NUCLEAR POWER PLANT SIMULATION ON THE AD10

W. Wulff, H.S. Cheng, A.N. Mallen, and A. Stritar
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, NY 11973

ABSTRACT

A combination of advanced modeling techniques and the modern, special-purpose peripheral minicomputer AD10 is presented which affords realistic predictions of plant transient and severe off-normal events in LWR power plants through on-line simulations at a speed ten times greater than actual process speeds. Results are shown for a BWR plant simulation.

The mathematical models account for nonequilibrium, nonhomogeneous two-phase flow effects in the coolant, for acoustical effects in the steam line and for the dynamics of the recirculation loop and feedwater train. Point kinetics incorporate reactivity feedback for void fraction, for fuel temperature, for coolant temperature, and for boron concentration. Control systems and trip logic are simulated for the nuclear steam supply system.

The AD10 of Applied Dynamics International is the special-purpose peripheral processor. It is specifically designed for high-speed digital system simulation, accommodates hardware (instrumentation) in the input/output loop, and operates interactively on-line, like an analog computer. Remote access via commercial telephone and an IBM-PC is possible.

Results are shown to demonstrate computing capacity, accuracy, and speed. Simulation speeds have been achieved which are 110 times larger than those of a CDC-7600 mainframe computer or ten times greater than real-time speed.

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INTRODUCTION

There is an urgent need to reduce the computing cost and manpower requirements for nuclear power plant simulations, now being performed for the purposes of safety and vendor audit analyses on large mainframe computers. There is also a need for training simulators which can simulate severe accident conditions at real-time computing speeds.

These needs can now be met with a newly realized technology that combines advanced thermohydraulic modeling methods with modern, special-purpose minicomputer architectures such as that of the AD10 from Applied Dynamics International (ADI) in Ann Arbor, MI. The plant analyzer, which was recently developed at Brookhaven National Laboratory, carries out plant transient simulations for a BWR nuclear power plant at simulation speeds up to ten times greater than real-time process speeds, with user conveniences achieved heretofore only on analog or hydrid computers.

The newly developed technology has also the potential of supporting nuclear power plant operations through continuous, on-line plant monitoring and through failure diagnostics. The plant analyzer can have, in principle, its initial conditions continually updated from plant conditions and, on demand, predict with high speed, the outcome of contemplated remedial actions before they are taken. This allows the operator to select optimum emergency responses.

THE PLANT ANALYZER

Hardware Components

The plant analyzer assembled at BNL is a general, fully digital simulation facility and now programmed to simulate any BWR-4 power plant. Plans are being developed to simulate also PWR power plants.

The plant analyzer components are: a PDP-11/34 host computer, two AD10 peripheral processors with the combined data memory of one megaword, two sixty-seven megabyte discs and one tape drive, a line printer, an operator console and five remote access terminals, a Model 4012 Tektronix storage oscilloscope (which serves also as a keyboard terminal), and an IBM personal computer with a four-color graphics monitor capable of displaying labelled diagrams and used for remote access.

To achieve ten times greater than real-time simulation speed in a BWR simulation, one needs two AD10 processors working in parallel.

The AD10 processor is specifically designed to integrate efficiently large systems of nonlinear ordinary differential equations. The AD10 consoles at BNL contain seven special-purpose microprocessors, each equipped with its own instructional memory. This enables five of the seven processors to operate in parallel. The seven microprocessors are the:

- Control Processor (COP) for control and timing of all processors,
- Decision Processor (DEP) for logic and binary search needed for function generation,
- Arithmetic Processor (ARP) for addition, multiplication and interpolation (function generation),
- Numerical Integration Processor (NIP) for numerical integration of differential equations,
- Memory Address Processor (MAP) for addressing data memory,
- Bus-to-Bus Interface Processor (BIP) for data transfer between AD10s,
- Input/Output Channel Controller (IOCC) for I/O control.

Program modules (for summation, function generation, etc.) are executed in sequence but most module executions involve several component processors working in parallel.

The microprocessors communicate with each other, with the interleaved data memory and with the Host Interface Controller via a Multibus at the rate of 20 million words per second. All microprocessors are synchronized and execute at the frequency of 10 MHz. Pipelining in the ARP and NIP processors affords composite operations (i.e., $(A+B)*C+D$ in the ARP) to be executed at the rate of 10 million composite operations per second. Arithmetic operations and function generation is carried out in 16-bit integer arithmetic, numerical integration is performed with a 48-bit mantissa. The AD10 is not suitable for matrix inversions.*

The IOCC processor gives the fully digital AD10 the added features of an analog or hybrid computer. This capability has been utilized by feeding 28 analog input signals to the AD10 from a specially constructed control panel. Each control channel has a polarity switch and a ten-turn linear resistor with readout dial to select any dc voltage between -10 and +10V. It also has indicator lights for convenient recognition of channel status. The channels are used to manually select any possible control system malfunction, valve malfunction or to select or change set points or to introduce trip signals. The control channel function assignment is through software and was chosen to emulate operator options and potentials of plant disturbances.

Sixteen output analog channels have been assigned through software to 15 selected plant parameters and time (horizontal sweep). The output from these 16 channels can be stored simultaneously in the memory of the IBM personal computer and afterwards displayed on the multicolor graphics monitor.

Up to 256 analog channels for input and output processing can be made available on the two AD10 units. Each channel is scanned 200 times each second with the currently used software package (5 millisecond cycle time). Two digital ports each capable of transmitting 30,000 words per second are used for data transfer to the host computer.

The computing speed in the AD10 processor results firstly from its architecture, namely the parallel processing by six microprocessors, pipeline executions (seven stages in ARP), interleaving of data memory, synchronous broadcasting of data, hardwired arithmetic and the combination of fixed-point 16-bit arithmetic with 48-bit pseudo-floating point arithmetic, and secondly from special progamming, namely the function generation via table interpolation, instead of the extended arithmetic (multiple evaluation of polynomials), in general purpose computers, and the efficient, high-order integration algorithms.

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*A New FX processor, now available with a 32-bit mantissa floating point arithmetic, would no longer require scaling.

Software Components

The computer program associated with the plant analyzer is called HIPA-BWR-4. HIPA stands for High-Speed Interactive Plant Analyzer program and BWR-4 indicates that the program is plant-specific for a BWR-4 power plant.

HIPA consists of two program parts, one for each console. Each part consists of three files, the CREATE, RELATE and SPECIFY DATA files.

One AD10 console is devoted entirely to the simulation of the hydraulics in the pressure vessel. This entails the integration of four field equations for 55 computational cells.[1,2,3] The second console is used to simulate neutron kinetics, thermal conduction in the fuel, steam line acoustics, the thermohydraulics in the balance of the plant and the control systems. Data transfer between the two consoles is direct via the bus-to-bus interface processor BIP.

RESULTS

The BWR Power Plant

Figure 1 is a schematic of the Peach Bottom-II plant as simulated in the plant analyzer. Shown in the schematic are also the feedwater controller FW, the pressure regulator P and the recirculation flow controller RF (shaded blocks). The feedwater controller FW generates the total error from the mismatch between the vessel's incoming and outgoing mass flows W, and from the mismatch between actual and desired levels L. It then regulates the admission of steam to the feedwater pump drive turbine. The pressure regulator P senses steam line pressure p and controls the flows through turbine control and bypass valves. The recirculation flow controller RF matches the rotational speed of the generator with the demand error D by adjusting the slip in the fluid coupler between drive motor and generator.

Current Simulation Capabilities

More than 40 different transients and malfunctions have been simulated so far. Developmental assessment of the plant analyzer is documented.[1] Preliminary comparisons with results published by General Electric Corporation show similar trends for most of the listed transients. Plant analyzer results agree with results from large systems codes TRAC-BD1, RELAP-5 and RAMONA-3B.

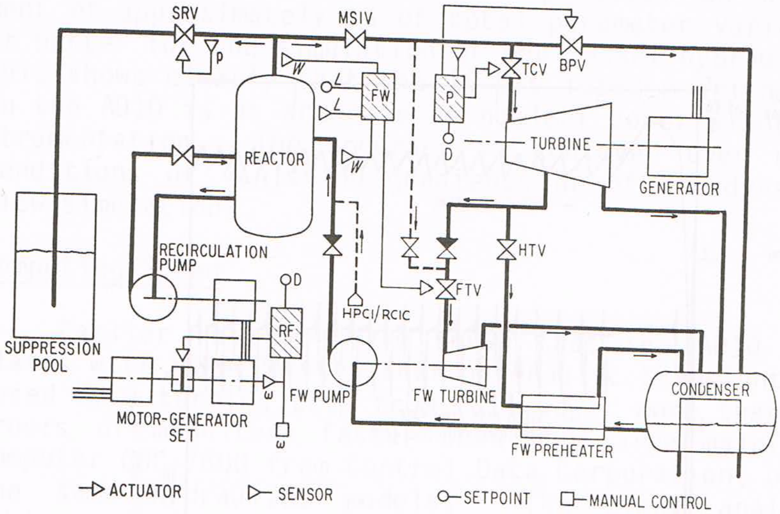

Figure 1. Schematic of BWR power plant simulated in plant analyzer.

Figures 2 and 3 show typical results from the plant analyzer as obtained through the Tektronix storage oscilloscope. The transient shown is an Anticipated Transient Without Scram (ATWS), induced by main steam isolation valve closures and executed without recirculation pump trips. Shown are the early reponse during the first five seconds and the pseudo-steady oscillations caused later by the relief valve actions.

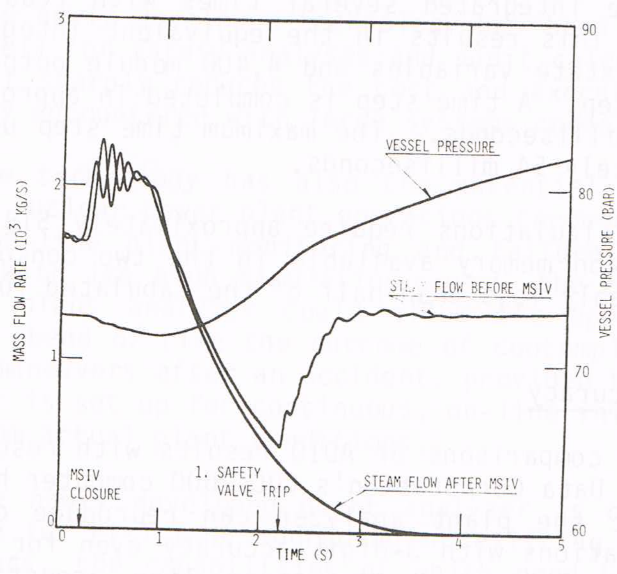

Figure 2. Early system response to ATWS transient.

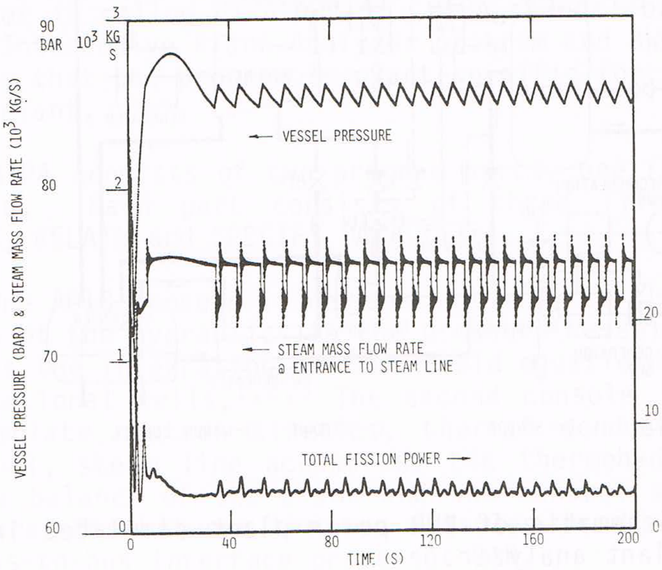

Figure 3. Long-term response to ATWS transient.

Computing Capacity

The BWR power plant simulation encompasses the integration of 225 state equations and the evaluation of 4,100 MPS10 module outputs including 712 function calls and 194 comparator switch calls. Some state equations are integrated several times with reduced time steps. This results in the equivalent integration of 325 state variables and 4,400 module outputs every time step. A time step is completed in approximately 6.3 milliseconds. The maximum time step used is approximately 54 milliseconds.

These calculations require approximately 518 of the instruction memory available in the two consoles and considerably less than half of the tabulated function memory.

Computing Accuracy

Earlier comparisons of AD10 results with results from Control Data Corporation's CDC-7600 computer have shown,[4] that the plant analyzer can reproduce component simulations with 3-digit accuracy even for the demanding simulation of the steam line acoustics.

Comparison of overall results[3] produced an agreement of approximately 5% of total parameter variation or better for the simulation of the vessel hydraulics. This shows clearly that the 16-bit integer arithmetic in the AD10 is as accurate as nuclear power plant instrumentation. The accuracy is achieved even under conditions of vanishing gradients or of steady-state flow simulations.

Computing Speed

Earlier results[3] have shown that the AD10 simulates with HIPA-PB2 the thermohydraulic transient induced by a turbine trip from full power more than two orders of magnitude faster than the large mainframe computer CDC-7600 from Control Data Corporation, using the same hydraulics models. The plant analyzer achieves simulation speeds of nine times greater than real-time process speeds for most transients. It is expected that all transients will be simulated at least at approximately nine times real-time computing speeds.

SUMMARY AND CONCLUSION

High-speed simulations of transients in a nuclear power plant have been achieved in a low-cost, special-purpose minicomputer. The hydraulics models employed for the nuclear steam supply system extend the simulation capabilities to encompass severe accidents which may lead to phase separation and two-phase flow conditions anywhere in the pressure vessel.

The newly developed technology has been shown to serve well for safety analyses and audit calculations, where it sharply reduces the cost and execution time normally encountered with large systems codes.

The technology has also the potential for supporting nuclear power plant operations through continuous, on-line plant monitoring and failure diagnostics. With its high simulation speed, the newly developed plant analyzer could allow the operator to predict ahead of time the outcome of contemplated remedial maneuvers after an accident, provided the plant analyzer is set up for continuous, on-line initialization from actual plant conditions.

The newly developed plant analyzer is certainly suitable for efficient upgrading of existing training simulators, the capabilities of which need to be extended to include severe accident conditions.

REFERENCES

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(3) WULFF, W. et al., "LWR Plant Analyzer Development Program," Ch. 5 in "Safety Research Programs Sponsored by Office of Nuclear Regulatory Research," Quarterly Progress Report, compiled by A. J. Weiss, NUREG/CR-2331, BNL-NUREG-51454, Vol. 2, No. 3, July-Sept. 1982.

(4) WULFF, W. et al., "LWR Plant Analyzer Development Program," Ch. 5 in "Safety Research Programs Sponsored by Office of Nuclear Regulatory Research," Quarterly Progress Report, compiled by A. J. Weiss, NUREG/CR-2331, BNL-NUREG-51454, Vol. 3, No. 1, January - March 1983.