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PLANT ANALYZER DEVELOPMENT FOR HIGH-SPEED INTERACTIVE SIMULATION OF BWR PLANT TRANSIENTS*

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ABSTRACT

Advanced modeling techniques have been combined with modern, special-purpose peripheral minicomputer technology to develop a plant analyzer which provides realistic and accurate predictions of plant transients and severe off-normal events in nuclear power plants through on-line simulations at speeds of approximately 10 times faster than actual process speeds. The new simulation technology serves not only for carrying out routinely and efficiently safety analyses, optimizations of emergency procedures and design changes, parametric studies for obtaining safety margins and for generic training but also for assisting plant operations.

Five modeling principles are presented which serve to achieve high-speed simulation of neutron kinetics, thermal conduction, nonhomogeneous and nonequilibrium two-phase flow coolant dynamics, steam line acoustical effects, and the dynamics of the balance of plant and containment systems, control syatems and plant protection systems. Principles for selecting numerical integration techniques are presented, as well as efficient techniques for reducing mathematical operations during the simulation. Available computer architectures are compared with regard to their suitability for simulating complex systems. The AD10 peripheral processor's architecture is presented. The BNL Plant Analyzer is described and simulation results are presented. It is shown that the plant analyzer surpasses supercomputers in simulation speed and produces the same results as large systems codes for a wide variety of transients, but at considerably lower cost than mainframe computers.

INTRODUCTION

Realistic and accurate interactive simulations at high computing speed and low cost for normal and accidental transients in nuclear power plants are sought in many sectors of the nuclear industry. Such simulation capabilities enhance both safety and plant utilization.

Training simulators cannot accommodate the necessary model complexity to achieve simulation fidelity while simulating at real-time speed within the computing capacity of a minicomputer.[1, 2, 3] Reactor manufacturers cannot fully utilize computer-aided design optimizations because their design codes are executed predominately on expensive mainframe computers in time-consuming batch mode.

Several detailed licensing codes have been developed in the U.S.A. (TRAC-PF1;[4] TRAC-BD1[5] and RELAP5[6]), in France (CATHARE[7]) and in Germany (DRUFAN[8]), which have grown to be so expensive to execute that needed simulations must often be forgone. These codes, when executed on large mainframe computers, take 10 to 100 times as long as the simulated transient takes in the reactor. The utilization of these codes depends increasingly on the availability of expensive supercomputers.

A number of attempts have been made recently to achieve real-time simulation speed (e.g., TOKRAC[9]), but invariably at the expense of compromises with regard to either modeling fidelity or simulation scope. Specifically, real-time simulation speed is attempted often by approximating what is actually nongomogeneous, nonequilibrium coolant flow behavior with a simple homogeneous equilibrium model, or by using coarse nodalization schemes and large integration time steps or by simply excluding important portions of the plant from the simulation. Needless to say, the resulting simulation capabilities are severely limited.

In summary, currently available simulation methods are either too expensive, too time-consuming, or, with regard to modeling fidelity, inadequate for efficient on-line simulations in support of nuclear power plant operations. A low-cost facility has now become available which can be fully dedicated to the staff of a particular plant, which is easy and convenient to use, which simulates realistically normal and severe off-normal events faster than with real-time

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speed and which can also interact on-line either with the power plant or, via telephone line, with a remote user.

The newly developed facility is the BNL Plant Analyzer, currently set up for BWR plant simulations. The plant analyzer is an outstanding tool for safety analysis, for optimization of design changes or emergency procedures and for supporting risk assessment, human factors research and generic training. The new technology can also serve for dynamic plant monitoring, failure diagnostics and for assistance in optimizing recovery strategies after an accident.

Below we present the principles and techniques used to achieve the high-speed, low cost simulation in a special-purpose minicomputer. We also show some results and discuss potential applications of this new technology.

INTEGRATED CONCEPT OF SIMULATION

The development of a simulation capability is expediently explained in a progressive sequence of distinct simulation activities, starting with the formulation of mathematical models and continuing with the application of numerical methods, selection of computer architecture, program implementation, and finishing with assessment or validation. Efficient simulation mandates, however, that an integrated concept be established at the outset, with all these elements simultaneously optimized in principle, both individually and as a whole. What is described below in sequence, actually evolved during the planning stage simultaneously as a single concept of synergism. Simulation objectives dictated the selection of numerical integration techniques, which in turn determined the choice of an optimum combination of computer architecture and programming language. Yet the computer architecture influenced in turn the formulation of mathematical models. Only the careful selection of modeling and programming techniques and the deliberate choice of a particularly suitable special-purpose computer has led to a new and unique concept for simulation and to achievements, which are impossible with conventional methods, standard FORTRAN programming and general-purpose computers, even supercomputers.

ADVANCED MODELING PRINCIPLES

The central problem of Light Water Reactor (LWR) plant simulation is the realistic and accurate modeling of two-phase flow thermohydraulics in reactor vessels and, where appropriate, in pressurizers and steam generators. Neutron kinetics and balance of plant simulation, while taxing computing capacity and input/output processing, is effectively achieved with well-known mathematical models. Consequently, the coolant dynamics simulation dominates the modeling strategies.

Modeling efficiency is achieved when the greatest possible simulation fidelity is accomplished with the smallest possible number of arithmetic and logical operations. It is achieved by the following five principles:

1. Model Selection

Select the least complicated thermohydraulic model for two-phase flow which accommodates all the available experimental information on two-phase flow.

There are three-, four-, five- and six-equation models for two-phase flow.[10] The three-equation model is the simplest but also the most restrictive model. It has three conservation equations for mass, momentum and energy of the gas-liquid mixture. Along with the thermal and caloric equations of state (two intrinsic constitutive laws) and with correlations for mixture wall shear, mixture form loss and convective heat transfer between walls and the mixture (i.e., three extrinsic constitutive laws), the three-equation model describes homogeneous equilibrium flow. It implies three restrictions: temperature, pressures and velocities must be equal in liquid and vapor phases. The model applies, therefore, to two-phase flows only under mutually exclusive conditions, namely when strong mixing occurs between the phases, while temperature and pressure change very slowly during weak heating and slow changes of coolant inventory. Thus, the model applies only to normal operating conditions (single-phase flow) in a PWR pressure vessel, but neither to the normal conditions in the pressurizer or the steam generators or a BWR pressure vessel, nor to any abnormal conditions. Particularly, homogeneous two-phase flow models are unsuitable for Small-Break Loss of Coolant Accident (SBLOCA) simulations, because phase separation dominates due to gravity and phasic density differences. Thermal nonequilibrium has a profound influence on the vapor generation rate and on cladding temperature.

Modeling restrictions are reduced by adding conservation laws and/or extrinsic constitutive laws. A slip* or a drift correlation can be added to the above homogeneous equilibrium model to simulate phase-separation when both phases are dynamically coupled as in bubble, slug, churn-turbulent and dispersed droplet flows.[10,11] Phasic mass, momentum and energy equations can be added to allow for both mechanical and thermal disequilibrium, until the maximum of six equations is reached for the two-fluid model. Phasic and mixture conservation laws can be derived from first principles.[12] Constitutive laws, however, must be derived from experiments. Extrinsic constitutive laws, such as the transfer laws for mass, momentum and energy between the phases and between each phase and the walls, are needed for every flow pattern

*Correlations must be based on relative velocity of phases, not on velocity ratio which breaks down under stagnation conditions.

and heat transfer regime.

The two-fluid model is the most complex and most rigorous model and considered by many to be the most powerful model. No model, however, can produce more information than is contained in its data base of extrinsic constitutive descriptions. Of all the models, the two-fluid model requires the largest number of such descriptions, namely, a total of seven: four correlations for momentum (friction and form losses) and heat transfer between each phase and the wall, plus three correlations for mass, momentum and energy exchange between the phases themselves. These correlations are not known now and in the near future for all reactor conditions except when the geometry of the interfacial surfaces between the phases is known, as for separated flows and for spherical bubbles and droplets of known size distributions. These phasic transfer correlations will not be known until significant advances have been made in two-phase flow instrumentation and in modeling of transfer laws.[13] All two-fluid models currently in use rely by necessity on mixture transfer correlations[4, 5, 6, 14] and on intuition.

In contrast, the four-equation drift flux model[15, 11] is intimately related to measurements, and it predicts two-phase flow phenomena well when there is tight dynamic coupling between the phases. The drift flux model describes all reactor coolant conditions except stratified horizontal flows in horizontal ducts.

The drift flux model consists of the vapor mass balance and the three mixture balances for mass, momentum and energy. Correlations for vapor drift in terms of the Zuber-Findley distribution parameter C_o[15] and the void-weighted, area-averaged vapor drift velocity $\langle v_{gj} \rangle$ are needed in addition to a correlation for vapor-generation rate Γ. The model predicts nonhomogeneous, nonequilibrium flow, that is, the phase distribution and mixture levels in the reactor vessel. It predicts subcooling, saturation and superheating in the liquid. The vapor is predominantly, but need not be assumed to be, saturated.

After carefully considering all aspects of modeling capabilities, complexities and computational efforts of simulation, one arrives at the conclusion that the drift flux is the most efficient model for reactor coolant dynamics simulation under all plant transient and SBLOCA conditions except in horizontal pipes of PWR plants under stratified flow conditions (reflux condensation). The drift flux model is always superior to the two-fluid model for BWR plant simulations because two-phase flow in vertical channels dominates, because the drift flux model is fully supported by experiments, and because it is far more economical to integrate during high-speed simulations. The indiscriminate use of the two-fluid model is unjustified because it is expensive but cannot produce information beyond its mixture model data base for constitutive relations.

2. Relevance of Phenomena

Eliminate from the models all irrelevant phenomena, while accounting for all possible flow patterns and important processes.

The implementation of this principle requires an in-depth familiarity with the system and the processes to be simulated. Such familiarity is fundamental to all of simulation, far beyond the concerns about the above principle.

An order-of-magnitude estimate, carried out for all plant conditions on all the terms of the selected mathematical model, reveals the relative significance of the phenomena represented by the individual terms. Such an analysis has been carried out for BWR simulations as part of the plant analyzer development. It was found, for example, that:

(i) Most covariance terms of time and area averaging are unimportant. This means that averaged products are set equal to products of averages. The only exception is the area-averaged product of void fraction α times volumetric mixture flux j

$$\langle \alpha j \rangle = C_o \langle \alpha \rangle \langle j \rangle \ . \qquad (1)$$

Here C_o is the Zuber-Findley distribution parameter.

(ii) The pressure distribution ∇p throughout the reactor vessel is too small to affect phasic property calculations, whence $\nabla p = 0$. Pressure disturbance can be taken to propagate instantly through the pressure vessel. Pressure gradients must be accounted for, however, in the momentum balance.

(iii) Mechanical energy is irrelevant in the energy balance.

(iv) Virtual mass effects are irrelevant except near the break.

High-speed simulation in minicomputers is not possible without the judicial elimination of irrelevant arithmetic operations.

3. Analytical Techniques

Execute as many integrations analytically as possible and evaluate the analytical solution dynamically during the simulation. Reduce algebraic expressions and implicit systems of equations analytically to their simplest form.

In conventional simulation codes, the governing partial differential equations are mechanically replaced by finite difference equations by following an adopted scheme of, for example, backward time differencing and donor-cell space differencing. The result is a huge system of nonlinear equations. Even after elaborate simplifications, there still remains invariably the herculean task for the computer to solve a large system of nonlinear equations iteratively.

Standard and advanced numerical intergration methods are afflicted with problems of unspecifiable truncation error accumulation, unspecifiable numerical diffusion, growth of round-off errors (numerical stability), numerical stiffness and convergence. Analytical solutions are transparent and amenable to quantitative error estimates. Analytical integration eliminates problems of numerical integration and contributes significantly to high simulation speed and efficiency, even though its implementation requires more time and judgment than conventional techniques.

Thus, instead of integrating the boron transport equation

$$\frac{\partial C_B}{\partial \tau} + \nabla \cdot (\vec{v}_\ell C_B) = 0 \qquad (2)$$

numerically and then averaging the volumetric boron concentration C_B over the core region to obtain the core average $\langle C_B \rangle$ for reactivity feedback in a BWR vessel, one can integrate analytically Equation (2), first for the injection and mixing region of the lower plenum, and then along the coolant flow path in the vessel.[16] One needs to recognize that the coolant flow is, under conditions after boron injection, quasi-steady relative to the time τ_{cy} it takes the liquid to circulate through core and downcomer and that the velocity gradient $\partial w_\ell/\partial z$ in flow direction can be approximated in the core by its mean value. Analytical integration yields for a circulation cycle $0 \le \tau < \tau_{cy} = \sum_i (L/w_\ell)_i$

$$\frac{\langle C_B \rangle}{(C_B)_{inj}} = \frac{\beta}{\kappa} \left\{ \frac{1}{\xi} \left(1-e^{-\xi\hat{\tau}}\right) - \frac{e^{-\xi\hat{\tau}} - e^{-\hat{\tau}}}{1-\xi} \right\} \qquad (3)$$

$$\text{for times } \tau < (L/\bar{w}_\ell)_c$$

$$= \frac{\beta}{\kappa} \left\{ \frac{1}{\xi} \left(1-e^{-\xi\kappa}\right) + \frac{1-e^{\kappa(1-\xi)}}{1-\xi} e^{-\hat{\tau}} \right\}$$

$$\text{for } (L/\bar{w}_\ell)_c \le \tau < \tau_{cy} . \qquad (4)$$

For subsequent circulation cycles one needs only to superimpose the solution of Eqs. (3) and (4) on the previous solution. The analytical solutions depend only on four characteristic parameters, three of which are fixed during a cycle: $\beta = (A\bar{w}_\ell)_c / (A\bar{w}_\ell)_{inj}$, $\kappa = L_c/(\bar{\tau}_m \bar{w}_\ell)$ and $\xi = \bar{\tau}_m / (\overline{\partial w/\partial z})$, while $\hat{\tau} = \tau/\bar{\tau}_m$ varies with time τ. Here A and L designate cross-sectional area and channel length, w_ℓ is the axial velocity component and $\bar{\tau}_m = V_{LP}/(A\bar{w}_\ell)_c$ is the characteristic time of mixing in the lower plenum volume V_{LP}. Subscripts c and inj designate core and injection, respectively. All parameters are known from hydraulics calculations.

The above example shows that the analytical solution, according to Eqs. (3) and (4), has no numerical diffusion or other errors of numerical integration. All assumptions and approximations are transparent. The results shown in Figure 1 below are copied from the monitor of an IBM-PC remote access terminal of the BNL Plant Analyzer and are the same as obtained from expensive detailed numerical integration.

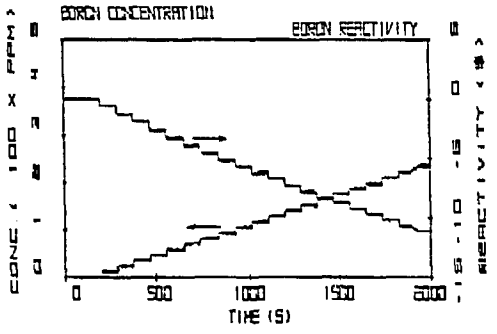

Fig. 1 Boron Concentration and Boron Reactivity During Natural Circulation Conditions of an MSIV-ATWS Event (43 GPM and 75% Mixing Efficiency)

4. Elimination of Iterations

Execute in advance all iterative procedures required for solving implicit nonlinear equations and tabulate the results in terms of explicitly known variables. Then interpolate the resulting multidimensional tables during the simulations.

This principle utilizes the availability of large low-cost memory capacities in modern minicomputers and the unique capability of interpolating at high-speed multidimensional tables, a capability which is found in the special-purpose peripheral processor for efficient high-speed simulation: the AD10 of Applied Dynamics International.

Conventional simulation codes sometimes carry out these time-consuming iterations at every time step. More frequently, however, implicitly specified unknowns are simply approximated by their past-time-step values. This time-skewing introduces in every time step, an error which is proportional to the time step size and the accumulation of which cannot be made arbitrarily small by time step size reduction.

The BWR plant simulation in the BNL Plant Analyzer has demonstrated that the use of pretabulated results from iterative solutions to implicit equations reduces the number of arithmetic operations during the simulation by one or two orders of magnitude.

5. Function Tabulations

Combine analytically in every equation all constitutive relations (material properties, correlations for exchange of mass, momentum and energy, etc.) into the smallest possible number of composite expressions. Then evaluate and tabulate the expressions for the whole range of state variables and interpolate the tables during the simulation.

It has always been thought that the evaluation of expressions produces more reliable results in computer simulations than table interpolation. However, since inexpensive computer memory has become available, data tabulations with extremely fine entry increments is affordable, and the table interpolations of thermodynamic properties has become increasingly popular. Conventional property tabulations involve two-phase functions for elementary properties such as temperature, density, specific heat or thermal conductivity. Such elementary functions appear rarely alone in a balance equation. Instead, properties appear in particular combinations in particular equations. As an example, the ratio

$$f(p,h)_m = (\rho_g h_g - \rho_m h_m)/(\rho_g h_g - \rho_f h_f) \qquad (5)$$

depends only on pressure p and mixture enthalpy h_m but involves the elementary functions of phasic density ρ and enthalpy h along the liquid (subscript f) and the vapor (subscript g) saturation lines and the composite function for mixture density

$$\rho_m(p,h)_m = \rho_f\rho_g/[\rho_g + (\rho_f-\rho_g)(h_m-h_f)/(h_g-h_f)] \qquad (6)$$

Evaluation of the elementary functions (rational polynomials), requires about 40 to 80 arithmetic operations (depending on range and accuracy of expressions). The evaluation of the ratio f above requires an additional 15 arithmetic operations. All this effort can be eliminated by carrying out a single two-dimensional table interpolation.

Completeness of Model Formulation. The formulation of mathematical models must be complete in its analytical form. It must be independent of any numerical solution algorithms, so that it describes the physics of the system to be simulated.

Several systems codes[5] contain discretization parameters such as time steps $\Delta\tau$ or spatial increments Δz, or they rely for local fluid descriptions on information from "adjacent cells" or previous time steps. Only the description of the solution algorithm, to be coded for computer execution, may contain discretization parameters.

The analytical problem formulation must have stable solutions for stable processes. The solutions must depend continuously on initial and boundary conditions.

Application of Modeling Principles. The above five principles have been used to implement the four-equation drift flux model in the BNL Plant Analyzer for BWR plant simulations. Below we show the consequences from applying the first three principles to the four partial differential equations for the conservation of vapor mass, mixture mass, momentum and energy.

$$\text{The system pressure } \langle p\rangle = \frac{1}{V_v}\int_{V_v} p\,dV \qquad (7)$$

is computed by integrating analytically[16] the volumetric flux divergence equation over the vessel volume V_v, by using the caloric equations of state for liquid and vapor and the phasic energy balance equation for the liquid, and then by integrating numerically this ordinary differential equation in time τ

$$\langle\dot{p}\rangle = \{(Aj)_{fw} - (Aj)_{s\ell} + \sum(Aj)_{inj} + \int_{V_2}\frac{\rho_\ell-\rho_g}{\rho_\ell\rho_g}\Gamma_v dV - \frac{1}{\rho_\ell^2}\left(\frac{\partial\rho}{\partial u}\right)_p\left[\int_{A_1} q''_w dA + \int_{V_1} q'''_\ell dV\right]\Big/ \left[\int_{V_2}\alpha\frac{\rho'_g}{\rho_g}dV + \int_{V_1}\frac{1}{\rho_\ell}\left(\frac{\partial\rho_\ell}{\partial p}\right)_u dV\right]. \qquad (8)$$

Previously not defined symbols in Eq. (8) are u, q''_w, q'''_ℓ, Γ_v and α for internal energy, wall heat flux, gamma heating power density, vapor generation rate per unit volume, and void fraction, respectively. V_1 and V_2 designate single-phase liquid and two-phase mixture or vapor, respectively. Subscripts fw and sℓ denote feedwater and steam line, respectively, g and ℓ denote saturated vapor and general liquid, respectively, and superscripted prime means differentiation with respect to pressure, superscripted dot with respect to time. The pressure $\langle p\rangle$ is used for all property calculations.

The partial differential equation for momentum conservation is integrated analytically along four closed contours in the pressure vessel and recirculation loop to yield the loop momentum balances for the average, the hot and the bypass channel loops and for the recirculation loop. The result for the three vessel loops is

$$\frac{dM_j}{d\tau} = \Delta p_{JTP} - \sum_{i=1}^{N_{s,j}}\{g_z\langle\rho_m\rangle + \frac{1}{2d_h}\int_0^L \frac{f_{\ell o}\phi^2_{\ell o}}{\rho_\ell} G_m|G_m|dz\}_{ij}$$

$$+\frac{1}{2}\sum_{\substack{i=1\\ i\neq JTP}}^{N_{s,j}}\{(w_\ell G_\ell + w_g G_g)^+ - (w_\ell G_\ell + w_g G_g)^-\cdot$$

$$\left[1+\left(\frac{\bar{A}}{A_{min}}\right)^2\zeta\right]\}_{ij}\ ,\quad j=1,\ldots,3\ . \qquad (9)$$

Here $\mathcal{M}=\oint_m G\,dz$ is the loop momentum, Δp_{JTP} the pressure rise across the jet pumps; g_z, G, $f_{\ell o}$, $\phi^2_{\ell o}$ and ζ designate, respectively, gravitational constant, mass flux ρw, wall shear, two-phase friction multiplier and form loss coefficient. Superscripted $-$ and $+$ designate up and downstream conditions at locations of sudden changes in cross-sectional area A, A_{min} is the smaller cross section at such changes, d_h is the hydraulic diameter. The ordinary differential equations, Eqs. (9), are integrated numerically. The result is used to compute for every loop the time-dependent starting value $j_m(o)$ in the integral of the volume flux divergence equation,* integrated along the flow path

$$j_m(z) = j_m(o) + \frac{\rho_\ell - \rho_g}{\rho_\ell\rho_g}\int_o^z \Gamma_v d\check{z} - \frac{\rho'_g}{\rho_g}\cdot\langle p\rangle\int_o^z \alpha d\check{z}$$

$$-\frac{1}{\rho_\ell^2}\left(\frac{\partial\rho_\ell}{\partial u}\right)_p\left\{\int_o^z[(1-\alpha)q''_w\frac{C}{A}\,d\check{z} - h_{fg}\int_o^z\Gamma_v d\check{z}\right.$$

$$\left.+\int_o^z(\alpha-1)q'''_\ell d\check{z}\right\}\ . \qquad (10)$$

Equation (10) yields the axial variation $j_m(z)$ of the volumetric mixture flux, which is the central kinematic reference of the drift flux model needed to compute the phasic fluxes $j_g = \alpha(C_o j_m + v_{gj})$ and $j_\ell = j_m - j_g$. Notice that, after substitution of Eq. (8) into Eq. (10), a simple numerical quadrature over axial distance z suffices to integrate the partial differential equation of mixture mass conservation.

The vapor mass (m_g) and the mixture energy equations are integrated over individual computational cells in the reactor vessel

$$\left(\frac{dm_g}{d\tau}\right)_j = V_j\langle\Gamma_v\rangle_j + (AG_g)_{j-1} - (AG_g)_j\ , \qquad (11)$$

$$V_j\left(\frac{d\langle u_m\rho_m\rangle}{d\tau}\right)_j = [A(G_\ell h_\ell + G_g h_g)]_{j-1} - [A(G_\ell h_\ell + G_g h_g)]_j$$

$$+ L_j[\langle q'_w\rangle + A\langle(1-\alpha)q'''_\ell\rangle]_j\ ,$$

$$j=1,\ldots,54\ ,\ G>0 \qquad (12)$$

*Area averaging is implied here for j_m, Γ_v, α and q'''_ℓ.

and are the only two out of four field equations which are integrated conventionally. Equation (11) yields the void fraction $\langle\alpha\rangle$ and Eq. (12) yields the liquid temperature $\langle t_\ell\rangle$ at locations z_j.

Equations (8) through (12) are supplemented with mass jump conditions producing the equation of motion for mixture levels.[17] This then completes the set of state equations governing the coolant dynamics. For details on constitutive relations we refer the reader to References 16 and 17. Integral techniques for thermal conduction are discussed in Reference 18.

EFFICIENT INTEGRATION METHODS

Computer simulations of transient processes in nuclear power plants involve either the solution to large systems of coupled transcendental equations or the integration of large systems of nonlinear first-order differential equations.[10] Transcendental equations arise from the simultaneous discretization in time and space of the governing field equations. Ordinary differential equations arise from space discretization, from cell averaging and from lumped-parameter modeling.[18]

Numerical integration techniques are either implicit or explicit. An algorithm integrates over time explicitly if it produces the future state $\underline{y}^{k+1}$ of the simulated system from the present and possibly from the past states only, $\underline{y}^{k+1} = \underline{F}(\underline{y}^k, \underline{y}^{k-1}, \ldots, \tau^k)$. Otherwise the algorithm is implicit.

Implicit integration involves iterative solutions to transcendental equations. The associated frame time T_i, or clock time required for advancing the entire simulation from one time level (k) to the next level (k+1), is orders of magnitude larger than the frame time T_e associated with straight-through calculations for explicit integration.

The permissible integration step size H is controlled by accuracy and stability requirements. Completely implicit integration schemes can be unconditionally stable and are limited only by accuracy requirements, while explicit schemes are normally of higher-order accuracy but only conditionally stable.

Because of a history in core physics calculations, there is a predominant preference in the nuclear industry for implicit integration schemes. Computing accuracy is often ignored in the preoccupation with stability.[19] Stability is absolutely necessary but not sufficient.

The rational choice between explicit and implicit integration schemes is based upon (i) the frequency f_ν of system stimulants (input data) and system responses (expected output data), (ii) the permissible integration step sizes H_i and H_e for implicit and explicit integration, respectively, and (iii) the frame times T_i and T_e.

The abscissa in Figure 2 below represents the relevant frequency f_ν of system stimulation tion and response, with the steady state at the left and with extremely rapid transients at the right. The frame times T_i and T_e are system independent since they depend only on the number of arithmetic and logical operations carried out in one time step. The vertical time scale is logarithmic and shows that the frame time is much larger for implicit algorithms than for explicit ones. The permissible time step size H_i for unconditionally stable schemes depends on truncation errors, i.e., on high-order derivatives which increase with f_ν, causing H_i to decrease with increasing f_ν. The permissible time step size H_e is larger than H_i because explicit schemes are frequently of higher-order accuracy (i.e., Runge-Kutta methods[20]). However, H_e cannot exceed its stability limit as indicated by the horizontal segment of the H_e-curve in Figure 2.

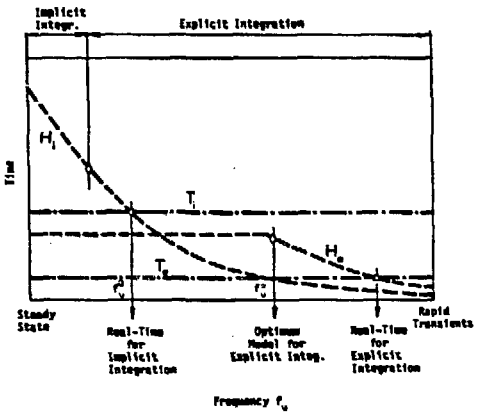

Fig. 2 Selection of Optimum Integration Method H Permissible Time Step, T Frame Time

The intersections of T and H curves give the relevant simulation frequencies for real-time computing speeds (H/T = 1). It is clear that explicit integration is superior for fast transients, and implicit for slow, near quasi-steady transients. An optimum model formulation can be achieved by eliminating irrelevant frequency content or numerical stiffness [i.e., sound propagation in liquid, cf. Eq. (8)] from the model so that an explicit scheme integrates for most transients of interest with the permissible step size lying just below the stability limit. The ratio H/T is the simulation speed ratio of simulated time over computer run time.

Figure 2 above shows that the maximum speed for explicit integration ratio H_e/T_e produces reliably the system response frequencies $f_\nu \leq f_\nu^e$. The same or better speed ratio can be achieved by implicit integration only for frequencies less than or equal to f_ν^0. This suggests the range of desired response frequencies for the two integration methods as indicated at the top of Figure 2.

Figure 2 is drawn only qualitatively and it applies only in principle to a particular time step. With appropriate weighting, one can apply the presented principles to variable time steps as well.

The TRAC code requires, on a CDC-7600 computer, the frame time per computational cell of approximately 3 milliseconds. For 200 cells in a model, one finds $T_i = 0.6$ sec. When simulating with TRAC an oscillation of interest with frequency f_ν by computing only 10 points per period, one can achieve real-time or faster simulation speeds ($H/T \leq 1$) only for system response frequencies $f_\nu \leq 0.17$ Hz. Small-break LOCA events produce 10 Hz, large-break LOCAs may produce 100 Hz (flow oscillations) system responses.

Explicit integration appears superior for simulating transients in LWR systems, but implicit integration may be superior for HTGR system simulations. The frame time for implicit integration (matrix inversion) must be reduced by two orders of magnitude below the time needed on current large mainframe computers (CDC-7600) before implicit integration can be used for high-speed simulation.

SPECIAL-PURPOSE COMPUTER

Nuclear power plant transients can be realistically simulated in minicomputers, mainframe computers or supercomputers. Mainframe and supercomputers, however, are too expensive for efficient high-speed interactive simulation because their operating cost is high and, being general-purpose computers, they cannot achieve the simulation speed of special-purpose computers for simulation. Program vectorization has produced only very modest improvements in computer speed for hydraulics codes, even on supercomputers. Minicomputers offer low-cost alternatives, they can be dedicated to the exclusive simulation of a specific plant for both plant management and operator assistance.

Array processors are widely available as minicomputers and often promoted for parallel processing of complex simulation codes. Such array processors consist of two or more identical central processing units. Array processors were originally developed for signal processing and are very powerful when operating in parallel on independent data streams, as from independent sensors (CAT scan, for example). They are far less useful for simulations because simulation codes cannot be separated into many independent segments for parallel processing, without inadmissible time-skewing or adverse idling of some of the processors.

AD10 Processor

Applied Dynamics International (ADI) in Ann Arbor, Michigan (USA) has developed the special-purpose peripheral processor AD10 particularly for high-speed simulations of complex systems.[21] Specifically, the AD10 is designed to integrate numerically large systems of nonlinear ordinary differential equations at high speed, low cost and with the convenience found only on analog computers. The AD10 is programmed in the high-level systems simulation language MPS10 which is superior to FORTRAN for simulation. MPS10 was developed and is maintained by ADI. The AD10 is programmed by a PDP-11 or VAX host computer but carries out all simulation tasks independently from the host. The AD10 is the central and indispensable hardware component of the BNL Plant Analyzer.

The BNL Plant Analyzer contains two AD10 units. Each AD10 contains six distinct, task-specific processors which operate in parallel and are synchronized at the computing cycle frequency of 10 MHz. The six processors serve (i) to link the AD10 with the host computer, (ii) to time and control the other five processors, (iii) to execute logical decisions and binary searches for table interpolation, (iv) to execute additions, subtractions and multiplications in integer or fractional arithmetic, (v) to carry out numerical integrations, and (vi) to address memory. Two additions and one multiplication can be carried out in one cycle, resulting in 30 million fractional operations per second. Twenty million words can be transferred each second between memory and processors. Internally generated digital data can be issued as digital data at the rate of 3 million words per second or converted to analog signals in the range from -10 volt to +10 volt. Input signals can be accepted as digital (3 million words per second) or analog signals (±10 volt).

The AD10 distinguishes itself from array processors, as it has six distinct, task-specific processors which work in parallel to carry out specific simulation tasks (function generation, integration, etc.) while executing code instructions in sequence. Each processor has its own instructions built in (furnished by ADI), has its own pipeline architecture for high-speed execution and is invoked by the programmer with a simple call statement.

Simulation Capabilities

The two AD10 processors installed at BNL can integrate as many as 1,950 state equations, with any combination of 17 built-in algorithms, such as first through fourth orders Adams-Bashford or Adams-Moulton and second through fourth orders Runge-Kutta procedures. The mix of algorithms can be altered with a single keyboard command, on-line and without reloading the program.

The two processors can generate as many as 18 nonlear functions of one variable, plus 34 functions of two variables, plus 12 functions of three variables in as little as 98 microseconds, regardless of the functions complexity. This feature is utilized by Modeling Principles 4 and 5.

Up to 256 input and output analog channels can be scanned for every computing frame. This makes the outside world (instrumentation and controls in a power plant) part of central core memory.

The BWR plant simulation presented here entails 530 integrations with 4,500 subroutine or module calls, including the interpolation of over 250 nonlinear multidimensional tables, many as often as 54 times during every computing frame. All of this is achieved in the frame time T = 6 ms. The maximum integration step size is H=54 ms, producing a nine times greater than real-time simulation speed. Twenty-eight analog channels are scanned 165 times per second to introduce operator actions and malfunctions any time before or during the simulation. Sixteen output channels are currently updated 165 times per second for graphic display and storage of computed results. This capability is indispensable for computer-aided emergency response.

Remote Access Capability

The BNL Plant Analyzer can be accessed and operated remotely by telephone from an IBM Personal Computer (PC) anywhere in the U.S. and in Europe. The IBM-PC must have at least 128 kbyte of memory, an RS-232 serial port connected to the telephone line through a 1200 baud modem, a Plantronics PC + Colorplus graphics adapter card, and a standard R-G-B color monitor.

The plant analyzer accepts via the IBM-PC keyboard operator actions and malfunction signals on-line interactively and displays simulated plant responses on-line in graphical or tabular form. In remote access mode, the simulations are four times faster than real-time speed.

SIMULATION ACHIEVEMENTS

Figure 3 shows the flow diagram of the BWR-4 power plant being simulated in the BNL Plant Analyzer. The control systems are shown in Figure 4. Figure 5 shows the details of nodalization in the reactor vessel.

The plant analyzer reliably simulates the consequences from any combination of a large number of malfunctions, including transients with system pressurization or depressurization, with moderator temperature changes, reactivity changes, loss or excess of inventory, core flow changes and control system failures. ATWS events induced by multiple failures can be simulated. Procedures following the Emergency Procedure Guidelines have been simulated as described in a companion paper by H.S. Cheng et al.

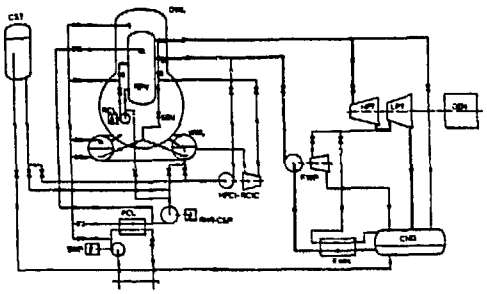

Figure 3 BWR-4 Flow Diagram

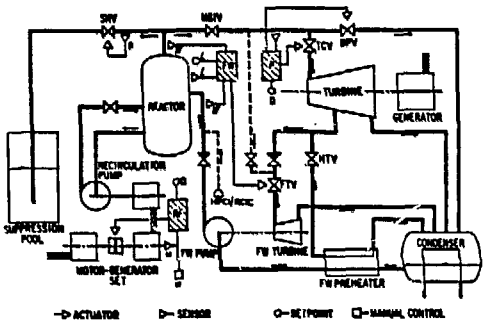

Figure 4 Flow and Control Diagram

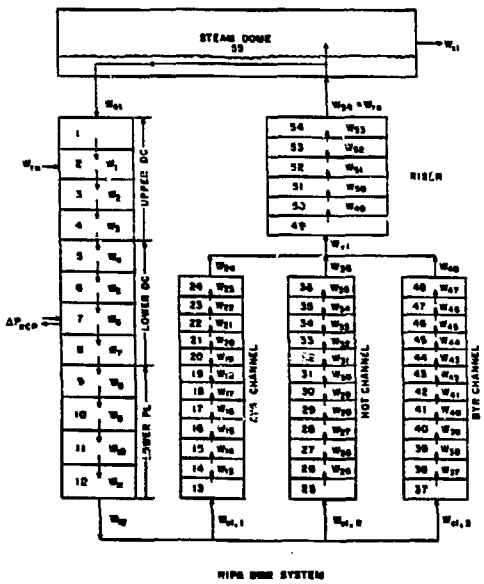

Figure 5 Nodalization Scheme for Pressure Vessel

The plant analyzer simulates SBLOCA events, induced by safety and relief valve failure, and steam line breaks outside the containment.

The plant analyzer accepts both analog input (from controls and instruments) and digital input data (from the SPDS system, for example). This capability affords direct coupling of the plant analyzer to a nuclear power plant for supporting plant operations. This feature also makes it possible to enter operator actions or malfunctions directly, on-line, into the plant analyzer, thereby producing instant plant responses without interrupting the simulation process.

The plant analyzer simulates at speeds which are two-orders-of-magnitude faster than the CDC-7600 and completes a simulation in about one-ninth of actual process time. High simulation speed and user convenience in the BNL Plant Analyzer have been shown to achieve the simulation, evaluation and documentation of over 30 different transients in less than four days.

Plant analyzer results have been successfully compared with BWR/4 plant data (Peach Bottom turbine trip tests*) and for over 30 different transients, with results from TRAC-BD1, RELAP5, RAMONA-3B and GE calculations.[16] These comparisons demonstrate that the plant analyzer reliably simulates the consequences from a large number of multiple failures in components and control systems. Figures 6 and 7 show two typical comparisons of plant analyzer results with RELAP5 and RAMONA-3B. Operating data from plants are needed to continue the assessment.

CONCLUSIONS

It has been demonstrated that the combination of five advanced modeling principles with available modern special-purpose minicomputer and software technologies achieves simulations of normal and accidental transients in nuclear power plants at high speed, low cost and with convenient on-line interactive access. This newly developed technology is implemented in the BNL Plant Analyzer.

The BNL Plant Analyzer is now the only operating facility that carries out realistic and accurate BWR plant simulations at speeds two-orders-of-magnitude faster than the CDC-7600 mainframe computer executing FORTRAN code. The plant analyzer is accessible to remote users by standard telephone. The plant analyzer meets the needs of the USNRC, of utilities and institutions with limited access to large computers. The BNL Plant Analyzer can be used to extend currently limited capabilities of full-scope training simulators. It can be used to monitor plant performance, to diagnose system faults and to assist in the optimization of remedial strategies after an accident.

*Comparison carried out with FORTRAN version in CDC-7600 prior to model implementation plant analyzer.

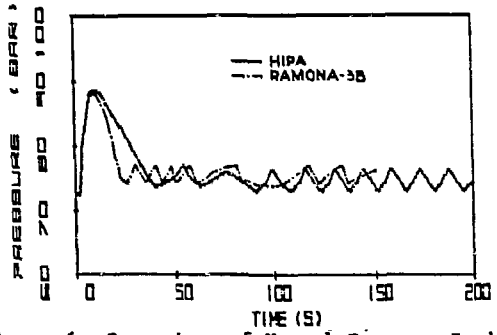

Figure 6 Comparison of Vessel Pressure Predictions from Plant Analyzer and RAMONA-3B Code

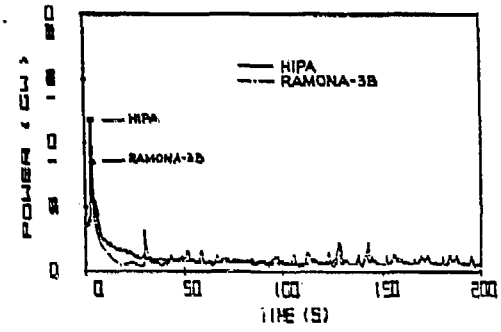

Figure 7 Comparison of Fission Power Predictions from Plant Analyzer and RAMONA-3B Code

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