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SIMULATION OF BOILING WATER REACTOR POWER PLANT OPERATIONAL TRANSIENTS USING THE TRAC-BWR CODE

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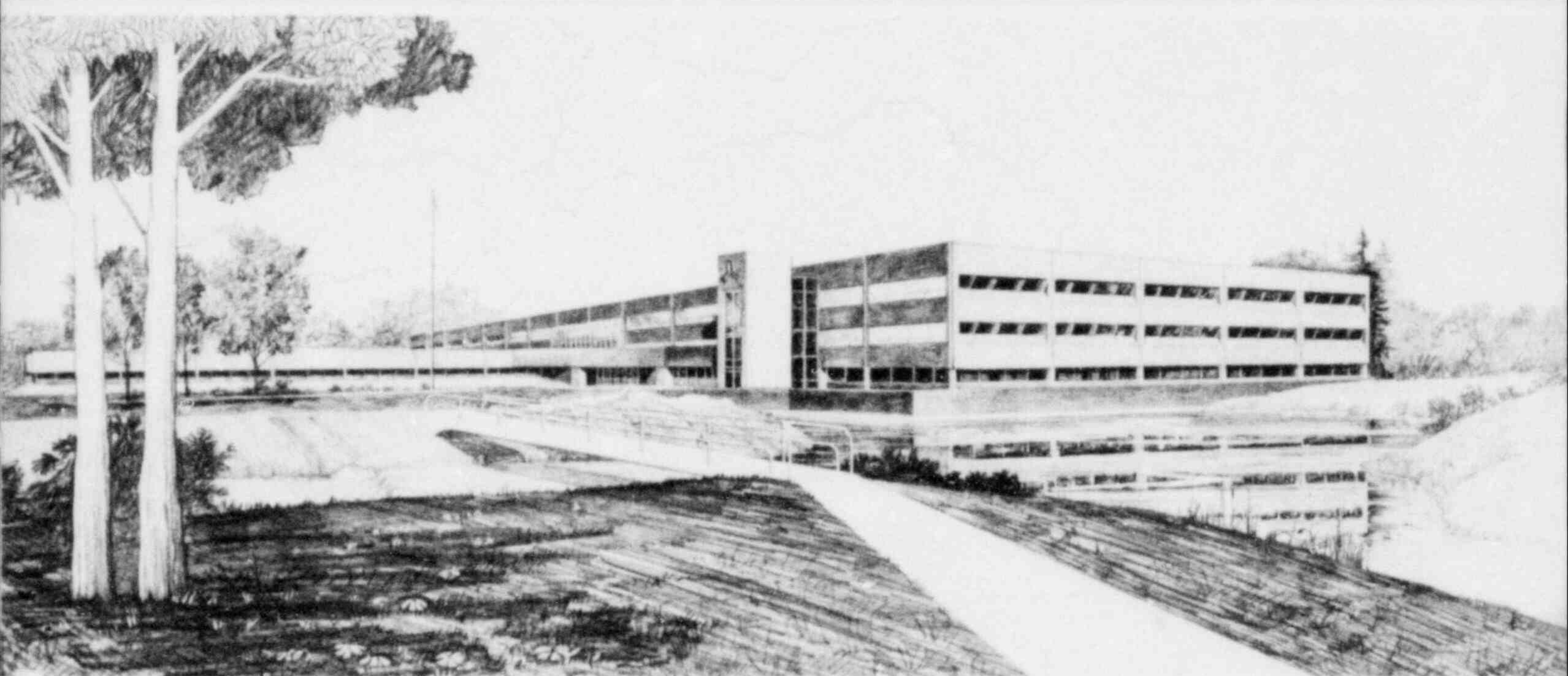

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EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

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SIMULATION OF BOILING WATER REACTOR POWER PLANT OPERATIONAL TRANSIENTS USING THE TRAC-BWR CODE

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ABSTRACT

Control systems features have been recently added to the TRAC-BWR (Transient Reactor Analysis Code-Boiling Water Reactor) state-of-the-art thermal/hydraulic code. This addition significantly expands the code's capability to analyze a wide variety of operational and anticipated transients without scram events. A new computational component, the Control Block, allows great flexibility when modeling BWR power plant controllers. Basic control system models enable the user to rapidly and cost effectively arrive at equilibrium plant conditions. The Browns Ferry reactor power plant is simulated using thermal/hydraulic and control system modular components. Predicted results agree well with Browns Ferry test data for generator load rejection and change of downcomer water level setpoint operational transients.

ACKNOWLEDGMENTS

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CONTENTS

FIGURES

1. INTRODUCTION

The boiling water reactor (BWR) version of the Transient Reactor Analysis Code (TRAC) is being developed at the Idaho National Engineering Laboratory to provide an advanced best estimate predictive capability for the analysis of postulated transients in BWRs. The first released version of the TRAC-BWR Code, TRAC-BD1, was developed to provide analysis capability for the simulation of design basis loss-of-coolant accidents (DBLOCA) in BWRs (1). The versatility of the initial version of the TRAC-BWR Code has been enhanced so that currently it may also be used for the analysis of a wide spectrum of loss-of-coolent accidents, selected operational transients, anticipated transients without scram (ATWS), as well as for the simulation of thermal/hydraulic experimental faciltiies.

Unique features of the code include: (a) a full nonhomogeneous, non-equilibrium two-fluid thermal/hydraulic model of the two-phase flow in all portions of the BWR system, including a three-dimensional thermal/hydraulic treatment of the BWR vessel; (b) a detailed model of BWR fuel bundles; (c) simplified models of BWR hardware components such as the jet pumps and the steam separator-dryers; and (d) a countercurrent flow limiting model. Other features of the code include a nonhomogeneous, thermal equilibrium critical flow model, and flow regime-dependent constitutive relations describing mass, energy, and momentum interchanges between the two phases, as well as between each phase and adjacent structures.

New control system capabilities were recently added to the TRAC-BWR Code (2). They greatly facilitate the establishment of reactor plant equilibrium conditions and enable prediction of control systems behavior during transient analysis. During the computer prediction of safety-related transients, control systems modeling plays an important role.

In this paper the new Control Block feature is described, a TRAC model of the Browns Ferry BWR/4 power plant is developed, and comparisons between test data and code predictions are given for generator load rejection and change of level setpoint transients.

2. CONTROLLER CAPABILITIES

The basic computational component recently added to TRAC-BWR is the "Control Block" which is illustrated in Figure 1. This module may have up to three inputs and a single output. The user specifies the Control Block Number (from 1 to 999) and the Type of mathematical operation desired. Currently programmed are 63 Types of Control Blocks. Examples are ADD (addition), INT (integration), DLAY (time delay), and FNG1 (function generator of 1 independent variable). Also included are discrete output Control Blocks whose Output values may only be either one or zero. Examples of these logical Control Blocks are IOR (inclusive or), AND (and), and FLFP (flip-flop). The Control Block gains C1 and C2 are applied to Input 1 and Input 2, respectively as required by certain block Types such as the WSUM (weighted summer). The overall gain factor G is similarly applied to the Output. For Control Blocks whose Outputs are continuously varying (as opposed to discrete), the Output values are constrained to lie between XMAX (maximum limit) and XMIN (minimum limit). An initial value for the Control Block Output at time equal to zero is user specified as XIV (for continuously varying) or LIV (for discretely varying). A ten-character Name completes the input description for a Control Block.

In the TRAC-BWR Code the thermal/hydraulic (T/H) computations are completed for each time step prior to calling the control system subroutines. As depicted in Figure 2, the control system (C/S) takes previously stored T/H information from the Data Base, performs the desired mathematical operations, and then returns updated C/S Outputs back to the T/H Data Base.

As an example of how these new control system features may be used, consider the simplified pressure controller given in Figure 3. The turbine inlet pressure is read from the T/H Data Base and the current value compared to a constant pressure setpoint (P_{set}). The error signal (P_{err}) is fed to a PI (proportional plus integral) controller represented by the INT and WSUM Control Blocks. The resulting demanded valve area change (ΔA_{demand}) is fed to a first order lag (LAG) Control Block

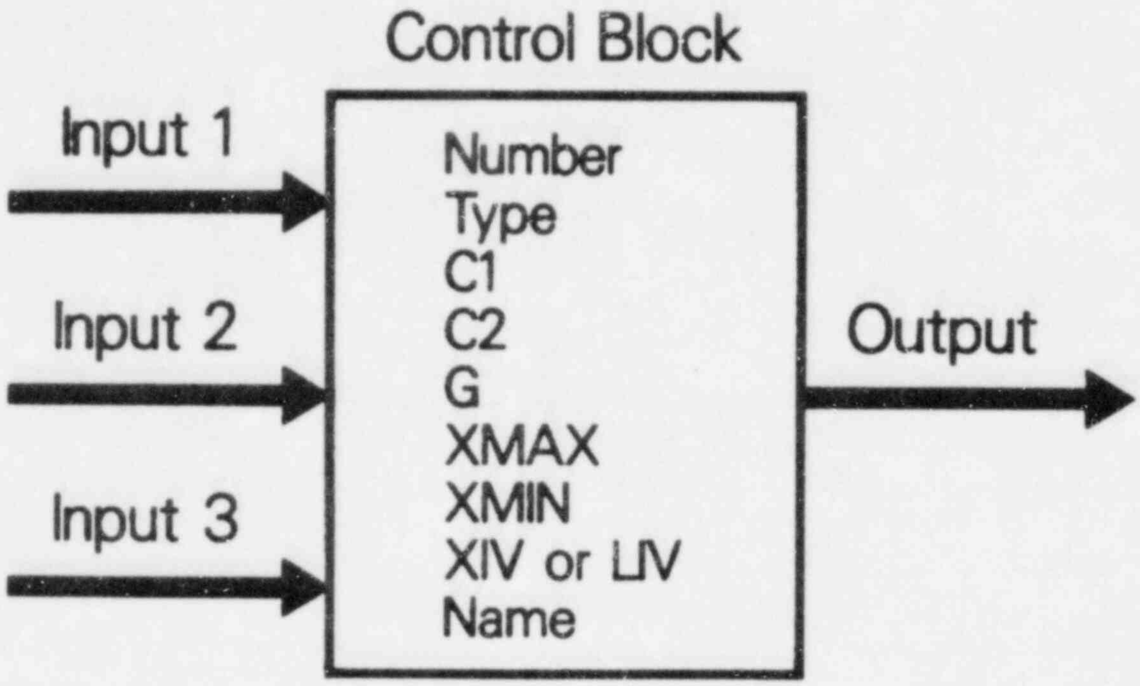

Figure 1. Control block diagram.

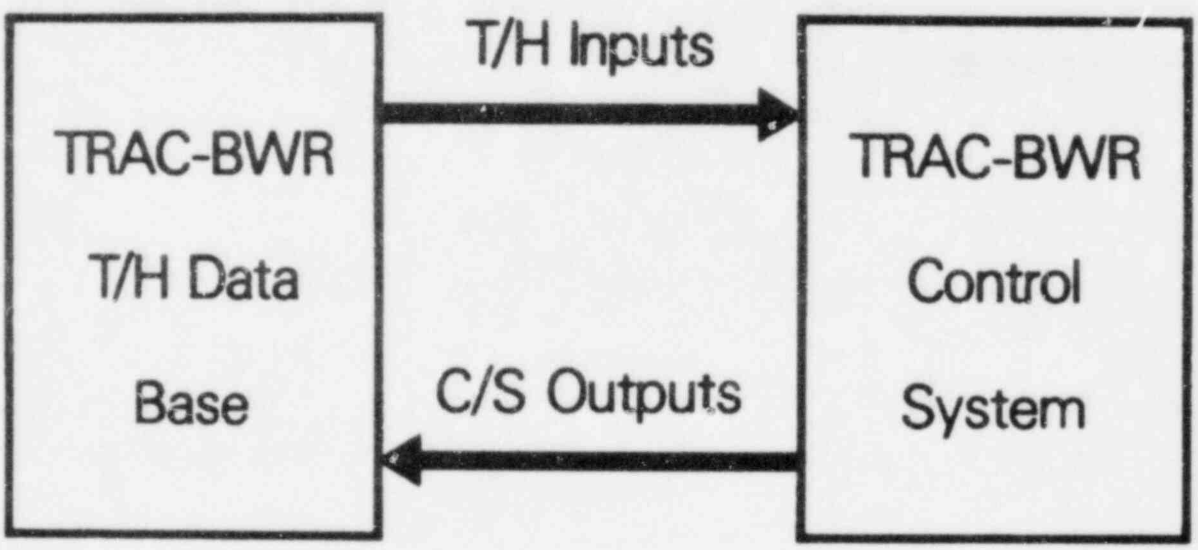

Figure 2. Information exchange between thermal/hydraulic data and control systems.

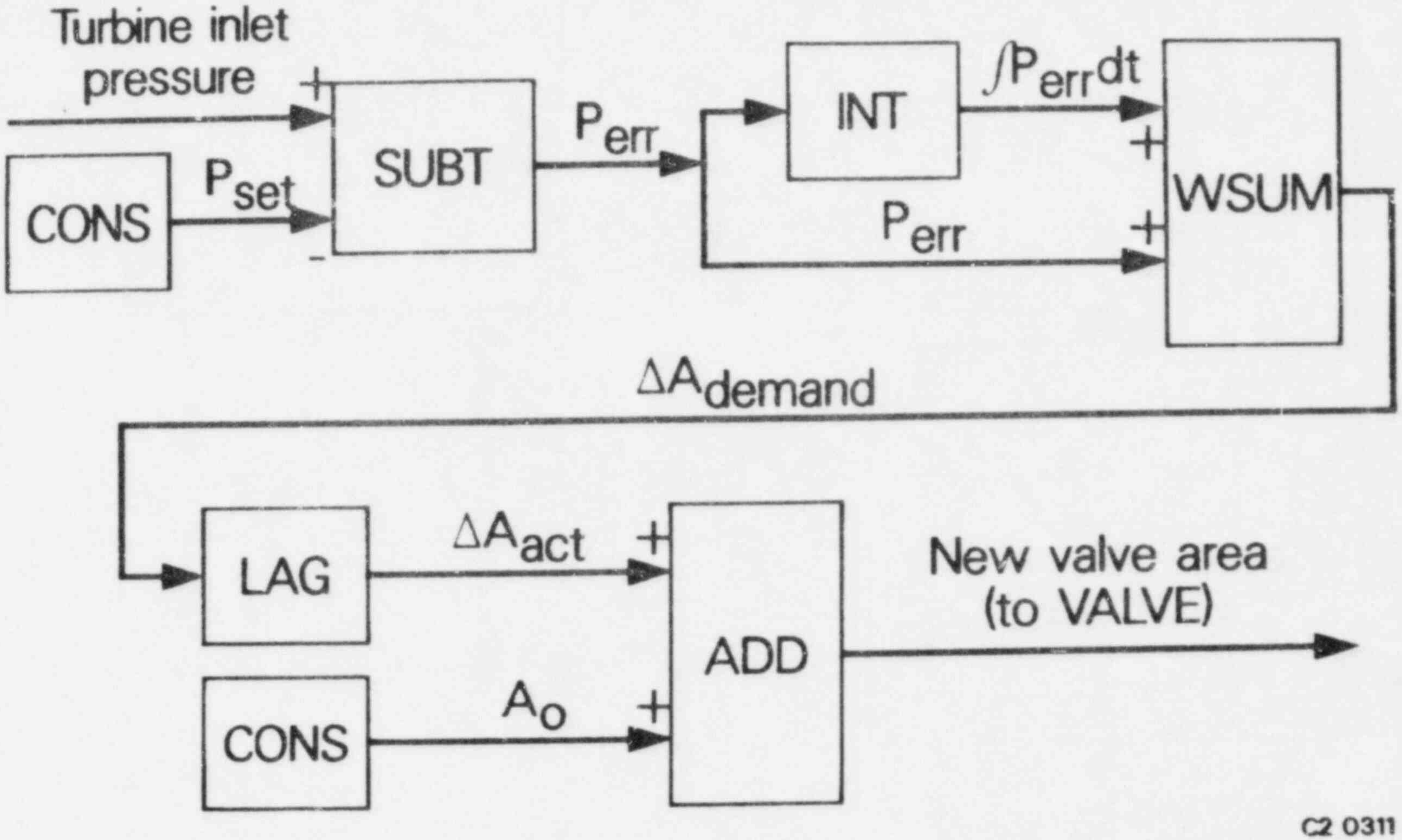

Figure 3. Simplified pressure control system model.

approximating the actuator dynamics. The actual change in valve area (ΔA_{act}) is added to the initial area (A_0). The updated area value is then sent to the T/H Data Base as the new turbine control valve area to be used during the next time step T/H computations. This example controller is used to bring the pressure of a simulated BWR plant to an equilibrium state and does not model an actual pressure control system which is significantly more complex.

3. BROWNS FERRY PLANT MODELING

As a demonstration of the Control Block capabilities, thermal/hydraulic and control system models for the Browns Ferry plant were developed using the TRAC-BWR Code. The three major control systems simulated were: (a) downcomer water level, (b) turbine inlet pressure, and (c) recirculation flow. To model these systems required 209 Control Blocks, 35 non-linear function generators, and 21 T/H Inputs and Outputs. This represents only approximately 25% of the currently programmed capacity in the code. Figure 4 shows the main fluid flow paths for the Browns Ferry power plant as solid lines and the control system signals as dashed.

Since the purpose of this simulation was to checkout and demonstrate the utility of the TRAC-BWR control system features,only a simplified T/H nodalization was included in the model as may be seen in Figure 5. TRAC has a component-based philosophy which means that a user connects the individual component modules together like computational "tinkertoys". Examples of these modular components used in the Browns Ferry simulation are: PIPE, PUMP, JETP, CHAN, VESSEL, TEE, VALVE, FILL, and BREAK. The CHAN component is used to model the reactor core using a single average fuel bundle. BREAKs are used to provide constant pressure system boundary conditions. The downcomer water level control system adjusts the feed-water flow rate by means of a FILL component which varies the liquid velocity appropriately. The recirculation flow controller simulates a variable-frequency motor generator set and fluid coupler to adjust the torque delivered to the recirculation pump motor. System pressure control is maintained by maneuvering the turbine control valve (TCV) to admit more or less steam. Other VALVE component areas such as

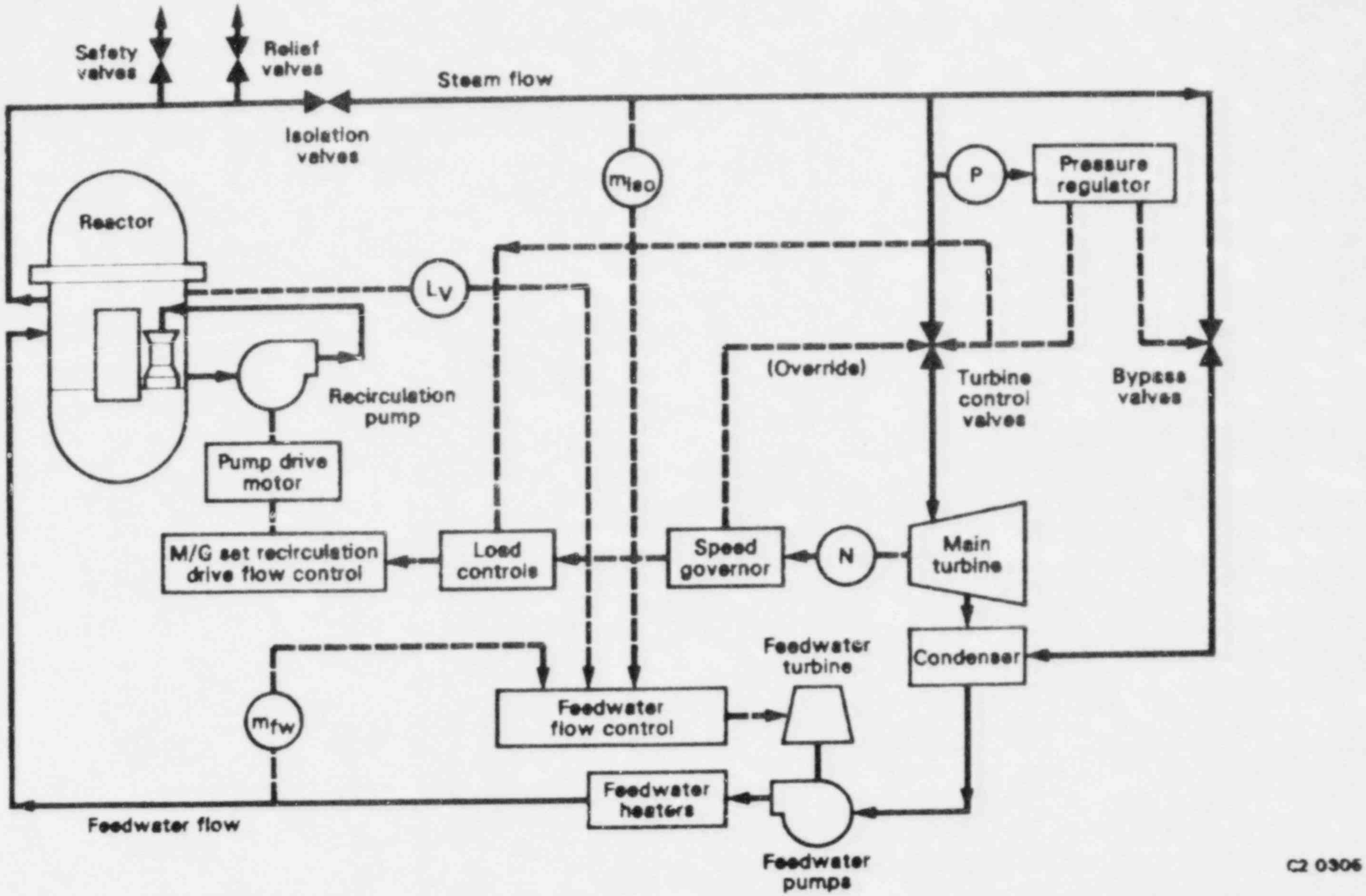

Figure 4. Browns Ferry plant configuration.

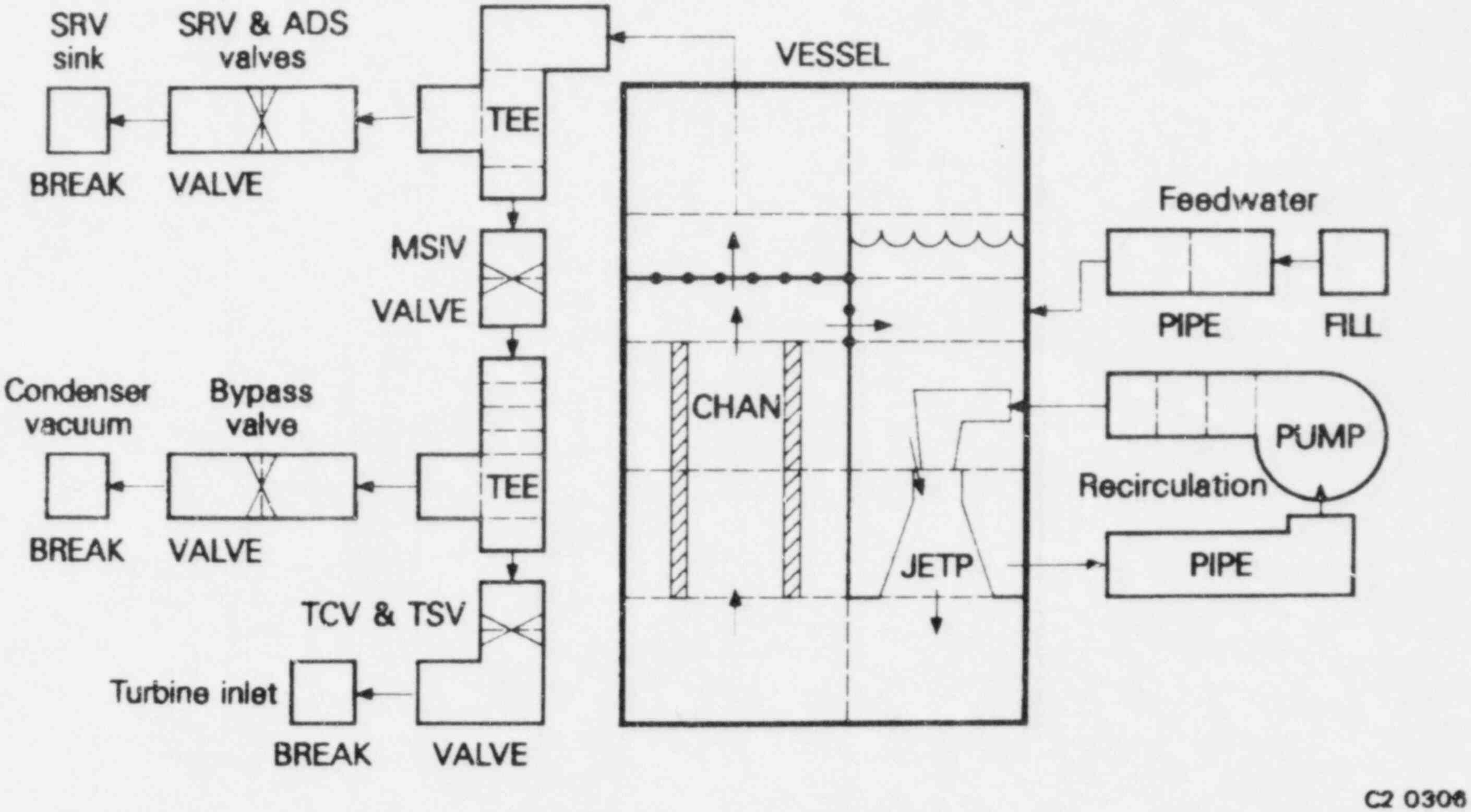

Figure 5. TRAC-BWR Browns Ferry thermal/hydraulic model.

bypass (BPV) and main steam isolation (MSIV) are also calculated by the control system. Safety relief valve (SRV) and automatic depressurization system (ADS) actuation is modeled using standard TRAC-BWR T/H trip logic.

4. STEADY STATE PLANT INITIALIZATION

The procedure used to establish simulated equilibrium reactor plant conditions is facilitated significantly when using the control system features. Formerly a time consuming trial-and-error technique with TRAC-BWR had to be employed to achieve a balanced plant condition. Now the user supplies desired setpoint conditions (downcomer water level, turbine inlet pressure, and jet pump discharge flow) together with initial rough estimates for T/H and control system values. The reactor power is specified to be constant at the desired power level. A reactor system transient is then simulated until a steady state condition is reached, requiring some 60 to 100 seconds of simulated time. For a 100 second Browns Ferry "steady state" simulation, the cost is only $67 and required 486 CPU (central processor unit) seconds on the INEL CDC Cyber 176. After examination of the resulting system pressure drops and core flow splits, loss coefficients are currently manually readjusted as needed. A series of additional steady state runs can be made until the desired convergence is achieved to all known reactor plant conditions. Future plans entail automatic adjustment of system loss coefficients by individual controllers to achieve the required conditions in a single plant balancing run.

To verify that the system is in an equilibrium state, a "null" transient is run with all controllers active and the reactor kinetics feedback adjusting the reactor power level for some 10 to 20 seconds. If "good" equilibrium initial conditions were achieved, no parameter should vary in greater than the fourth significant place. This has been found to be easily achievable.

5. GENERATOR LOAD REJECTION TRANSIENT

During pre-startup testing of the Browns Ferry Nuclear Reactor Power Plant, the Tennessee Valley Authority (TVA) performed a systems test by tripping the electrical generator when the plant was at full power conditions. Some of the key events which occurred during the resulting generator load rejection (GLR) are highlighted in Figure 6. The TRAC-BWR Code simulated times of these key events can be seen to compare favorably with the TVA reported times (3). It should be noted that due to the failure of a mechanical relay, the fast closure of the turbine control valve (TCV) did not occur as originally planned for the test. Consequently, the simulation of the generator load rejection transient also omits fast closure of the TCV.

The only model tuning that was performed for the GLR transient was to raise the downcomer low water level trip setpoint by approximately 10 inches. This was necessary to match the timing correctly at 6.4 seconds when the MSIV trips and the recirculation system starts to coast down. The times enclosed in parentheses indicate TVA simulated values using the RETRAN-02 Code (4).

Figure 7 demonstrates that very good agreement is achieved between the code prediction and reactor power test data. The initial dip in the reactor power is a result of a reactor core pressure decrease which causes an increase in steam voids and a corresponding decrease in reactivity. Increasing core flow causes the void fraction to decrease, thus increasing the power level. The turbine overspeed setpoint (110%) is reached at 1.54 seconds and the control rods are inserted thereby making the reactor subcritical with an accompanying rapid dropoff of power. The simulated reactor power is comprised of both gamma decay heat and fissions caused by neutrons. However, the measured power comes from a neutron measurement device. Consequently, this difference explains why the predicted power is approximately 5% higher (which is the decay heat contribution after shutdown).

In Figure 8 the agreement is again seen to be quite good between the

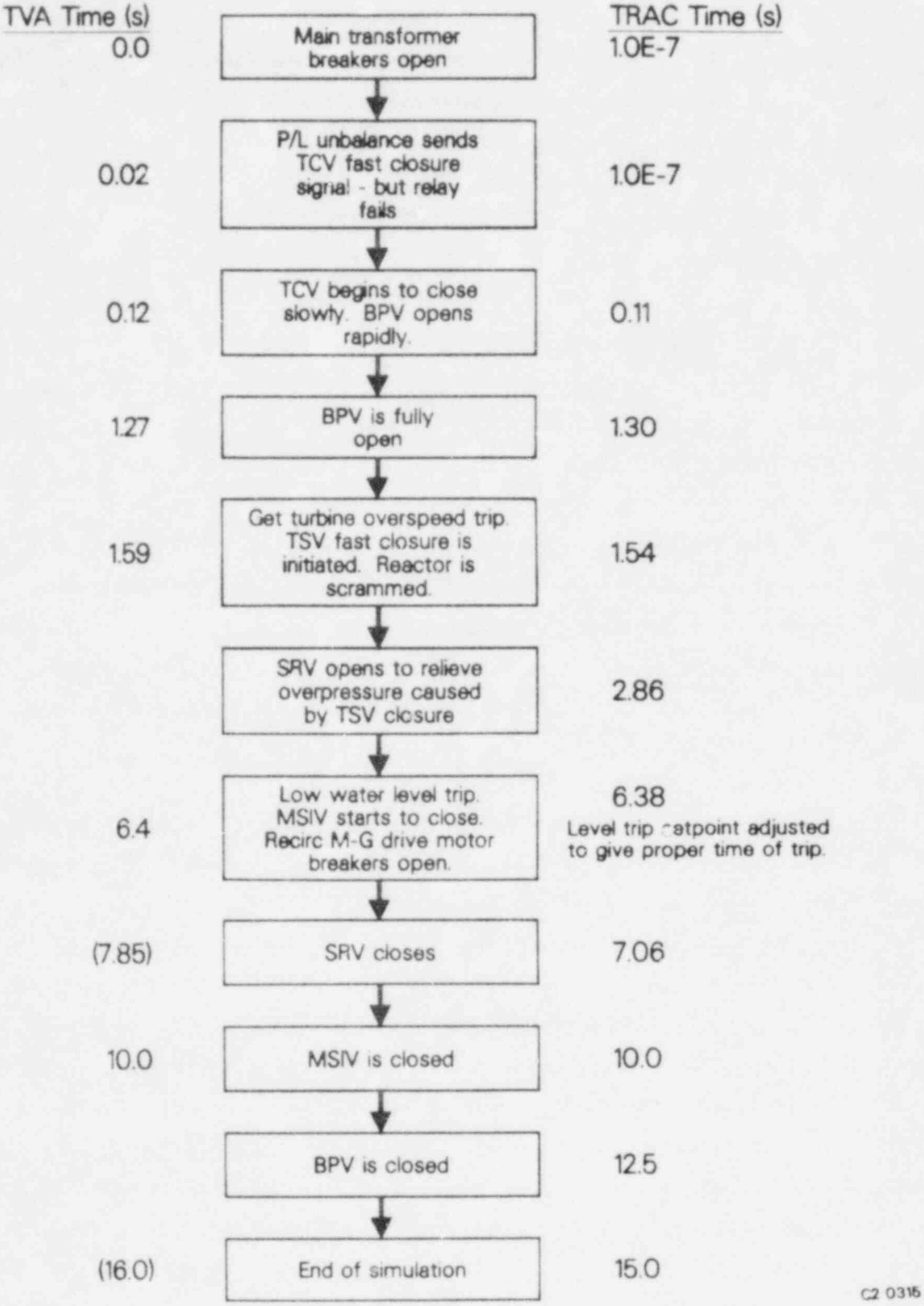

Figure 6. Browns Ferry generator load rejection key events.

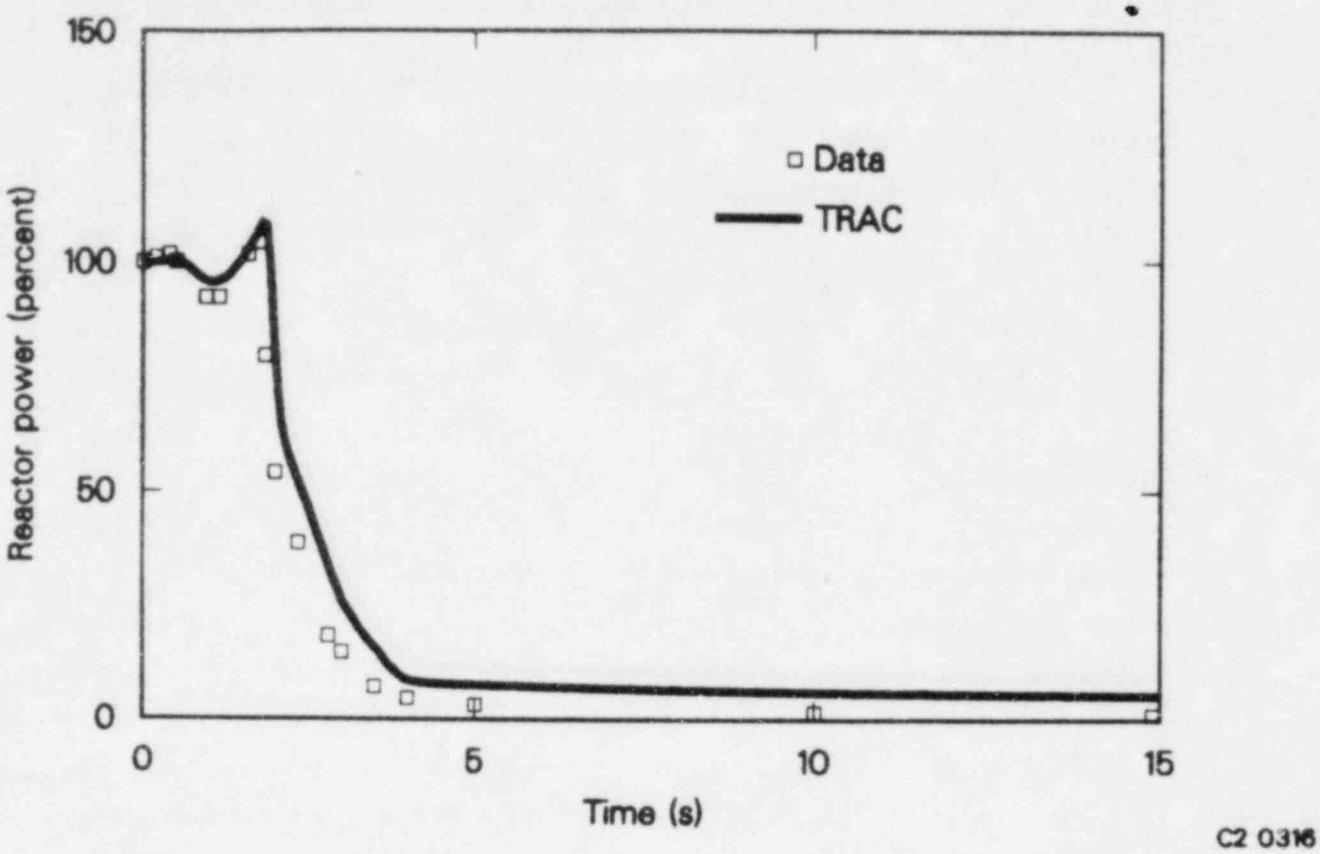

Figure 7. Reactor power response for GLR transient.

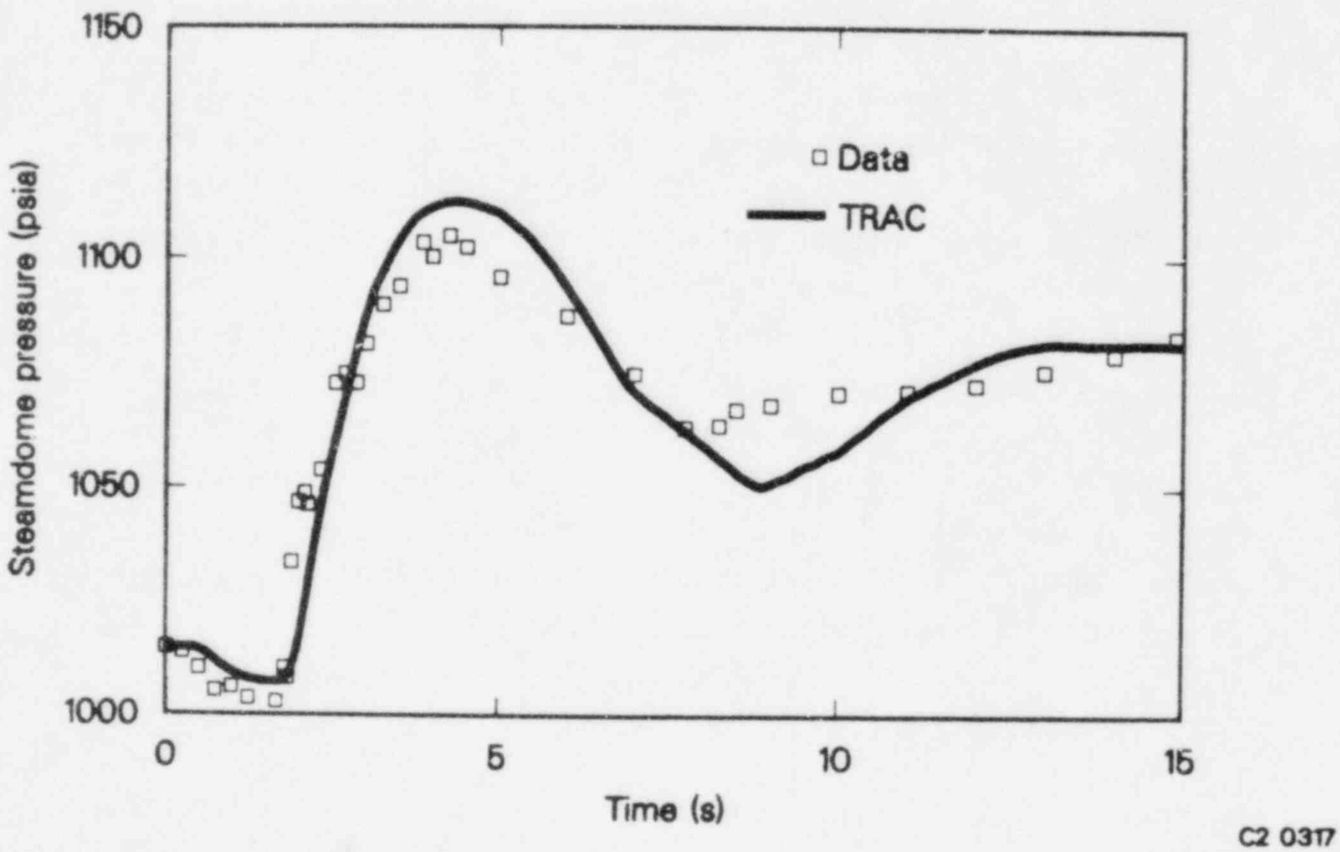

Figure 8. Steamdome pressure response for GLR transient.

predicted and measured steamdome pressures. The turbine stop valve (TSV) fast closure causes a rapid pressure rise such that a safety relief valve opens at 2.86 seconds. Also aiding in pressure reduction is that both the bypass valve (BPV) is fully open and the reactor is shutdown; consequently less steam is being generated. By 7.06 seconds the pressure has decreased sufficiently that the SRV closes. Between 6.38 and 10.0 seconds the main steam isolation valve (MSIV) is closing as a result of a low water level trip. As the MSIV closes, the pressure again increases.

The simulated core flow rate in Figure 9 is observed to replicate the major experimental trends reasonably well. However, the predicted changes in core flow rate are somewhat less than the measured changes. After 10 seconds the predicted flow coastdown rate is also less than that observed. Model changes could have been made to improve the agreement with test data. This was believed to be unnecessary since the primary purpose of this simulation was to demonstrate that the newly added control system features worked correctly and not to fine tune T/H and C/S models.

Figure 10 indicates that the simulation of the measured steam flow out of the reactor vessel is accurate. There is a rapid drop in steam flow when the TSV is closed and the reactor is shutdown (so that less steam is being produced). Between 2.86 and 7.06 seconds the safety relief valve (SRV) is open and the predicted steamline flow shows a marked increase. A corresponding increase is not observed in the test data possibly indicating an overprediction of the SRV flow. The experimental data is somewhat suspect however, since the measured steamline flow rate should have gone to zero after 10 seconds when both SRV and MSIV were closed. To model what appears to be a sensor inaccuracy, the simulated flow sensor measurement was constrained by a lower limit of 12.75% to be in better agreement with the TVA reported data. The simulated actual steam flow rate (not shown here) was unaffected by limiting the sensor value so the T/H solution was not modified in any way.

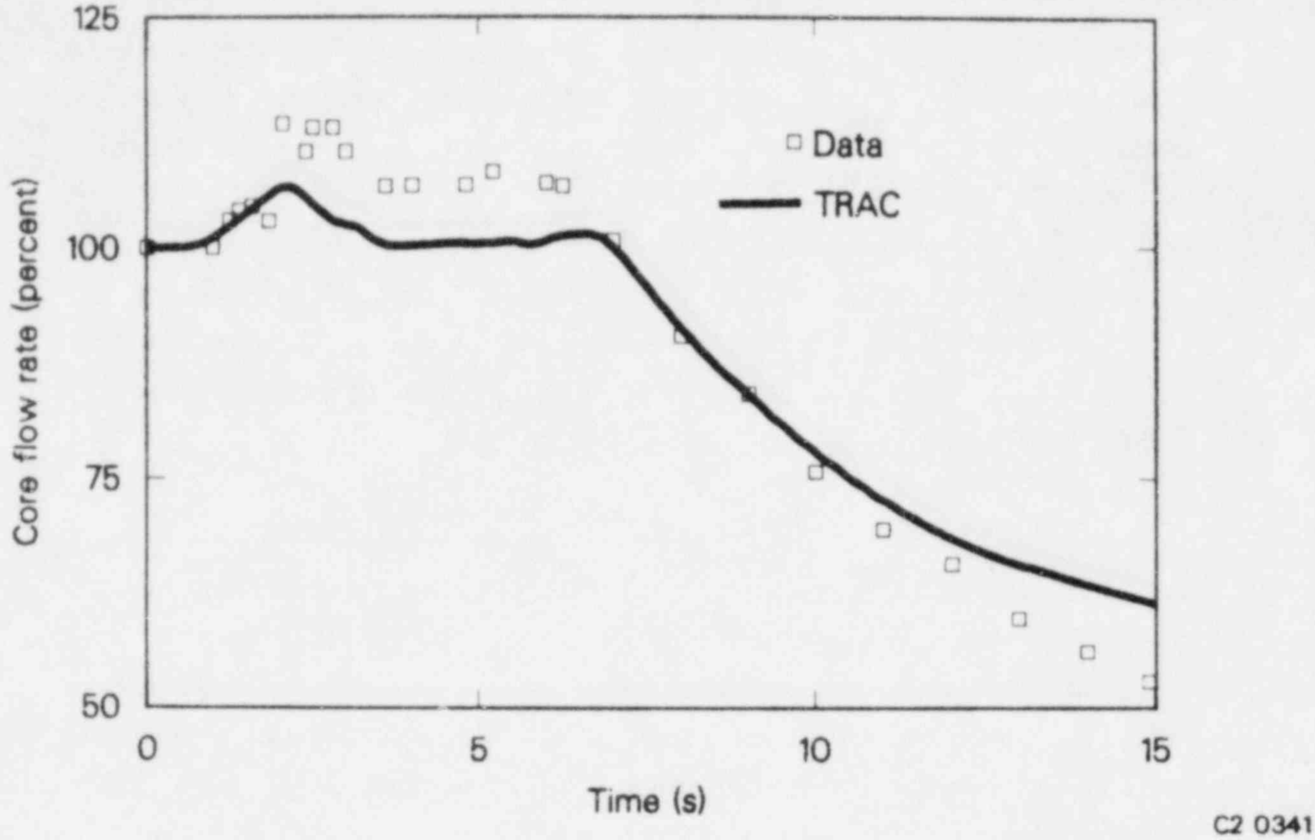

Figure 9. Core flow rate response for GLR transient.

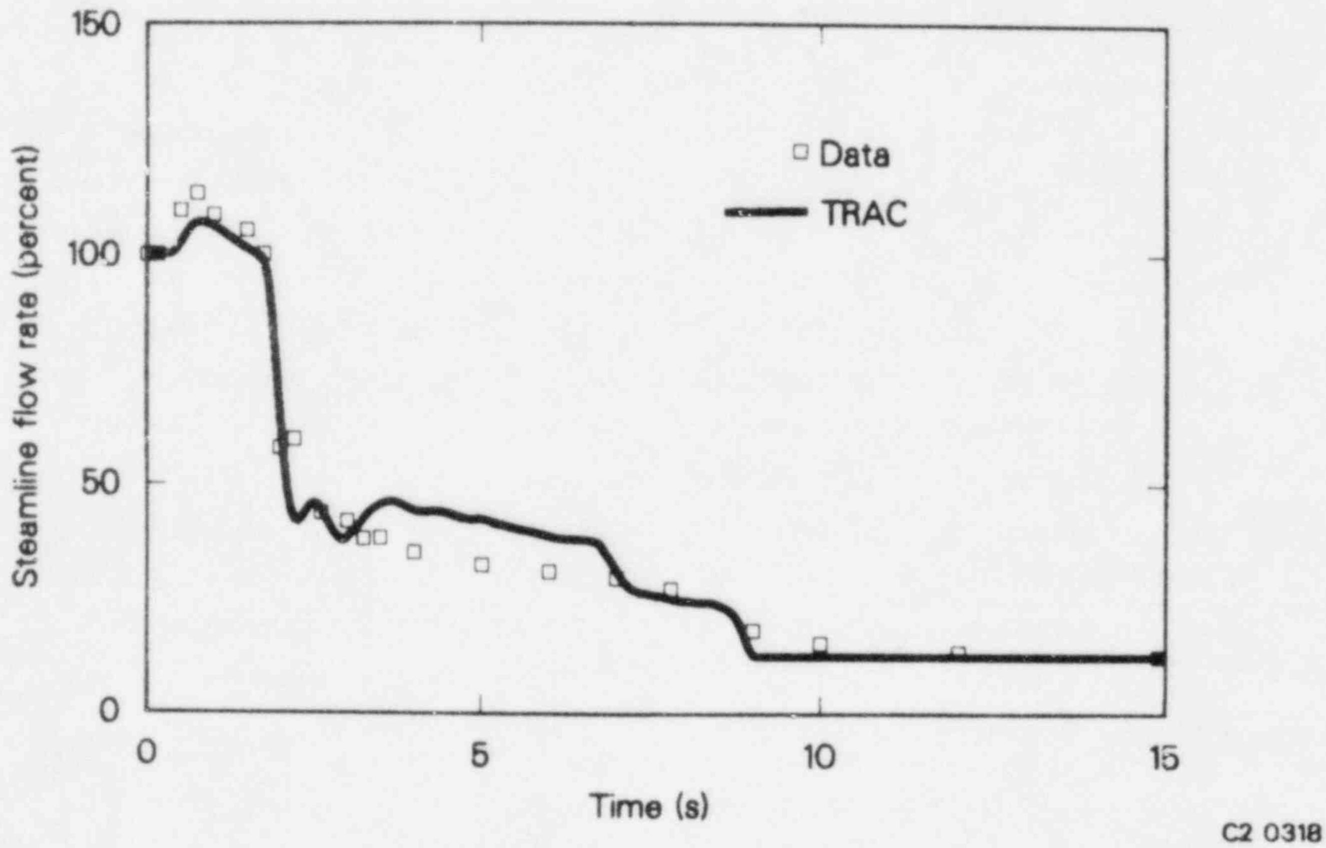

Figure 10. Steamline flow rate response for GLR transient.

As can be seen in Figure 11, the control system simulated feedwater flow response differs significantly from the experimental behavior. A second order differential equation is used to approximate the dynamic response of the feedwater pump being driven by its steam turbine. The best method to reduce this discrepancy is believed not to lie in finding "better" coefficient values for the second order model; but rather the solution is to provide accurate mechanistic feedwater turbine and pump models that are based more upon the actual physical processes and less upon a simplified "black box" approximation.

The measured downcomer water level shown in Figure 12 exhibits a periodic oscillatory behavior that is not predicted by the TRAC-BWR T/H model. Three explanations are postulated to account for this "ringing" phenomenon: (a) there is side-to-side sloshing or wave rippling in the annular downcomer; (b) there is manometer-like coupling between the downcomer water level and the reactor core steam voids; and (c) there are sensor line dynamic effects in the differential pressure measurements used to calculate the downcomer water level height. For the GLR transient, the code-predicted water level falls more slowly than the measured data. Note that a low water level trip is generated at 6.4 seconds when the measured level drops to approximately -25 inches. The predicted level is 10 inches higher at that time. Consequently, the low water level trip setting was accordingly increased by 10 inches so as to obtain the correct trip event time. Another observed characteristic which is not replicated by the predicted water level is the upward trend of the test data from 10 to 15 seconds. The predicted level is just starting to turn around when the simulation is terminated. A possible explanation for this discrepancy in behavior is that the code is predicting more rapid reactor core steam void reduction than is actually occuring. Since no appreciable amount of steam is leaving the BWR vessel after 10 seconds and the subcooled feedwater flow is above 100%, conservation of vessel mass indicates that the excess incoming mass is apparently going into the core region (which is approaching a predicted subcooled state by the end of 15 seconds).

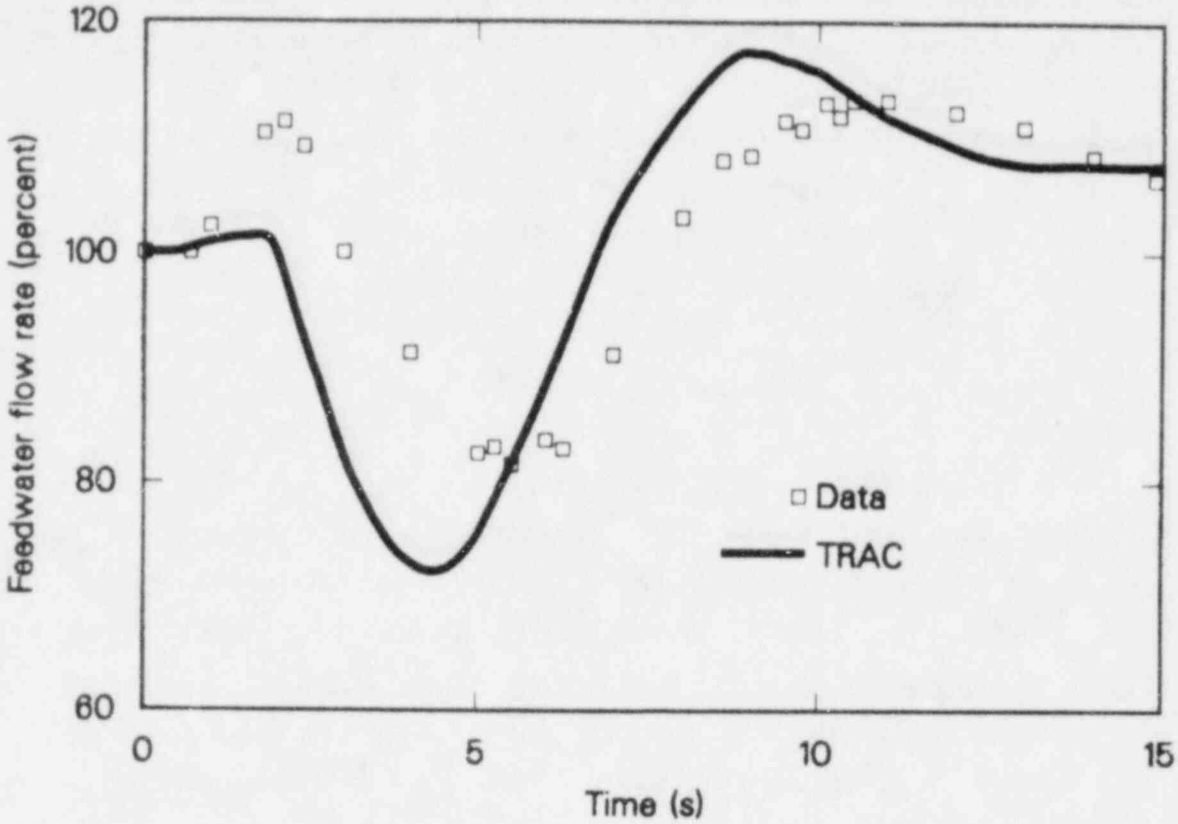

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Figure 11. Feedwater flow rate response for GLR transient.

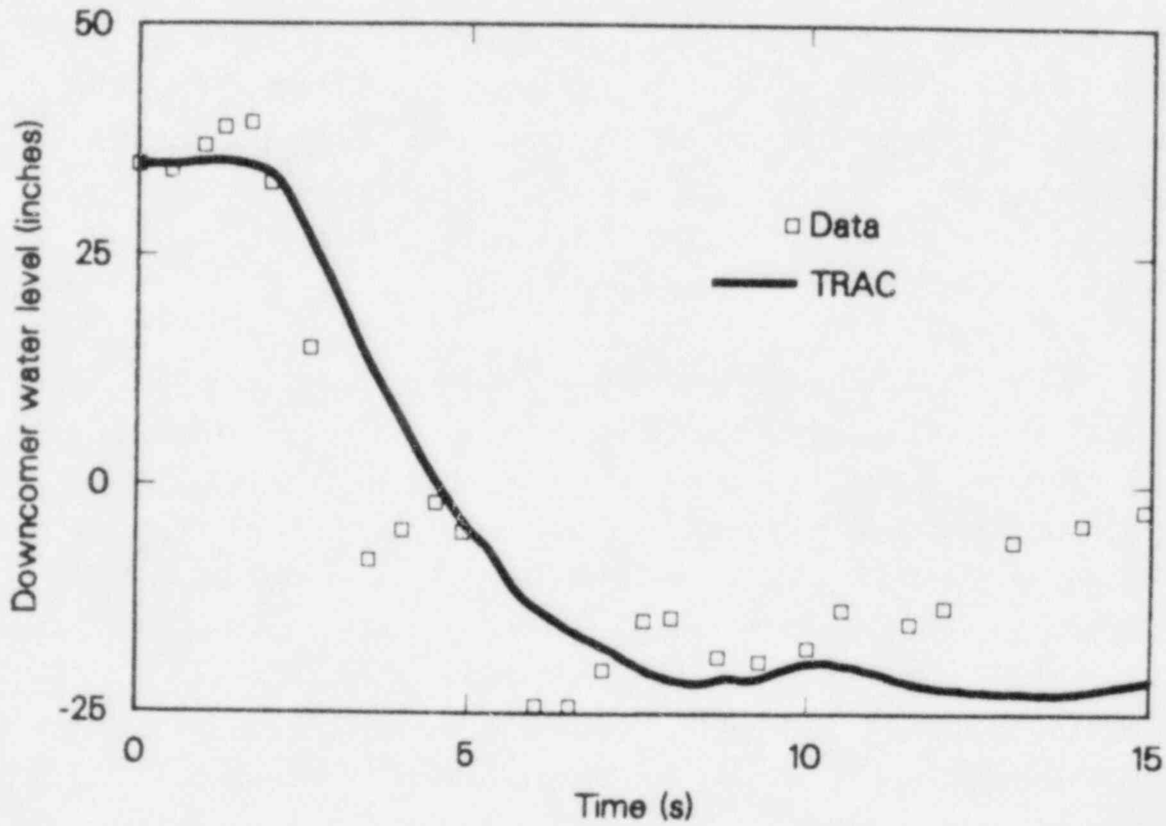

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Figure 12. Downcomer water level response for GLR transient.

The simulation of the GLR transient is quite inexpensive requiring 161 CPU seconds and a charge of $25 for the 15 second transient. The fraction of the CPU time required by the control system calculations is only 5.09%. Consequently, an original design goal of making the controller computations efficient so that their impact on run time costs would be minimal (under 10%) has been reached.

6. CHANGE IN LEVEL SETPOINT TRANSIENT

An additional Browns Ferry operational transient was simulated to further investigate the apparent discrepancies between code predicted and measured feedwater flow and downcomer water level. A 3-inch change in water level setpoint was analyzed. This is a much less severe system transient than previously encountered during the GLR test. No trips are activated. The reported data (5) for this transient is for a 30 second period whereas GLR data was previously given for 15 seconds.

The simulated change in level setpoint is introduced as a step during the first time step. As Figure 13 indicates, the feedwater flow is gradually reduced from 100% reaching a minimum at 5.45 seconds. The test data has a minimum value of 92.5% as compared to a predicted minimum of 93.3%. The predicted and measured transient responses demonstrate qualitatively similar shapes. However, a slight overshoot is predicted in the return to equilibrium (100%) feedwater flow conditions which is not indicated by the test data.

Figure 14 again demonstrates the oscillatory character of the experimental downcomer water level response. Note that the predicted level falls faster than that measured. This is opposite to what occurred in the GLR transient. There is a predicted slight undershoot of the new 30-inch setpoint which is not observed in the Browns Ferry data. Since the reactor is not scrammed during this operational transient, the simulated power level and core average void fraction remain essentially constant, varying less than 1%. Consequently, differences in core void collapse rates cannot account for the difference between predicted and measured level response.

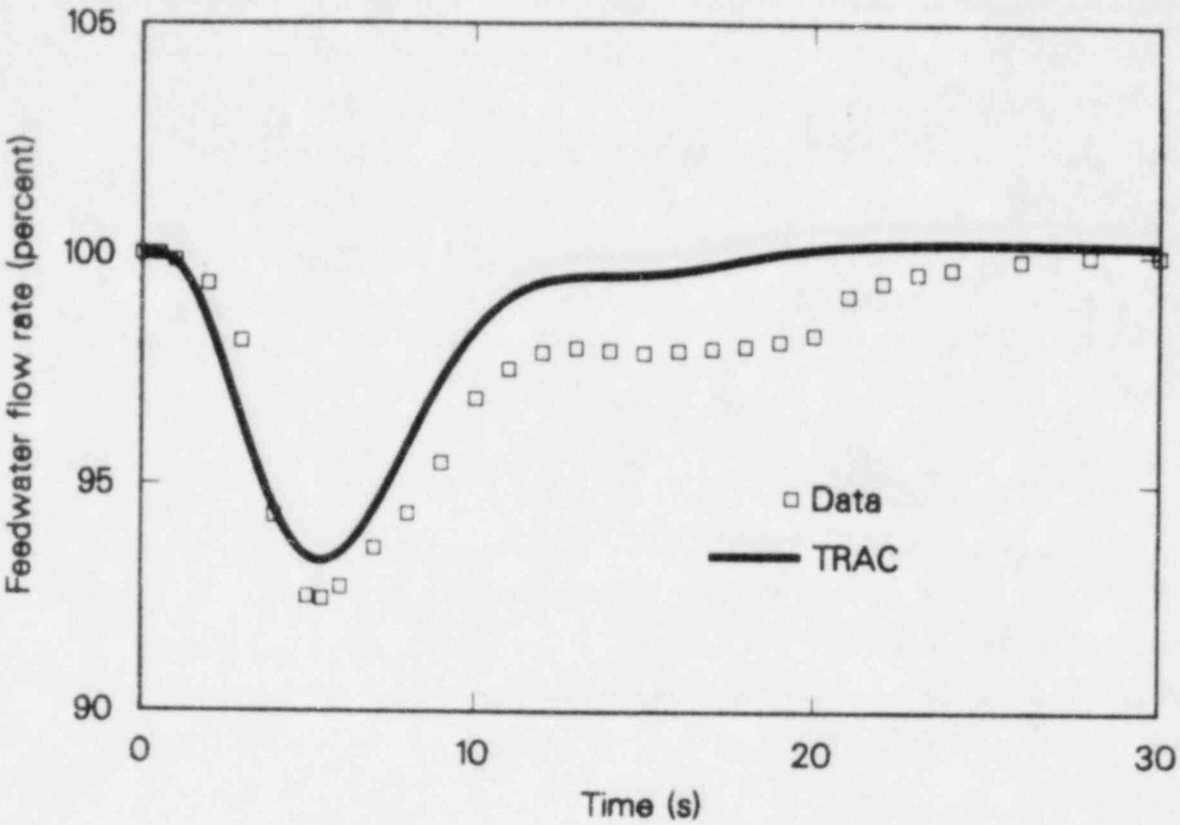

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Figure 13. Feedwater flow rate response for change in level setpoint transient.

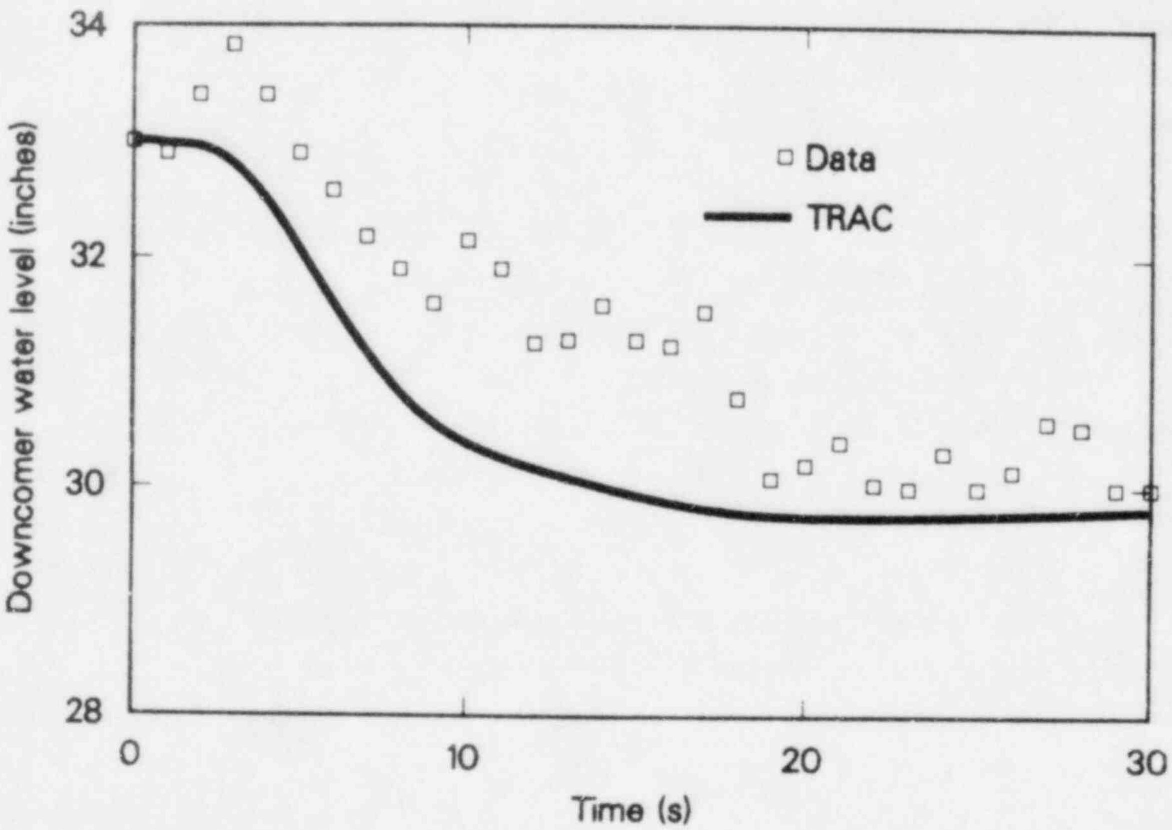

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Figure 14. Downcomer water level response for change in level setpoint transient.

Even though the simulated level setpoint change transient is twice as long as the GLR transient, the computer costs are not directly in proportion. This is a consequence that due to the "mildness" of the system changes, the T/H solution is able to converge in a single iteration for each time step. During the GLR transient, the average number of T/H iterations taken per time step is 1.87. For the level setpoint change analysis the CPU time required is 165 seconds and the cost is $27.

7. FUTURE TRAC-BWR CODE ENHANCEMENTS

Since the TRAC-BWR Code is continually being enhanced in a great many areas, it is not possible to provide an exhaustive list of proposed improvements. Only a few areas will be mentioned together with representative examples of current or recommended improvements.

Additional user convenience features will be added to assist in the process of building and initializing a BWR plant model input description. Automatic sorting of control blocks will properly sequence controller operations thus relieving the user from performing this task. Default BWR system controllers will provide a rapid and cost effective means of initializing a plant to steady state conditions.

To further expand the utility of the control system modeling capabilities, additional Control Block Types will be added. Examples of these proposed new features include the hysteresis function and an implicit loop solver. The former block would allow the user to specify a path dependent tabular function. The latter capability would solve algebraic loops using an iterative technique for each time step.

Mechanistic balance of plant (BOP) component models will be developed to simulate a steam turbine and a heat exchanger. These components will be used to simulate high and low pressure turbines, feedwater turbines, feedwater heaters, reheaters, and condensers. Thus, a closed BOP flow loop may be simulated if desired for BWRs.

A faster numerical integration technique will allow increases in time step size of up to an order of magnitude without the thermal/hydraulic solution going unstable. This gives promise to providing more economical solutions for very long operational and ATWS transients.

8. SUMMARY AND CONCLUSIONS

The recently developed control systems capabilities greatly extend TRAC-BWR's ability to simulate a wide spectrum of safety-related transients. Utilization of reactor power plant controllers facilitates the initialization of the model to steady state conditions. The method is cost effective and easy to use. Code predictions of selected operational transients show acceptable agreement with test data without extensive model tuning.

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