirements on models used at the simulator.

- As some procedures involve the entire unit, most of the systems must be simulated and the interactions between systems elucidated.

- The models for each system must cover the entire operating range from full power steady-state to shutdown.

- The model design must anticipate the consequences of all proper (and the more common improper) operator interactions as well as over three hundred malfunctions and instructor manipulated parameters.

- The responses of the numerous variables and displays must be qualitatively and, in most cases quantitatively, similar to the station itself. Where analysis using more sophisticated models have been used to develop operating procedures, the simulator models must be able to duplicate the results.

- The requirements listed above must be achieved subject to the constraints imposed by the real-time operating system.

Thus sophisticated models and time consuming mathematical procedures have to be avoided. The operating system also requires that the models be easily subdivided into separate modules which can be executed at different times and frequencies.

Simulator Operating System

The simulator makes use of three Texas Instruments TI980A mini-computers which operate in a one master - two slave configuration. The two slaves serve only to increase foreground (process model execution) capability and run under master CPU control. In addition to executing foreground tasks, the master performs all other functions including input/output and background (user) tasks.

The basic iteration time period is 50 ms. Master/slave and master/panel interface transfers take place on each cycle. Most of the simulation involves synchronous foreground modules which execute with period of 50 to 800 ms, 200 ms being the most common. Some tasks are asynchronous and are executed only if time is available in an iteration.

The execution frequencies of the programs and of the master/slave transfers permit adequate simulation of most transients. However, those events which take place over a time period (<1 sec) comparable to the program iteration times expose the discrete nature of the calculations. Thus careful attention must be paid to the ordering of modules and of equations within each module.

A. Reactor System

The simulation of the reactor system is contained within twelve modules which cover the areas of:

1. reactor kinetics
2. reactivity effects
3. reactor control and protection

1. Reactor Kinetics

Because of the potentially rapid variation of neutron power values, the reactor kinetics module is executed on the fastest (50 ms) time band. Variables are generally computed in either double precision arithmetic or specially constructed floating point format.*

Neutron power values are simulated by utilizing a combination of point and zonal models as shown in Figure 1. Using gross reactivity as an input, the point model computes:

a) overall concentrations of 6 delayed and 9 photoneutron groups. The final value of this delayed component is used to normalize the single-group fractions of the zonal model.

b) overall neutron power via

$$\frac{dN}{dt} = \frac{\rho - \beta}{\tau} \cdot N + L_c \qquad \text{(A1)}$$

$$L_c = \sum_{i=1}^{15} fi.\,\lambda i.\,Ci$$

where λi, Ci are the decay constant and concentration of group 'i', and as usual

ρ = reactivity
β = delayed fraction
τ = mean neutron lifetime
fi = 1 $(i = 1,\dots,6)$
= fraction of moderator in calandria $(i = 7,\dots,15)$

(fi allows for the reduction of deuterium targets for photoneutron creation in a partially full calandria.)

---

* The TI980A is a fixed point machine.

Simple linear integration of (A1) leads to instability for high power and ρ approaching prompt critical. Rather than (artificially) shortening the time step, (A1) is solved by the algorithm

$$N(t + \Delta t) = N(t) + [\xi . N(t) + L_c . \Delta t] . \frac{e^{\xi} - 1}{\xi} \quad \ldots\ldots\ldots\ldots (A2)$$

with $\Delta t = 50$ ms

$$\xi = [(\rho - \beta) . \Delta t]/\tau$$

Spatial power variation is simulated by using the 14-zone, single delayed group model of the PARD program (Ref. 1). For each zone, a single delayed component is calculated on the basis of zonal power (c.f. Figure 1); the overall sum is normalised to the point model version. Coupling coefficients are taken to be linear in zonal reactivities and are updated every 200 ms. In the original implementation of PARD, instabilities in the prompt components necessitated (artificial) lagging by 300 ms. As may be expected, this was found unsatisfactory from the standpoints of

a) slow response to large change in ρ (e.g. during a reactor trip) and

b) complete instability as ρ approaches prompt critical. [This can of course be avoided by increasing the artificial lag at the further expense of (a).]

Normalization of zonal power to the point model solution (A2) removes both deficiencies.

2. Reactivity Effects:

An outline of those reactivity effects included in the simulation is given in Figure 2. Computation and summation thereof is performed every 200 ms. With regard to those contributions of particular relevance to a LOCA situation, the following should be noted:

a) Temperature - related contributions are taken to correspond to those of an equilibrium core. Reactivity arising from fuel temperature changes is not calculated dynamically but merely interpolated from an experimental curve.

b) Void fractions are calculated in the PHT modules for each of the 12 thermal zones then redistributed to correspond to the 14 reactivity zones. A similar remark applies to fuel and coolant temperatures.

c) Moderator level reactivity is interpolated from a calculated curve (Ref. 2).

3. Reactor Protection:

At Pickering 'A' the shutdown mechanisms available to the protective system are shutoff rods and moderator dump. The general trip philosophy is to use shutoff rod drop with moderator dump available as a backstop (and therefore actuated only in the event that power rundown following rod drop is deemed unsatisfactory). The exceptions to this are where LOCA-type conditions transpire, viz. through low gross flow or high boiler room pressure; the pressure of either trip above 2% power triggers both shutdown mechanisms.

It is in regard to protective system operation following major LOCA initiation that the simulation shows its rather coarse-grained quality; almost all modules associated with the protective system are run on the 200 ms time band.* 200 ms therefore represents the limit of accuracy for trip initiation, etc. Despite this, the simulation yields

a) order of trip signals, and

b) reasonable values for the timing of events

which are consistent with the safety report analysis.

- - - - - - - - - - - - - - - - -

* An exception to this is boiler room pressure which is computed every 400 ms. Note that due to the execution times of the modules involved, increasing iteration frequency is not a viable proposition on a training simulator.

B. <u>Heat Transport System</u>

Although the simulation of the heat transport system comprises over twenty modules, the block diagram shown in Figure 3 illustrates the main interactions. The reactor power in each of the fourteen reactor zones is mapped, via matrix multiplication, onto the twelve thermal zones of the heat transport model. In this model, twelve coolant channels, one associated with each thermal zone, are used to represent the 390 channels in the real plant. The fuel temperature in each zone is calculated and fed back to the reactor modules for fuel temperature reactivity calculations. Under normal conditions, no mixing of the flows from each thermal zone occurs in the outlet header. Therefore, the power generated inside a given thermal zone is transferred by the coolant to a single boiler. In this way, flux tilts are reflected by differences in boiler steaming rates. The heat transfer in the boilers takes place in two discrete places, the boiling and preheater regions, and is calculated using temperatures determined in the steam system modules.

The primary circulating pumps are extensively modelled. Detailed pump characteristic curves have been coded to give proper responses under a variety of conditions including reverse flow. Pump cavitation is accounted for via the ANC two phase pump model (Ref. 3). As a number of pump parameters is available to the operator in the plant, such quantities as pump gland cooling and stator winding temperatures are dynamically modelled. Thus improper starting procedure of a pump can result in high stator winding temperatures and a pump trip.

The pressures in each loop are determined using the concept of a reference pressure. One pressure in the loop (one of the reactor outlet headers) is determined from the net inflows into the loop and changes in coolant density. Other pressures in the loop are determined relative to the reference pressure.

For instance, the pump suction header pressure is given by

$$P_{PS} = P_{ROH} - \frac{W_B^2}{A_B}$$

where P_{ROH} = reference pressure in the outlet header

W_B = flow through the boilers

A_B = admittance through the boilers

All admittances throughout the loops take into account the possibility of coolant boiling via Martinelli-Nelson two phase flow friction factors (Ref. 4).

The reference pressure itself is calculated from the equation

$$P_{ROH} = P'_{ROH} + C(M - \rho V)$$

where P'_{ROH} = pressure on the previous iteration

M = loop mass

V = loop volume

ρ = average loop density

C = variable whose value depends on the compressibility of the loop. It is large when the system is "solid" but smaller when voiding occurs.

The reference pressure is adjusted to ensure that the actual loop mass and the desired mass (as calculated from steam tables) are equal. Thus as long as the states before and after a transient are the same, this method ensures conservation of mass. This is of importance in operator training, as the heavy water inventory is carefully monitored.

Using the pressures and enthalpies calculated in the relevant modules, the steam tables module calculates other relevant quantities, such as density, temperatures and void fractions assuming equilibrium conditions in each pressure node. The form of the reference pressure calculation requires that the compressibility of the liquid be taken into account. The properties of superheated steam are not included as such a condition rarely occurs.

Other modules associated with the heat transport system cover the feed and bleed system, shutdown cooling system, valve and pump logic, alarms, panel displays and the like.

In modelling leaks and pipe ruptures, the model described above has proved to be extremely versatile. The only additional information which has been inserted into the model to account for such failures is the rate of coolant discharge.

C Containment System

The block diagram associated with the Containment System is shown in Figure 4. The extent to which this system is modelled allows for realistic response to a loss of coolant accident. The pressure in the reactor building is calculated dynamically taking into account discharge rates from ruptured pipes, flow to the vacuum building and the status of the reactor building ventilation system. The openings of the pressure relief valves, the vacuum building pressure, and the dousing flow, are all modelled so that the panel displays and alarms properly reflect the status of the unit under accident conditions.

D Moderator

Although the graphs in the next section deal mainly with the effects of a LOCA on the reactor, heat transport and containment systems, the modelling effort expended on the moderator deserves mention. The Emergency Core Cooling System at Pickering involves initial injection from the moderator. When this source of cooling is used up, the operator must retrieve water which has collected in the various sumps. This is entirely a manual operation and, from a training point of view, the most important part of the LOCA simulation. Thus the modelling of this recovery operation includes sump levels, recovery flows, pump cavitation, gas locking, and motor overload. In this way, the operators learn correct action to take based on his observations of various displays.

Loss of Coolant Accidents

The training of control room operators in coping with loss of coolant accidents centres on two main points:

- recognition of the type of failure
- correct execution of the relevant operating manual procedures.

There is a large number of possible break sizes and locations. However, an adequate variety is provided by the four loss-of-coolant accident available on the simulator:

- reactor inlet header rupture (50% of maximum)
- feeder break
- dual seal failure on a main circulating pump
- adjustable leak occurring at a reactor outlet header.

Although the inlet header rupture is the severest of these from a number of viewpoints, it has been used primarily for demonstration purposes so far. The reactor power transient associated with the break is shown in Figure 5 and is comparable to that predicted in the Safety Report. It is more than sufficient to bring in the Linear Rate and High Power Trips by which the operator can recognize the problem. High Boiler Room Pressure and Low Flow trips also come in almost immediately. As indicated previously, the simulation yields correct ordering of trip signals together with reasonable trip timing values - bearing in mind the 200 ms iteration time of the protective system modules.

The pressure decay following the rupture is shown in Figure 7. The time taken to blowdown is almost exactly the same as predicted by more sophisticated models. Thus the operator gains an appreciation of the time he has to react following a large rupture. Figure 8 illustrates the characteristic reversal of flow through the reactor in the first few seconds followed by subsequent stagnation. The bulk fuel temperature in the broken loop is plotted in Figure 9 and shows an appreciable rise following the rupture. While the simulation of this transient is not tremendously accurate for a number of reasons, it cannot be observed by the operator and hence has a lesser significance from a training viewpoint. The boiler room pressure transient is shown in Figure 10.

The feeder break has been used extensively for operator training. Recent analysis has shown that small breaks of this type can result in fuel failures due tostratification of the coolant during the long blowdown. As a result, the Emergency Core Cooling logic at the station is being changed so that the Steam Release Valves (SRV's) open automatically under accident conditions. By reducing the boiler secondary side pressure, a rapid blowdown is assured as shown in Figure 11. The associated boiler room pressure transient is shown in

Figure 12 and shows that the pressure is reduced below atmospheric within seconds by the pressure relief valves. The timing and order of the primary and backup trips are very close to those predicted by recent analysis.

The logic which was used to isolate the two heat transport loops and was also going to be used to open the SRV's required that a low heat transport pressure condition occurs simultaneously with high boiler room pressure. However, the modelling effort on the simulator revealed that for small breaks, boiler room pressure would be dragged subatmospheric before heat transport pressure decayed sufficiently. Thus the logic would not operate in the very situation for which it was intended. As a result, the logic presently being implemented at the station includes a seal-in feature on high boiler room pressure. This example shows the ability of the simulator to illustrate the interaction between various systems.

Less severe malfunctions such as a dual seal failure and a leak whose size is selected by the instructor, have also provided valuable training, in that they allow the operator to review events which have actually occurred in the station. In these instances, the safety systems do not give the first signs of the failure. The operator must rely on process system alarms to give a warning of the fault. In addition, the procedures to be followed are not quite so clear cut and depend on a number of factors such as the reserve inventory of heavy water.

Conclusion

In spite of the limitations on the sophistication of the models, the simulator gives realistic responses to piping ruptures. While such responses cannot be used as the bases of a safety analysis, they can point the way to more efficient safety systems logic and operating procedures.

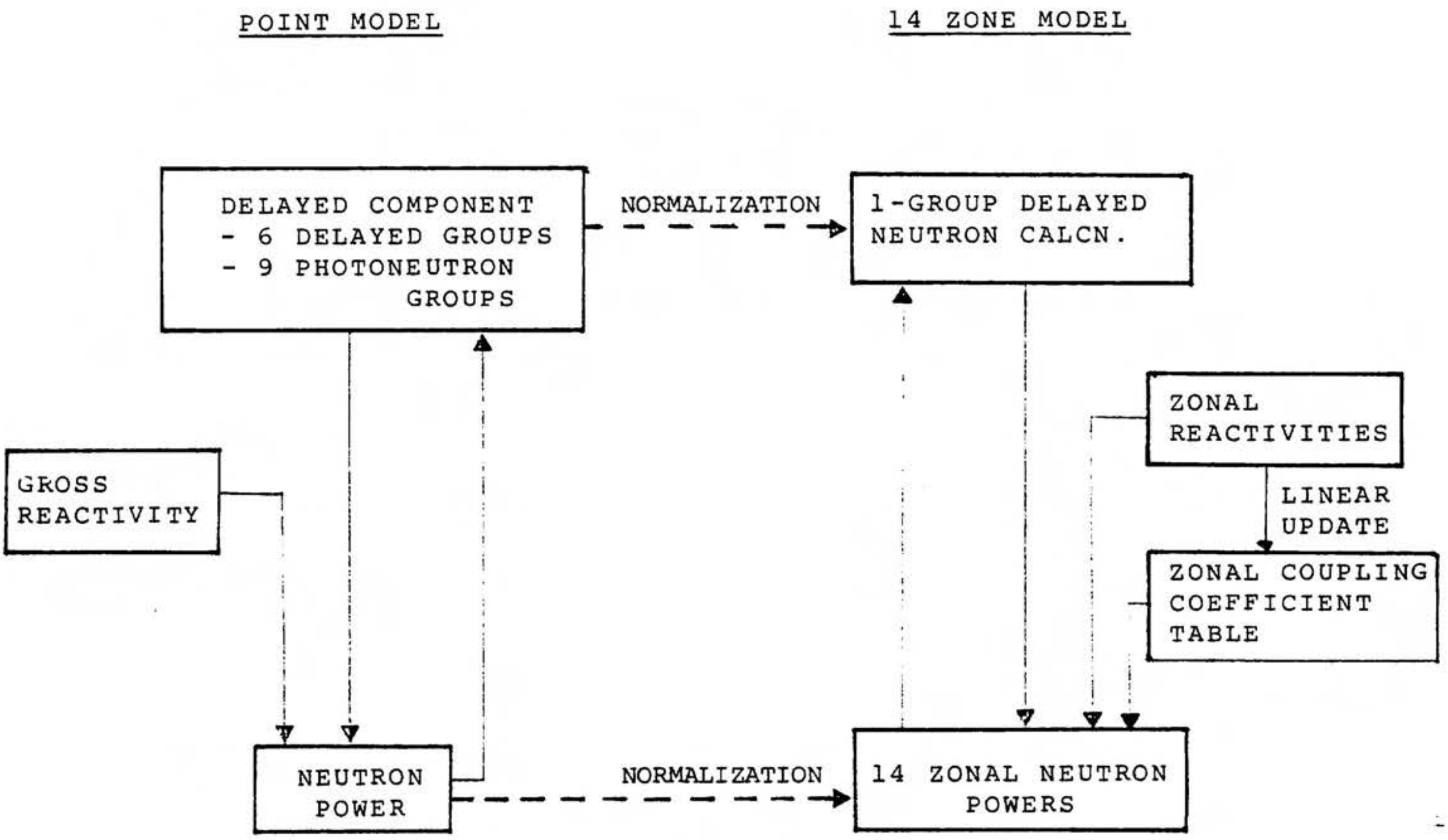


FIGURE 1: REACTOR KINETICS COMPUTATION SCHEME

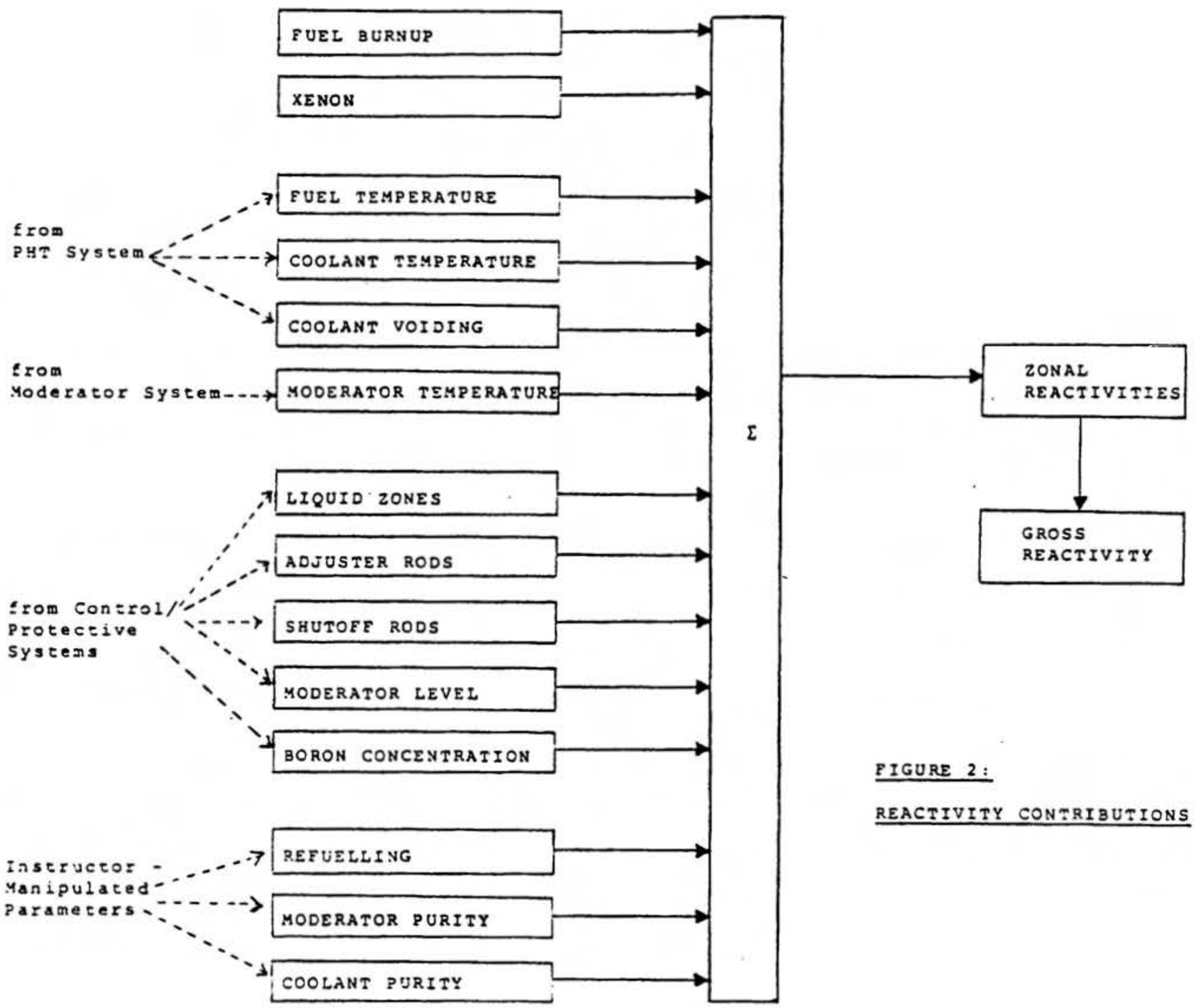
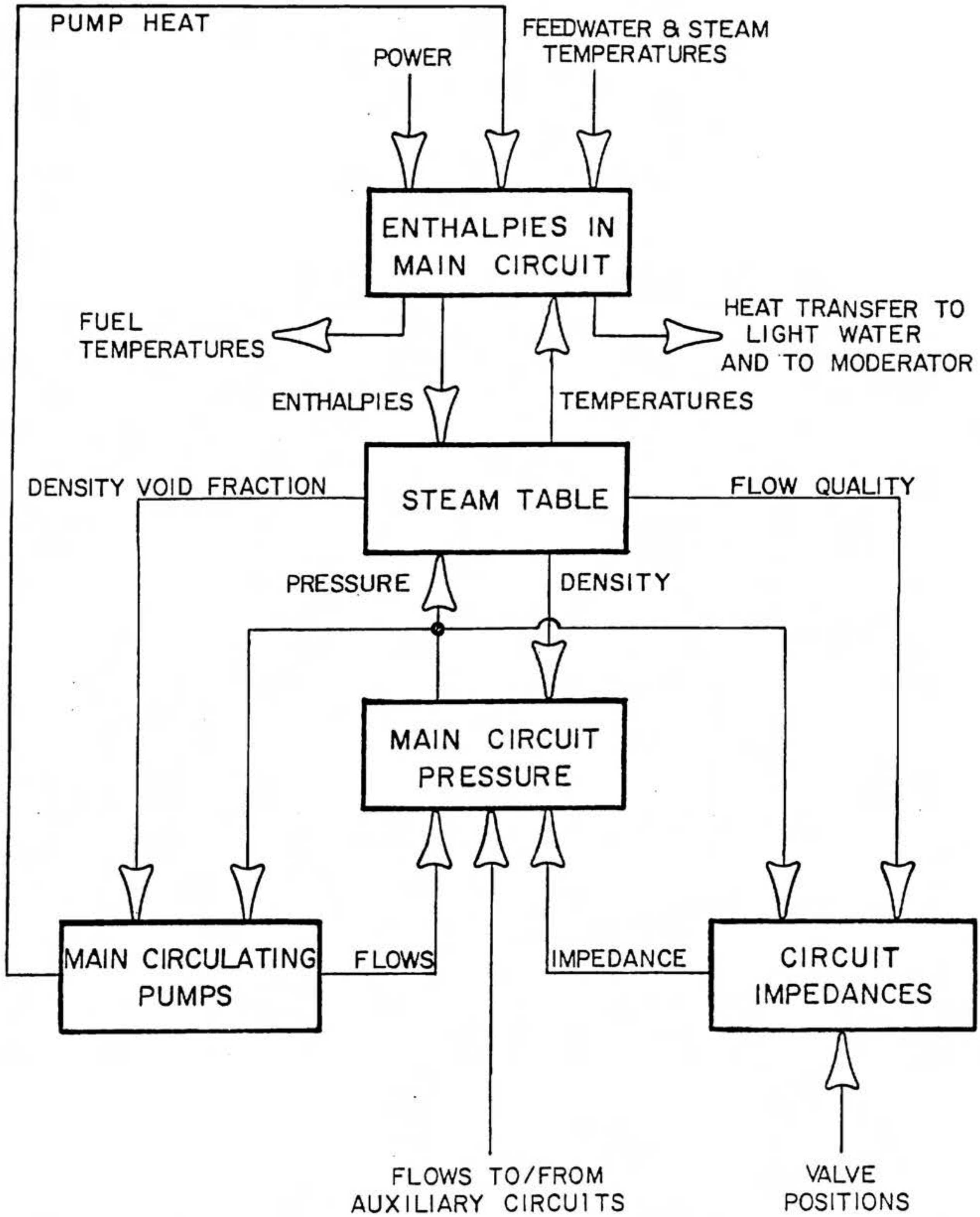


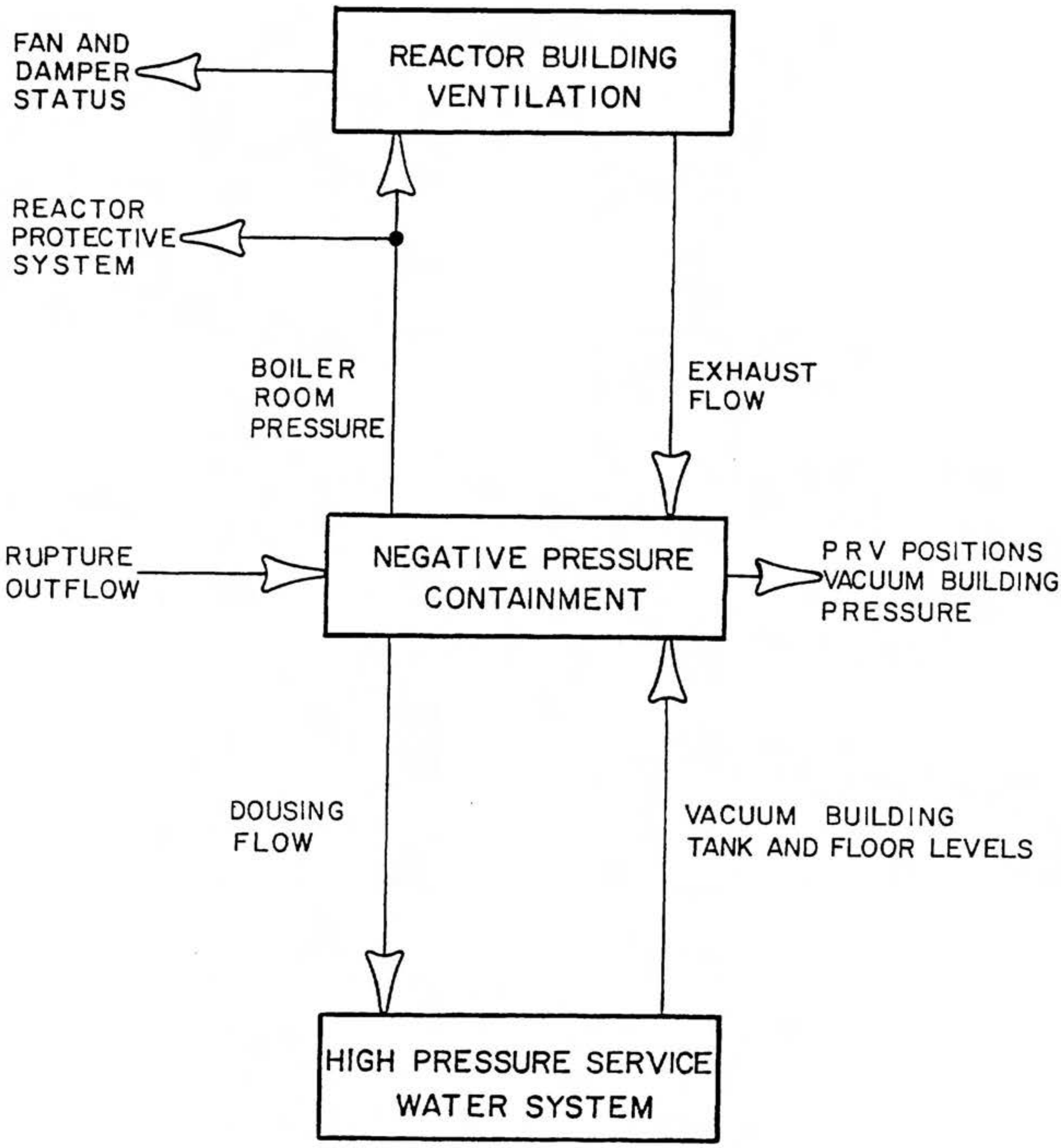
FIGURE 2:

REACTIVITY CONTRIBUTIONS



HEAT TRANSPORT SYSTEM BLOCK DIAGRAM

FIGURE 3.



CONTAINMENT SYSTEM BLOCK DIAGRAM

FIGURE 4.

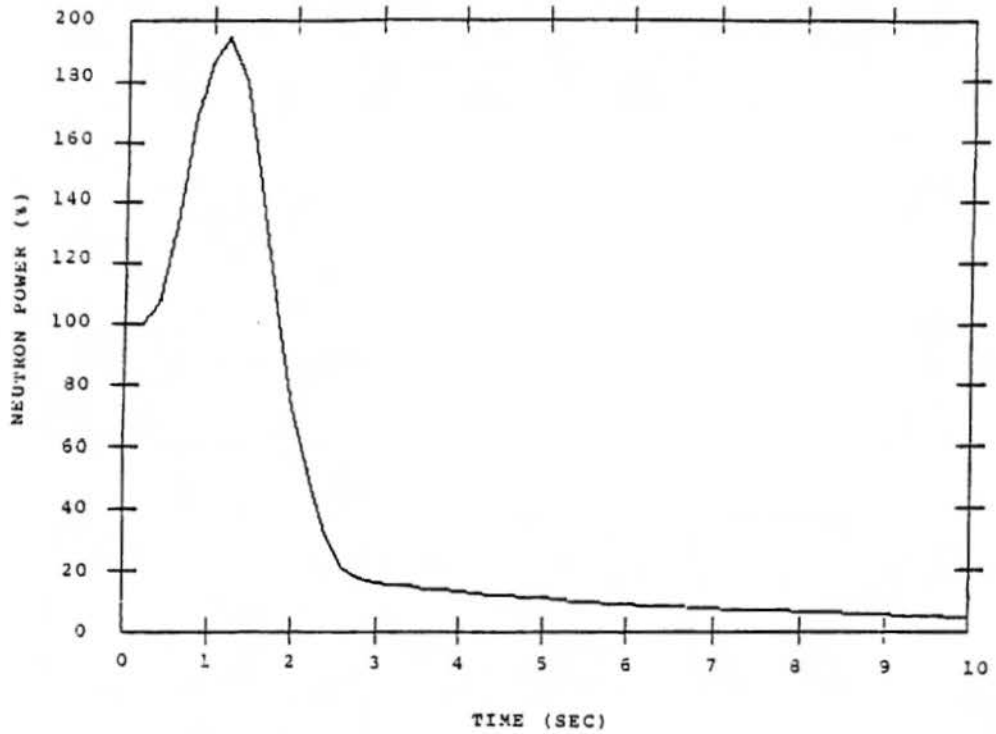


FIGURE 5: NEUTRON POWER FOLLOWING RIH BREAK

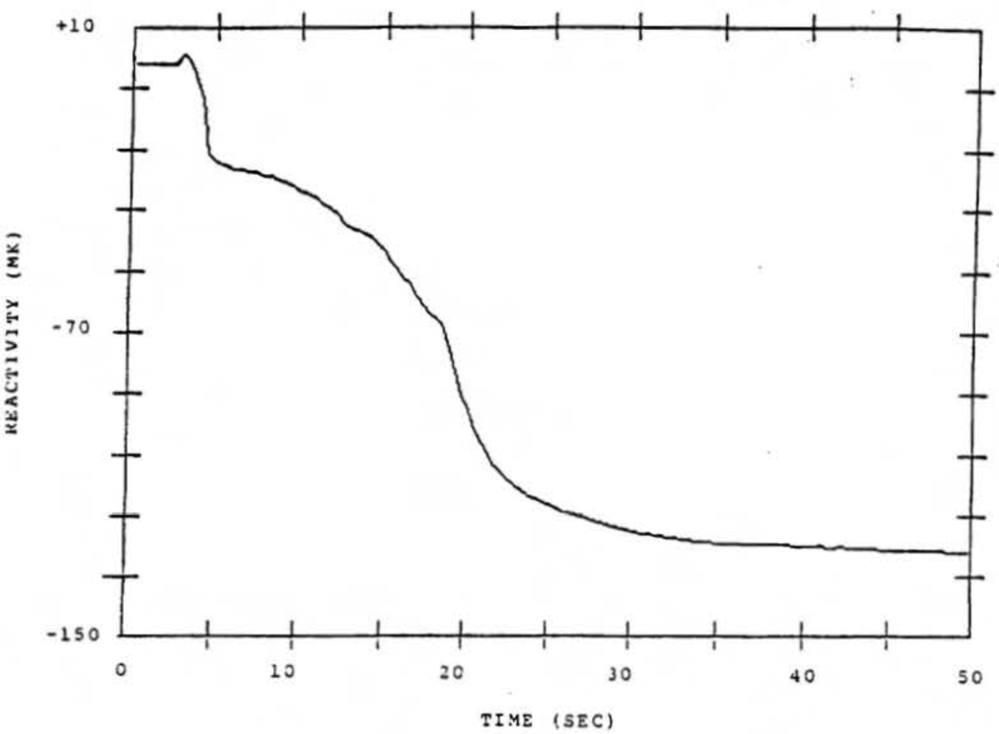


FIGURE 6: REACTIVITY EVOLUTION

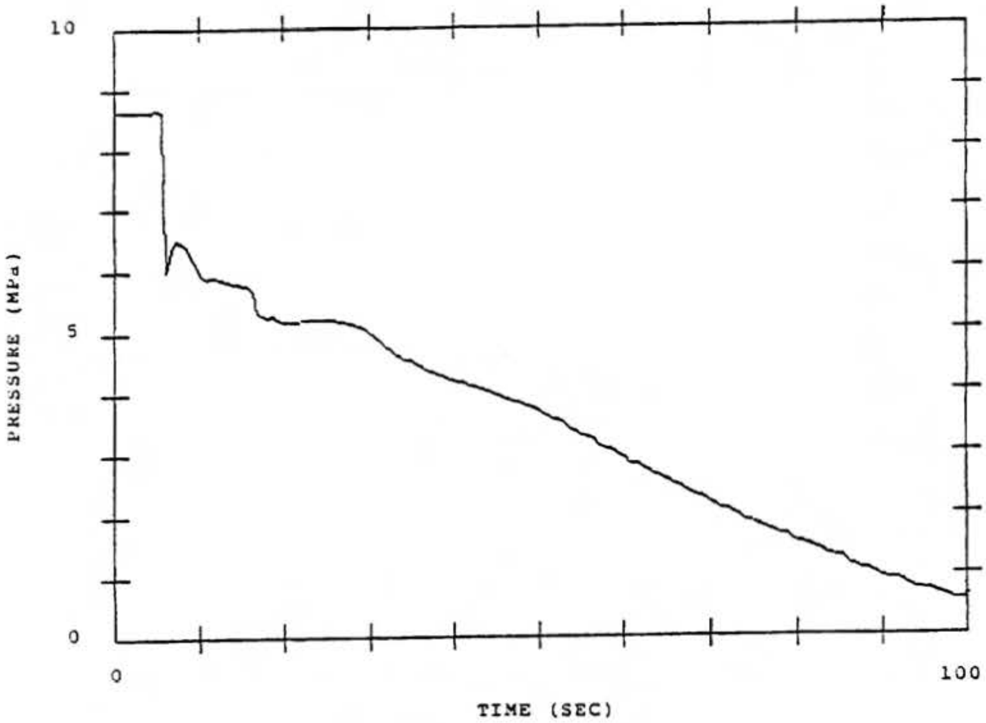


FIGURE 7: OUTLET HEADER PRESSURE

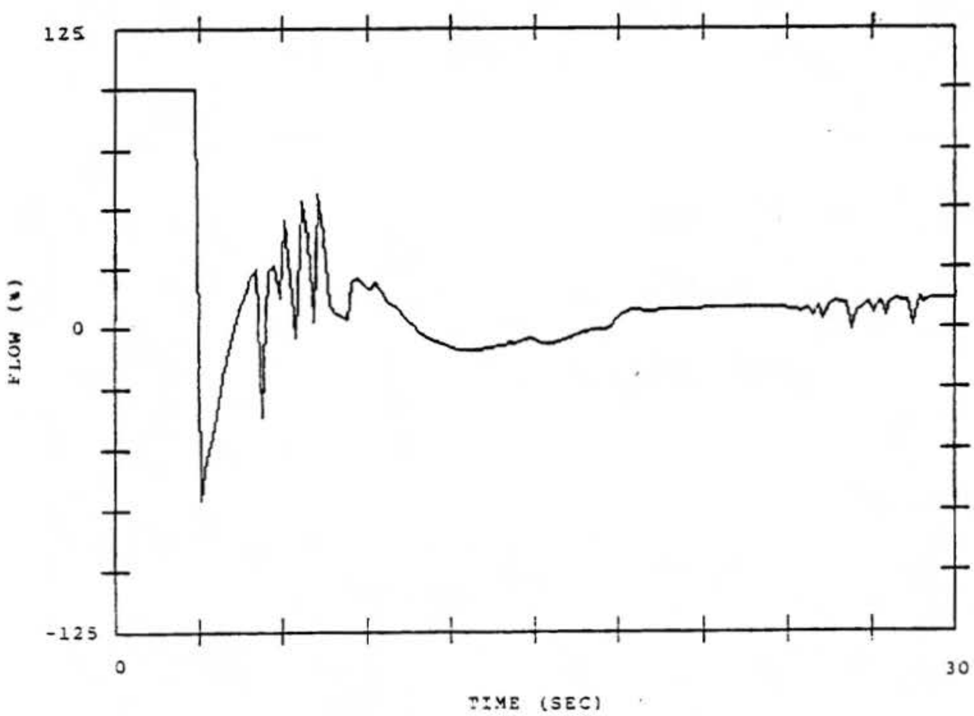


FIGURE 8: CHANNEL FLOW 'DOWNSTREAM' OF BREAK

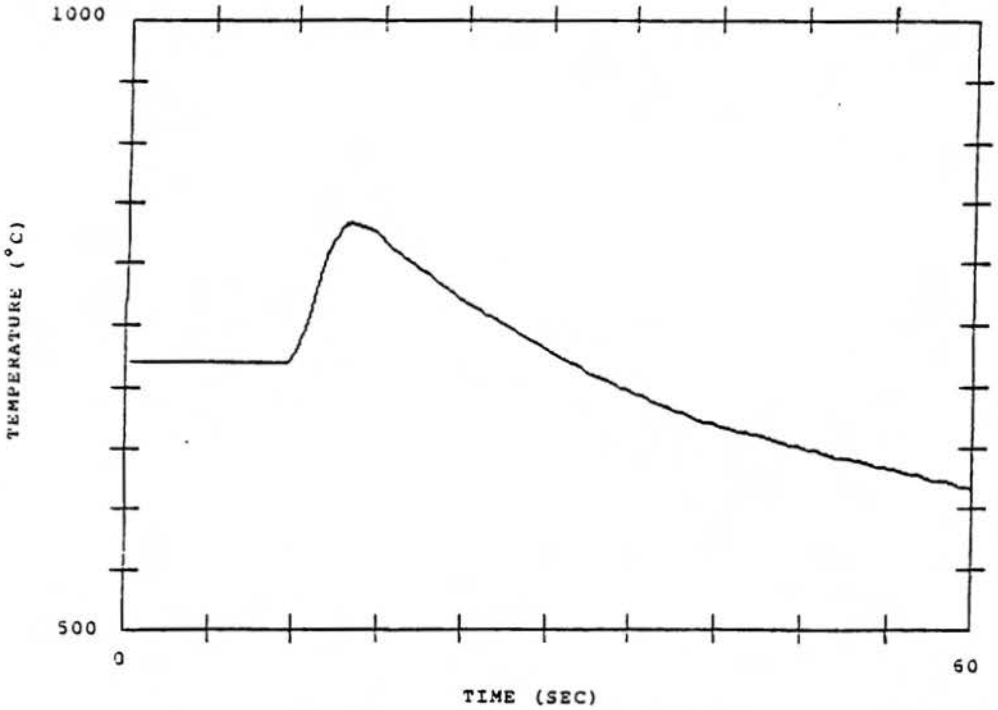


FIGURE 9: AVERAGE FUEL TEMPERATURE 'DOWNSTREAM' OF BREAK

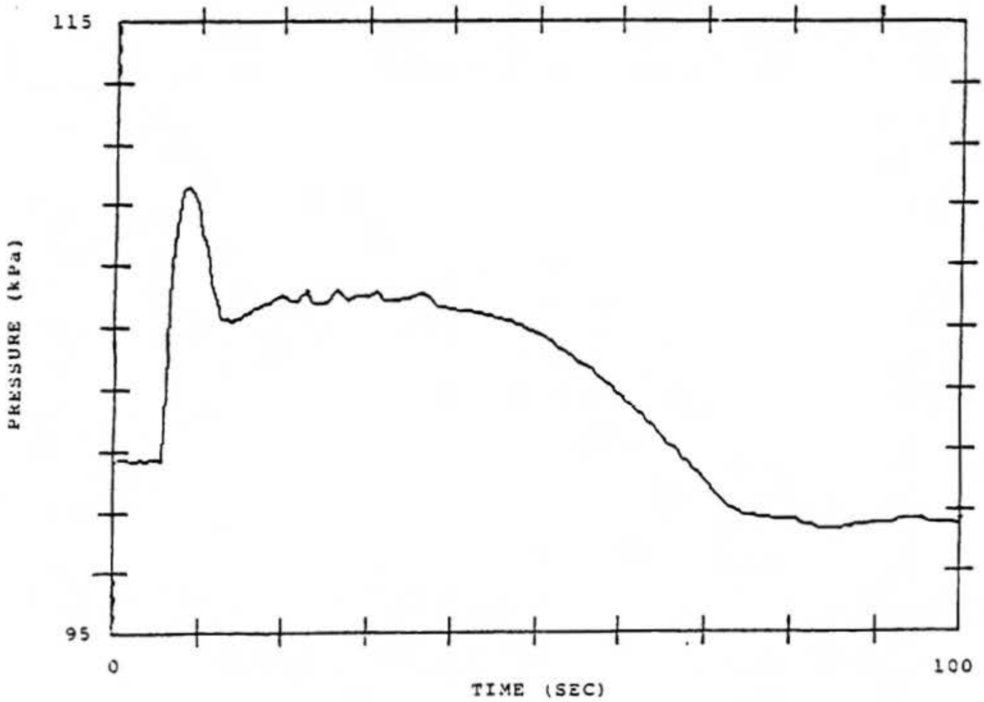


FIGURE 10: BOILER ROOM PRESSURE

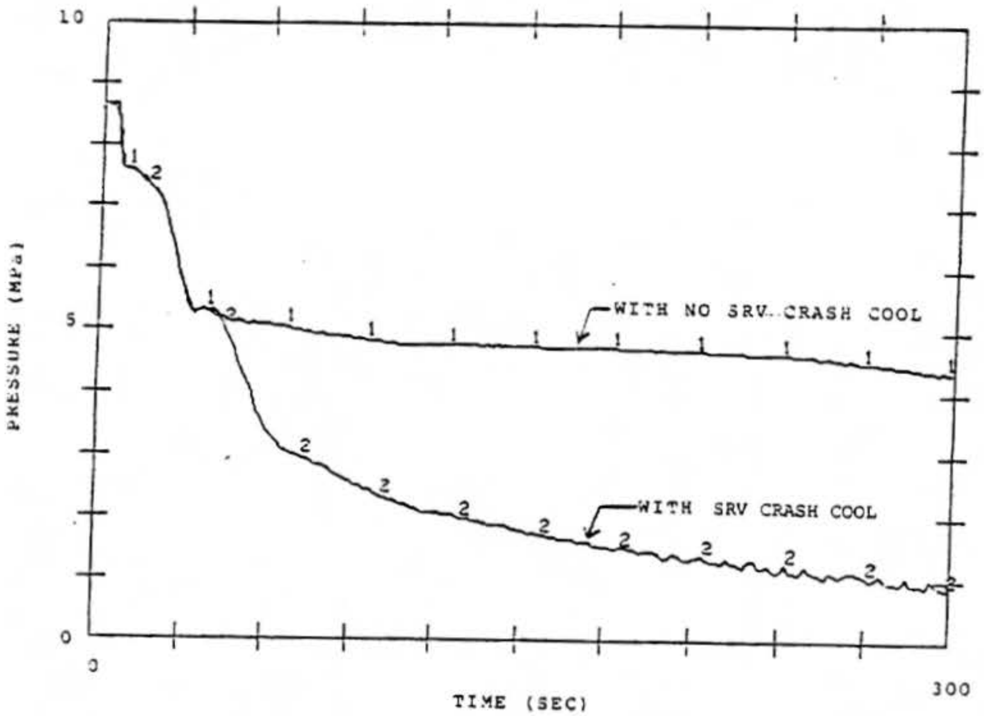


FIGURE 11: OUTLET HEADER PRESSURE (FEEDER BREAK)

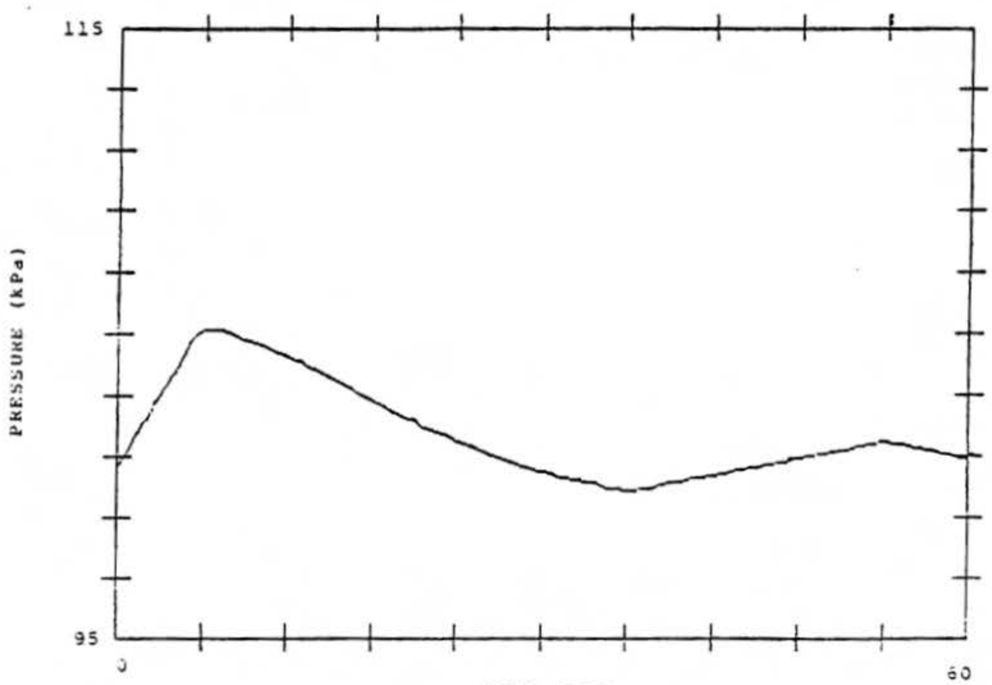


FIGURE 12: BOILER ROOM PRESSURE (FEEDER BREAK)

REFERENCES

1. Chow, Q.B., de Ruyter, M. and Bereznai, G.T., "Development of a Low-Cost Spatial Candu Reactor Simulation Program for Power Plant Control Studies", 1975 Summer Computer Simulation Conference, San Francisco.

2. Loken, P.C. and Doran, F.W., "Reactor Physics", Pickering GS Design Manual 44-01100.

3. Aeroject Nuclear Corporation Best Estimate Pump Model (Progress Report) AECL, Power Projects, P & A file #91-6000, May 1974.

4. L.S. Tong, Boiling Heat Transfer and Two Phase Flow, Kreiger Publishing Company, 1975