INTEGRATING CATHENA WITH CANDU PLANT CONTROLLERS

by

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ABSTRACT

This paper describes how CATHENA, a two-fluid thermalhydraulic computer code, may be coupled with other codes to allow integrated simulations. Specifically, the integration of the LEPCON code with CATHENA is presented. LEPCON simulates the major control functions of the Point Lepreau CANDU-600 reactor. An interface was designed to exchange information between CATHENA and the LEPCON controllers. CATHENA performs the thermalhydraulic calculations for the reactor system while control of the thermalhydraulic circuits is specified by the control routines. Pressures, temperatures and flows calculated by CATHENA are input to the control routines. The control routines use this information to calculate parameters such as the position of the control valves, reactivity insertion, and heat input to the pressurizer. This information is then returned to CATHENA. Examples of integrated CATHENA/LEPCON calculations are given and compared with reference solutions.

1.0 INTRODUCTION

The CATHENA [1] code uses input data to model control systems of considerable complexity. The form of this data, in fact, forms a simulation language where the user can create constant and/or derivative and/or integral control "blocks," time-dependent functions, and table lookups. As well, logical functions, including "trips," can be defined. The results of these calculations are used to control boundary conditions imposed on the simulation. Examples of these boundary conditions are controlling a valve opening time, specifying a time-dependent power history for reactor fuel, and initiating a pump trip. This system has been used to model boiler level/pressure control, inventory control, and emergency coolant injection (ECI) control (including trips) [2].

New Brunswick Power (NBP) has developed detailed control routines, written in standard FORTRAN, as part of the homogeneous SOPHT code [3] representing control functions for the primary and secondary coolant circuits of the Point Lepreau CANDU-600 reactor. Considerable effort and resources have been spent to generate and validate this model, named LEPCON. Rather than translate the extensive logic employed in LEPCON to CATHENA control models, a more economic approach was to couple these routines with CATHENA. The CATHENA/LEPCON combination offers an important advantage over SOPHT/LEPCON – a two-fluid predictive capability.

The methodology of coupling two distinct codes is described in this paper using the CATHENA/LEPCON combination as an example. The objective is to "link" the two codes, making minimum changes to each code.

The CATHENA code is described first, followed by the LEPCON code. The methodology of coupling the two codes is then presented. Finally, results are presented to demonstrate the viability of the method.

2.0 CATHENA

CATHENA, developed by AECL Research, has evolved with the objective of providing a high degree of flexibility in modelling thermalhydraulic systems. Although developed primarily for the analysis of CANDU nuclear reactors, the code has been successfully applied in the analysis and design of experimental test programs. CATHENA is also being used to support the design, safety and licensing of research reactors developed by AECL (e.g., MAPLE-X10 [4]).

The CATHENA code uses a non-equilibrium, two-fluid thermalhydraulic model to describe fluid flow. Conservation equations for mass, momentum and energy are solved for each phase (liquid and vapour), resulting in a 6-equation model. Also, up to four noncondensible gases may be represented as part of the vapour phase, yielding a 7- to 10-equation model. Interphase mass, momentum and energy transfer are flow-regime-dependent, and are calculated using constitutive relationships obtained from the literature or are derived from separate-effects experiments.

The numerical-solution technique used to solve the conservation equations is a staggered-mesh, semi-implicit, finite-difference method. The dependent variables defining the state of a node or cell are pressure, void fraction, and phase enthalpies. If noncondensible gas(es) are present, the noncondensible fractions are also dependent variables. For connections between nodes (called links), the dependent variables are the velocities of the gas and liquid phases. Conservation of mass is achieved using a truncation error correction technique similar to that used in RELAP5/MOD2 [5].

A one-step finite-difference numerical solution scheme has been adopted that is not transit-time-limited. A time-step controller implemented in CATHENA automatically selects the next time step at each finite-difference time step. This is accomplished by monitoring changes in the dependent variables, selected derived variables, and the truncation error. If the maximum change is below a prescribed value, the time step is increased; if the change is above the maximum prescribed value, it is decreased. The user may alter the default selection criteria through input data and thus check the temporal convergence of a given simulation.

Heat transfer from metal surfaces is handled by an extensive wall-heat-transfer package. A set of flow-regime-dependent constitutive relations specifies the energy transfer between the fluid and the pipe wall and/or the fuel element surfaces. A variational finite-element method is used to model the heat transfer by conduction within the piping and fuel in the radial direction, and the heat transfer can also be modelled in the circumferential direction. The radiative heat transfer and the zirconium/steam reaction rates can also be calculated. The ability to calculate the heat transfer from individual groups of pins in a fuel bundle subjected to stratified flow is built into this package. Under these conditions, the top pins in a bundle are exposed to steam, while the bottom pins are exposed to liquid.

Component models that describe the behaviour of pumps, valves, pressurizers, steam separators, and discharge through breaks are available to complete the idealizations of the reactor systems. As discussed previously, control systems may be modelled through user-specified input data or by coupling with other plant-control codes.

3.0 LEPCON

The LEPCON (LEPreau CONtroller) code was developed by New Brunswick Power Corporation, and consists of 75 subroutines (~25 000 lines of FORTRAN code). This code represents logic from the Point Lepreau Generating Station in the FORTRAN subroutines. The systems modelled include:

(1) the important elements of the overall plant controller - boiler pressure (digital) control, unit power (digital) regulator, electro-hydraulic governor (analog) control and main steam safety valves (MSSV) (analog) control,

(2) the reactor regulating system (including both shutdown systems),

(3) the normal mode of the primary heat transport system (PHT) (digital) pressure and inventory control,

(4) the solid mode of the PHT system and pressurizer (analog) pressure control,

(5) the degasser-condenser analog pressure and inventory control,

(6) the PHT system over-pressure protection (liquid relief valves (LRV) analog control), and

(7) the steam generator(boiler) (digital) level control.

LEPCON is updated routinely, as required, to ensure the routines represent the current state of the Point Lepreau Generating System control systems.

4.0 CATHENA/LEPCON INTEGRATION

To couple CATHENA and LEPCON, an interface was designed for the exchange of information between CATHENA and LEPCON, and a new model was designed for the CATHENA code. This model allows the interface to be specified <u>through user input data</u>, and provides the necessary linkage between the two codes. CATHENA performs the thermalhydraulic calculations for the reactor system while control of the thermalhydraulic circuits is specified by the LEPCON control routines. Pressures, temperatures and flows calculated by CATHENA are input to LEPCON. The control routines use this information to calculate parameters such as the position of control valves, reactivity insertion, and heat input to the pressurizer. Information is exchanged every CATHENA time step.

This process is shown schematically in Figure 1.

```
                               INTERFACE
             CATHENA              ||          LEPCON
                                  ||
        thermalhydraulic          ||
          information:    }  ++++||+++
        (pressures, flows,        ||
         etc.)                    ||          control of
                                  ||          thermalhydraulic
                             ++++||++++  {   circuit:
                                  ||          (valve openings,
                                  ||           reactivity insertion,
                                  ||           etc.)
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Figure 1: CATHENA/LEPCON Interface

These steps were performed to implement this methodology:

(1) The interface was defined first. The thermalhydraulic information required for the LEPCON calculations was identified. The LEPCON results that control the CATHENA simulation were also identified. It was then verified that the LEPCON and CATHENA calculations were kept separate - i.e., common blocks must be separate between the two codes.

(2) The LEPCON routines were modified to pass information through the interface.

(3) A CATHENA "plant controller" model was designed to create the second half of the interface.

The PLANT CONTROLLER model implemented in CATHENA is general and can be used to model different plants. The user first specifies the controller name (e.g., LEPREAU or G-2), the number of inputs and outputs required for the specific controller, and the restart files. Next, the interface input parameters (CATHENA to LEPCON) are defined through the input data using variables accessible to CATHENA. For example, 'PRESS:OHD1(1)' would be specified to reference the pressure in Outlet Header 1. The second part of the interface (LEPCON to CATHENA) is then defined where CATHENA models to be controlled are listed. For example, 'OPENFR' of 'VALVE1' would be specified to control the opening fraction of a valve labelled VALVE1. This approach allows maximum flexibility in allowing multiple interfaces (for different controllers) as well as for modifying individual interfaces when required.

The user may also override any control action taken by LEPCON by defining CATHENA control models such that a defined set of control variables calculated by LEPCON will be changed to values calculated by the CATHENA control models.

5.0 RESULTS

To test the integration of LEPCON with CATHENA, a CATHENA idealization of the Point Lepreau Generating Station was first generated (a SOPHT idealization already existed). Both idealizations model the two figure-of-eight loops of the primary-side heat transport system, key elements of the secondary-side heat transport system, and other necessary systems. A power reduction from 100% to 60% full power in the normal mode at a rate of 10 MW(e)/min was simulated because it exercises:

(1) the interaction (information exchange) between the boiler pressure control, the unit power regulator, the electro-hydraulic governor and the demand power routine of the reactor regulating system,

(2) the interaction between the reactor regulating system and the reactivity control mechanisms (for the current case that would be mainly between the demand power routine and the liquid zone),

(3) the interaction between the pressure and inventory (digital) control and the respective controlled device:

- for pressure control, the controlled devices are the steam bleed valves, variable heater and the ON/OFF heaters,
- for inventory control, the controlled devices are the D_2O feed and bleed valves, and

(4) the interaction between the boiler level control and the main and small feedwater valves.

Figures 2, 4, 6, and 8 show selected results of the SOPHT simulation. Figures 3, 5, 7, and 9 give the corresponding CATHENA results. The duration of the transient was 3000 s. The SOPHT/LEPCON results are described first, then the CATHENA/LEPCON results are compared to these results. Each page contains two figures - the SOPHT/LEPCON calculation on the top, and the corresponding CATHENA/LEPCON calculation on the bottom.

It should be noted that the thermalhydraulic initial conditions in SOPHT and CATHENA are slightly different. This causes minor differences in the transients when simulations are compared.

Figure 2 shows the transient boiler pressure in 3311-B01. At the beginning of the transient, there is a slight decrease in pressure, mainly because of slight inconsistencies between the LEPCON controller initial conditions and the SOPHT initial conditions.

At 10 s, a new target load (with its rate of change) are input in the Digital control computers (DCCs) by an operator (simulated by LEPCON), and the boiler pressure experiences a sharp increase followed by decaying oscillations. The sharp increase in pressure is caused by the unit power regulator reducing the load setpoint that "pulses down" the speeder gear on the turbine governor valves. This in turn initiates the electro-hydraulic governor to close the governor valves, resulting in the increased boiler pressure. This increased pressure causes a lower reactor power setpoint to the demand power routine of the reactor regulating system.

The pressure oscillations are the result of the interaction between the unit power regulator and the demand power routine via boiler pressure control. As the unit power regulator reduces the power at the specified rate, boiler pressure control attempts to maintain the boiler pressure at or near the pressure setpoint. To accomplish this, the boiler pressure routine sends a new reactor power setpoint to the demand power routine.

Figure 4 shows the reactor power during the transient. The slight irregularities in the power reduction are caused by the interactions described previously. Around 1700 s there is a normalized power undershoot resulting from the response of the reactivity mechanisms attempting to match the reactor power setpoint given by the boiler pressure control. This is followed by a gradual increase as the boiler pressure control sends a higher reactor power setpoint to the demanded power routine, allowing the boiler pressure to recover.

Figure 6 shows the variation of the pressure in Reactor Outlet Header (ROH) HD-1. Initially the variation of the pressure follows the variation of the normalized power. The small fluctuations observed on the normalized power are reflected in the variation of the ROH pressure; in particular, the notable normalized power fluctuation shortly before 500 s is reflected in the ROH pressure. As the ROH pressures fall below the setpoint of 9.99 MPa(a), pressure and inventory control switches on the variable and ON/OFF heaters and the pressure eventually returns to the pressure setpoint.

Figure 8 shows the variation of the pressurizer level. It can be seen that initially the variation of the level follows the variation of the ROH pressures, resulting in an outsurge of the pressurizer inventory because of loop "shrinkage." Again an oscillation occurs shortly before 500 s following the notable fluctuation in normalized power at the same time. The rate of change in pressurizer level is different after the oscillation occurrs. This results from the effect of the pressurizer heaters.

The results from CATHENA show essential the same behaviour as SOPHT. Figure 3 shows the variation of boiler pressure in 3311-B01, where similar events occur at about the same time:

- The notable decrease in boiler pressure shortly before 500 s is present in the results from CATHENA.

- The sharp pressure decrease at about 1700 s is also present in the results from CATHENA; however, the oscillation observed at 2250 s in the SOPHT results is not present in the CATHENA simulation. This discrepancy is thought to result from the different thermalhydraulic modelling of the boilers in SOPHT and CATHENA.

In Figure 5, the normalized power predicted by CATHENA has a similar behaviour to the results from SOPHT: small fluctuations in the normalized power are superimposed on the general decreasing trend.

Figure 7 illustrates the same trend for the ROH HD-1 pressure as in the SOPHT prediction. The CATHENA simulation shows that the pressure follows the normalized power decrease until the effect of the variable and ON/OFF pressurizer heaters is felt in the reactor outlet headers shortly before 500 s.

The pressurizer level changes predicted by CATHENA show the same features as in the simulation by SOPHT (see Figure 9).

6.0 SUMMARY AND CONCLUSIONS

This approach offers an important advantage over generating a "tightly coupled" combination of CATHENA and LEPCON. Development can proceed independently with each code without affecting the other code. If both codes were "tightly coupled," then a new LEPCON version would have to be generated for each new CATHENA version. That could lead to problems!

This paper describes the interface generated for the CATHENA/LEPCON combination, and demonstrates that the integration produces similar results to the original SOPHT/LEPCON code. The concept of the interface and the implementation of a "general interface" in CATHENA allows this approach to be extended to a number of other applications. Also, since both codes can execute separately, they could be run on different computers in a parallel processing mode. This approach is described by McDonald [6].

7.0 ACKNOWLEDGEMENT

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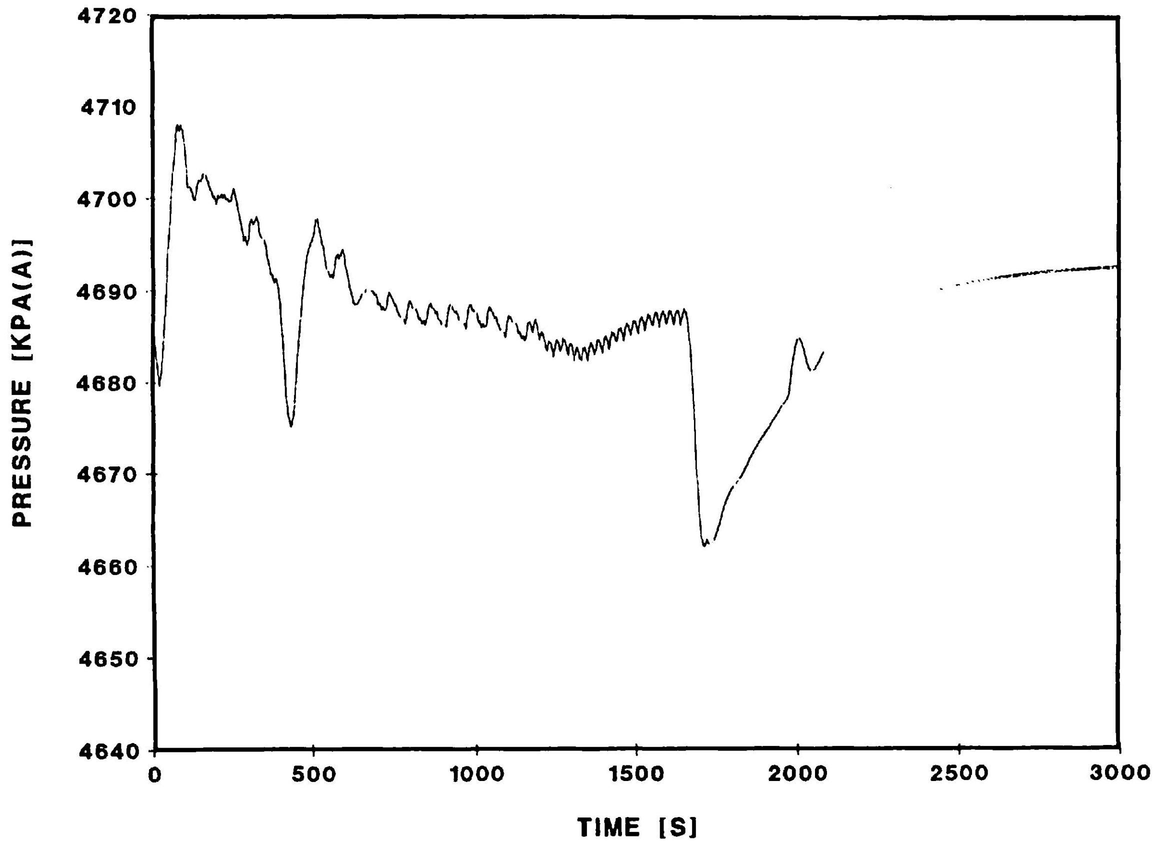

FIGURE 2: SOPHT/LEPCON Simulated Boiler 1 Pressure

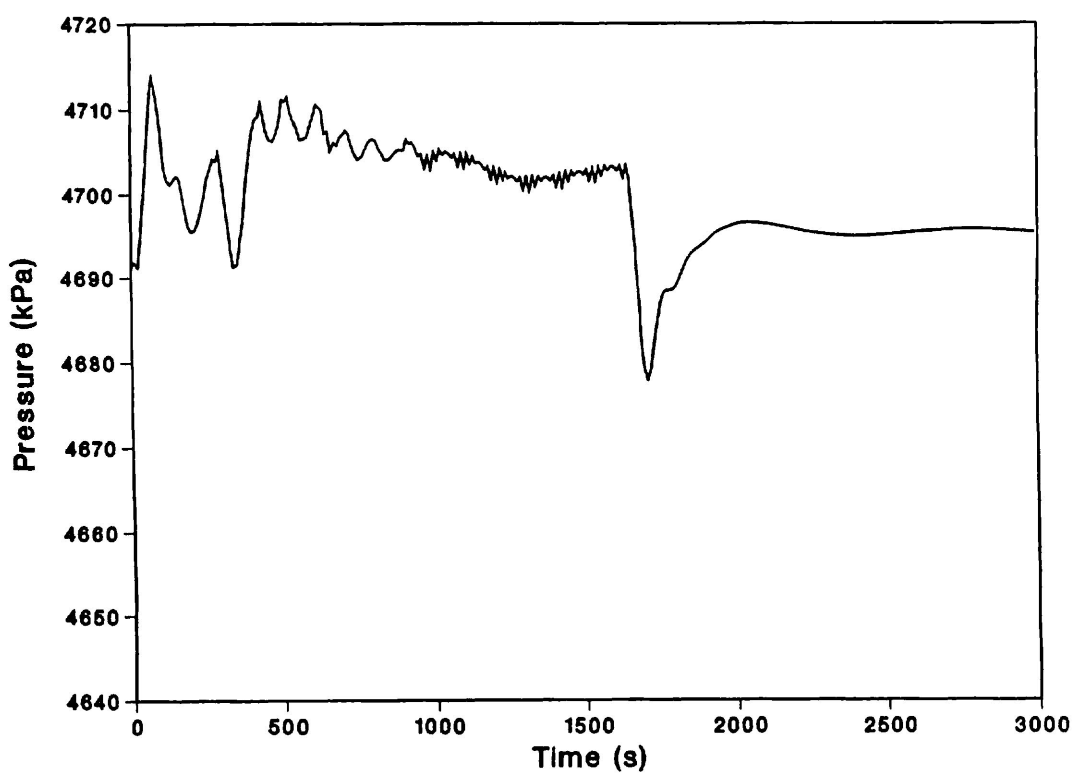

FIGURE 3: CATHENA/LEPCON Simulated Boiler 1 Pressure

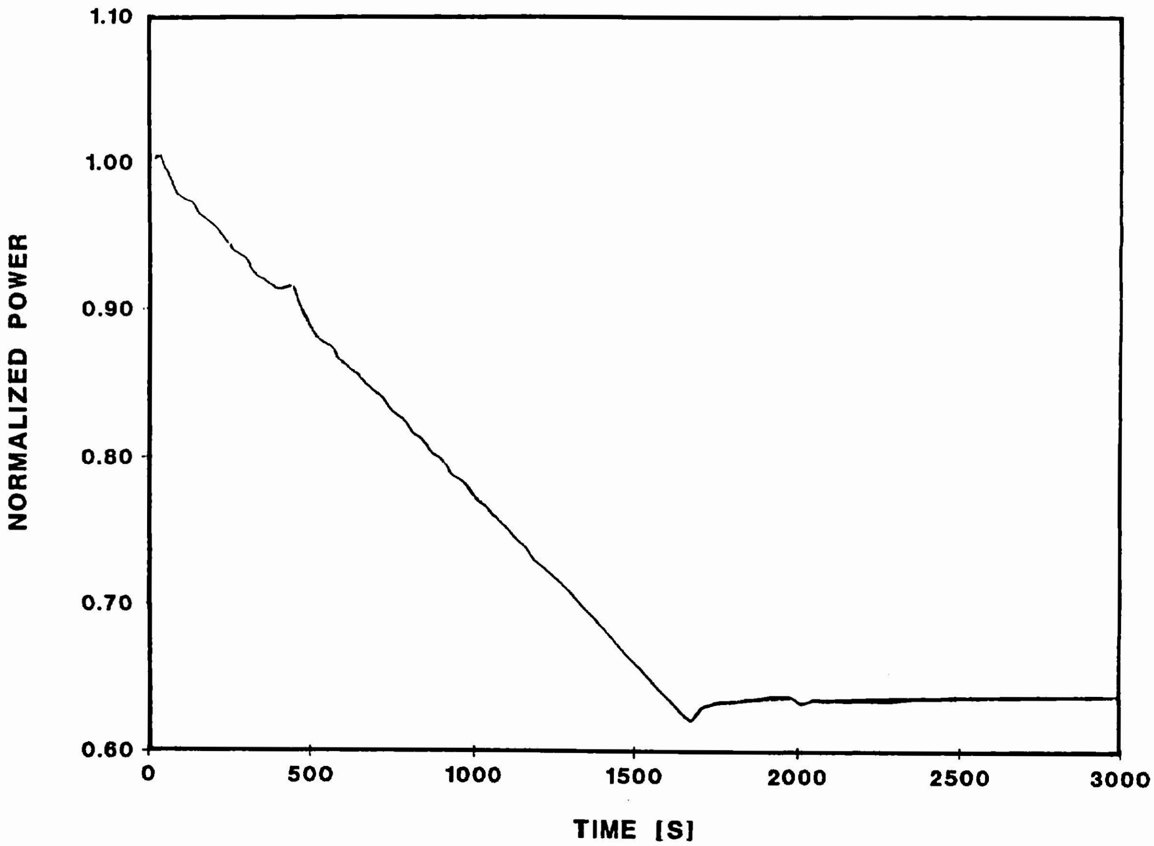

FIGURE 4: SOPHT/LEPCON Simulated Normalized Reactor Power

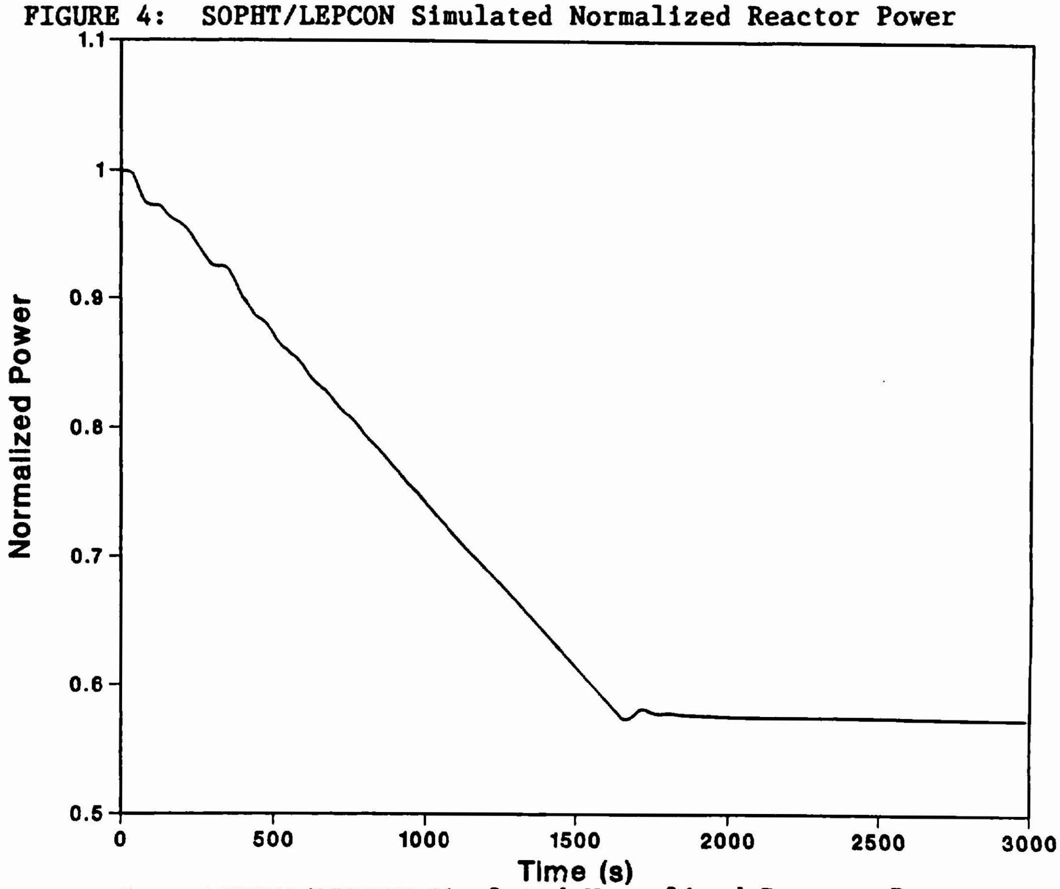

FIGURE 5: CATHENA/LEPCON Simulated Normalized Reactor Power

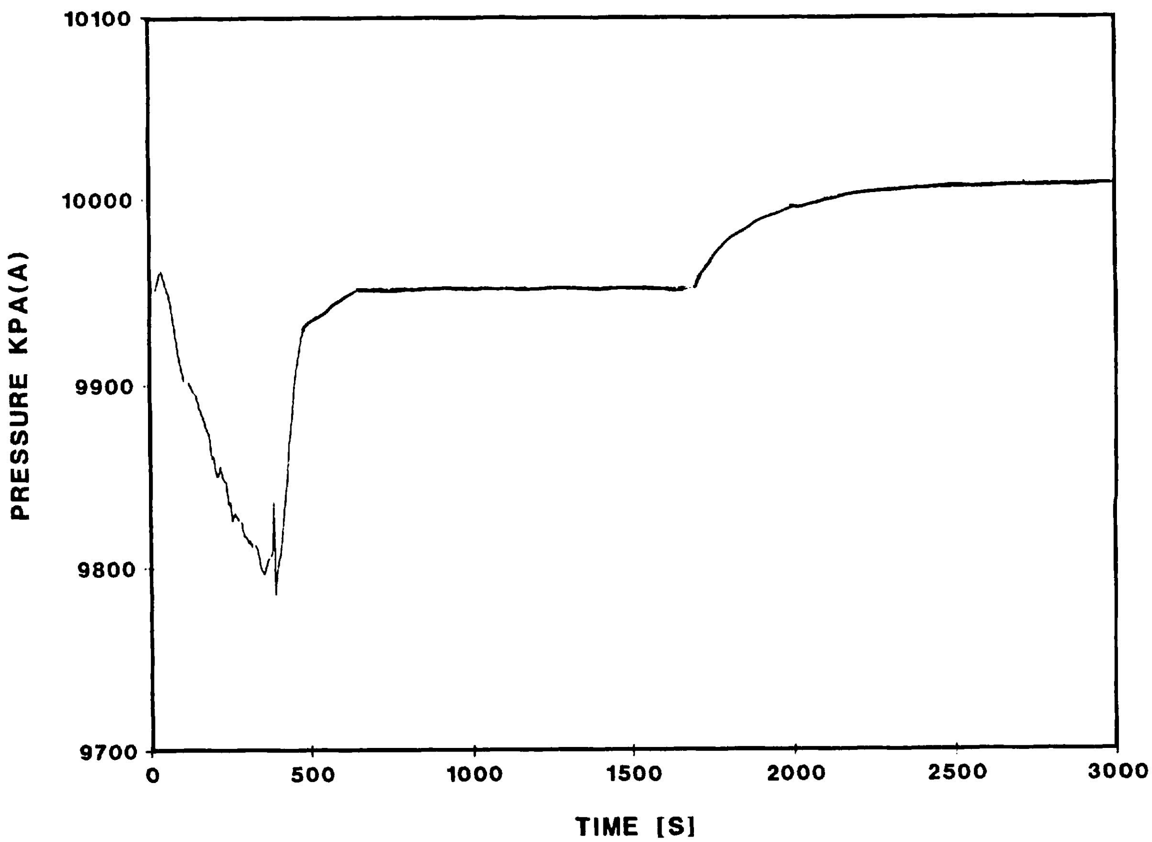

FIGURE 6: SOPHT/LEPCON Simulated Outlet Header 1 Pressure

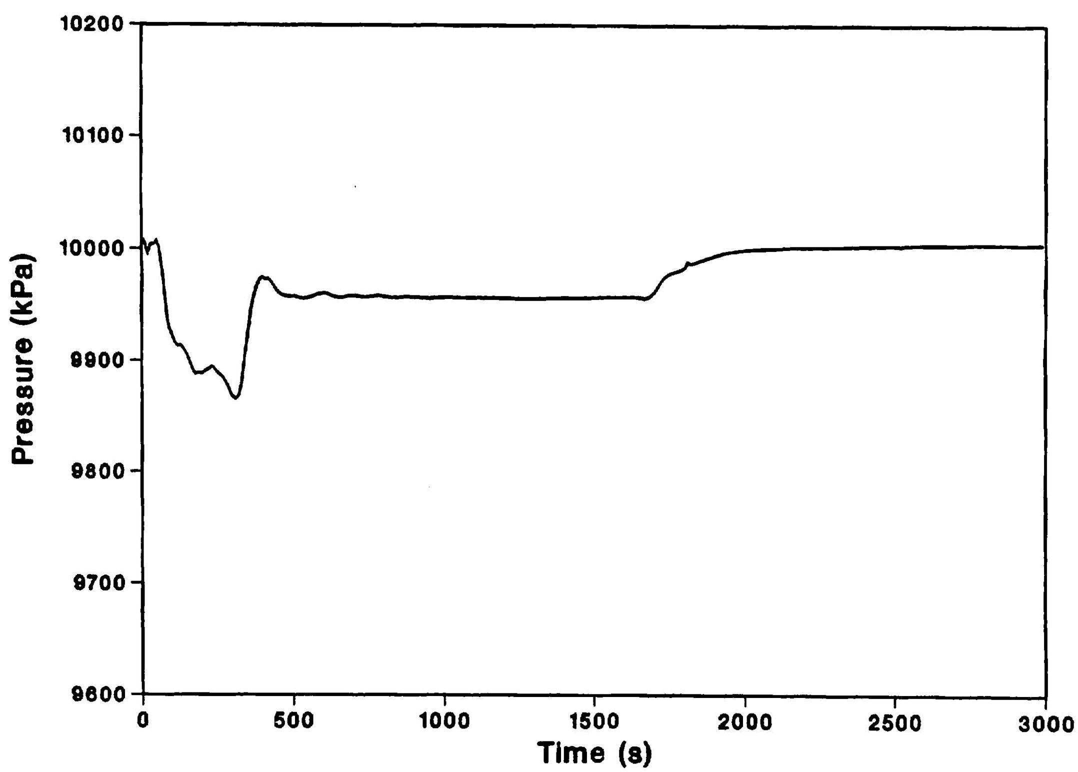

FIGURE 7: CATHENA/LEPCON Simulated Outlet Header 1 Pressure

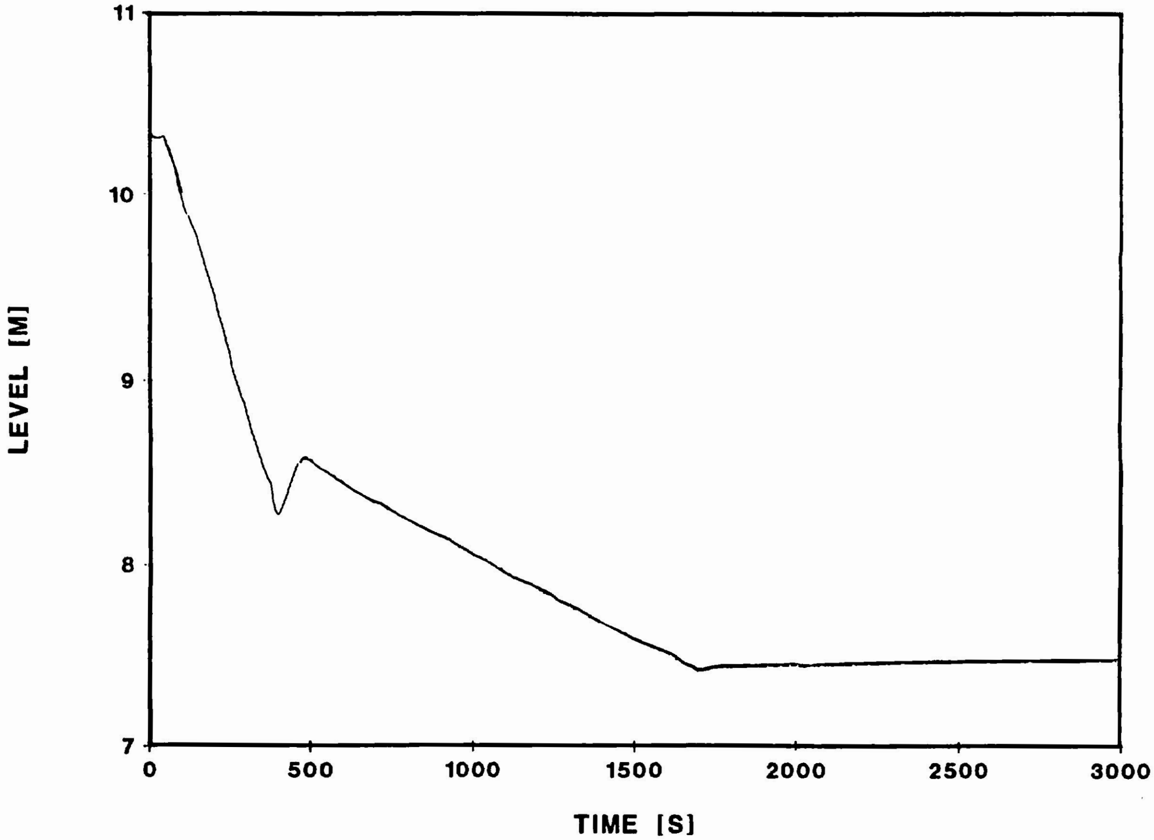

FIGURE 8: SOPHT/LEPCON Simulated Pressurizer Level

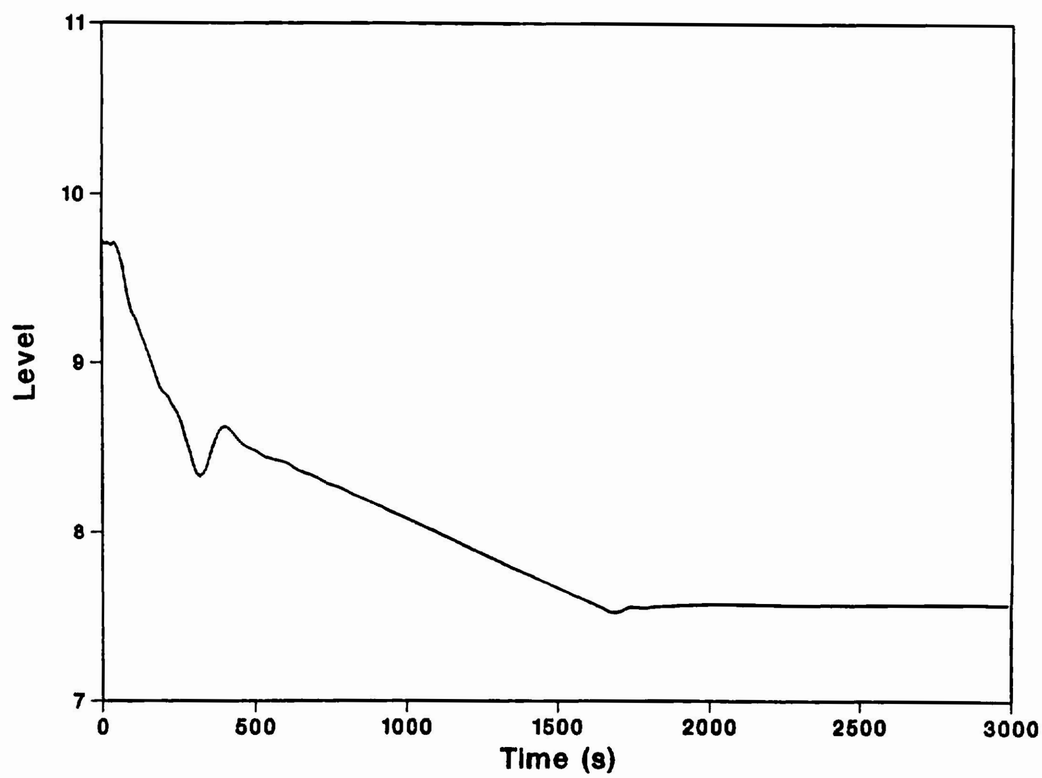

FIGURE 9: CATHENA/LEPCON Simulated Pressurizer Level