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FASTER-THAN-REAL-TIME SIMULATION OF NUCLEAR REACTOR ACCIDENTS: THE TRAC-NPA CODE*

by

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ABSTRACT

A reactor safety code that provides faster-than-real-time capabilities greatly enhances the effectiveness of an analyst. We have developed a new version of the Transient Reactor Analysis Code, TRAC-NPA, which is capable of running many one- and three-dimensional transients faster than real time on current computers. TRAC is an Eulerian finite-difference code designed to model transient, two-phase, multidimensional, steam-water flow in nuclear reactors. TRAC-NPA is fast running both because it employs the efficient stability-enhancing two-step (SETS) numerical method and because much of the coding is vectorized. Adaptation of TRAC for computers with parallel architectures can further increase the computational speed. We anticipate that new generations of supercomputers will allow creative new uses for reactor safety codes running significantly faster than real time.

TRAC-NPA has been coupled to an interactive graphics executive to create a version of the Nuclear Plant Analyzer. The features of the executive include instantaneous user-friendly display of calculational results, replay, restart with parameter variation, and interactive simulation of operator actions. The graphics executive thus provides an interface that can further enhance the effectiveness of an analyst when the underlying safety code provides faster-than-real-time simulation.

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I. INTRODUCTION

The Transient Reactor Analysis Code (TRAC)[1] is an advanced best-estimate systems code for analyzing light-water reactor (LWR) accidents. It is being developed at the Los Alamos National Laboratory under the sponsorship of the Reactor Safety Research Division of the US Nuclear Regulatory Commission (NRC). TRAC is used around the world for reactor safety applications.

A preliminary TRAC version was completed in December 1976. The first publicly released version was TRAC-P1 (Ref. 2), completed in December 1977. Later versions, primarily TRAC-PD2 and TRAC-PF1, have been released to over 60 organizations. The last code in the TRAC series, TRAC-PF1/MOD1 (Ref. 3), was ready to be released in July 1983. An extension of TRAC-PF1/MOD1, TRAC-NPA, was designed especially for real-time simulation. TRAC-NPA is described in Sec. IV.

The TRAC code originally was designed primarily for the analysis of large-break loss-of-coolant accidents (LOCAs) in pressurized water reactors (PWRs). However, following the Three-Mile Island (TMI) accident, the necessity for analysis of longer term small-break transients became very apparent. The semi-implicit numerical method used in TRAC-PD2 and earlier TRAC versions is adequate for shorter term large-break transients but is extremely inefficient for slower transients; that is, the time-step sizes resulting from the material Courant stability limit of the semi-implicit method are much smaller than reasonable error control requires. An obvious cure for this problem is the use of a fully implicit numerical method; however, this alternative is not attractive because it requires substantial changes in the TRAC code and multiplies the cost per cell per step of the fluid-dynamics solution by a factor of six. The stability-enhancing two-step (SETS) method[4] was created to improve the running time of the existing TRAC code with minimal impact on the code structure and results. The SETS method, described in Sec. II, eliminates the material Courant stability limit by adding a stabilizer step to the basic semi-implicit equations. This method increases only the computation cost per step by 20 to 50%.

The SETS method was implemented for the one-dimensional hydrodynamic components of TRAC-PF1 and TRAC-PF1/MOD1 and has resulted in faster running times for systems that are modeled using only the one-dimensional components. For example, the Semiscale Mod-3 small-break test was run ~10 times faster using TRAC-PF1 as compared to TRAC-PD2. A one-dimensional simulation of a TMI-type accident runs 10 times faster than real-time on a Cray-1S computer when the SETS method is used. The success of the one-dimensional SETS method led us to formulate a three-dimensional extension that has been incorporated into the TRAC-NPA code.

TRAC provides for variable-dimension fluid dynamics; that is, a complete three-dimensional flow calculation can be used wherever necessary for accurate modeling of multidimensional flow patterns; the flow within the other components then is treated one dimensionally. The availability in TRAC-NPA of the SETS method for both one- and three-dimensional hydrodynamic components increases the variety of transients that can be simulated accurately in real-time.

II. THE SETS METHOD

To demonstrate the SETS numerical method,[4] we consider a simplified model for one-dimensional, single-phase flow in a horizontal pipe. The differential equations for this model are

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho V = 0 \quad , \tag{1}$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot \rho e V = -p \nabla \cdot V \quad , \tag{2}$$

and

$$\frac{\partial V}{\partial t} + V \cdot \nabla V = -\frac{1}{\rho} \nabla p - K V |V| \quad . \tag{3}$$

Here, ρ is the microscopic density, t is the time, V is the velocity, e is the internal energy, p is the pressure, and K is a wall friction coefficient that may be a function of velocity and fluid properties.

A staggered spatial mesh is used for the finite-difference equations, with thermodynamic properties evaluated at the cell centers and the velocity evaluated at the cell edges. To ensure stability and to maintain consistency with differencing in previous TRAC versions, flux terms at cell edges use donor-cell averages of the form

$$\langle YV \rangle_{j+1/2} = Y_j V_{j+1/2} \quad , \quad V_{j+1/2} \geq 0$$
$$= Y_{j+1} V_{j+1/2} \quad , \quad V_{j+1/2} < 0 \quad . \qquad (4)$$

Here, Y may be any state variable. With this notation, the one-dimensional finite-difference divergence operator is

$$\nabla_j \cdot (YV) = (A_{j+1/2}\langle YV \rangle_{j+1/2} - A_{j-1/2}\langle YV \rangle_{j-1/2})/vol_j \quad . \qquad (5)$$

where A is the area of the cell edge and vol_j the cell volume. The term $V\nabla V$ becomes

$$V_{j+1/2}\nabla_{j+1/2}V = V_{j+1/2}(V_{j+1/2} - V_{j-1/2})/\Delta x_{j+1/2} , \quad V_{j+1/2} \geq 0$$
$$= V_{j+1/2}(V_{j+3/2} - V_{j+1/2})/\Delta x_{j+1/2} , \quad V_{j+1/2} < 0 \quad . \qquad (6)$$

where

$$\Delta x_{j+1/2} = 0.5(\Delta x_j + \Delta x_{j+1}).$$

For the flow model given by Eqs. (1)-(3), the combination of basic and stabilizer equation sets can be written in several ways. One ordering that is stable even for three-dimensional, two-phase flow begins with the stabilizer step for the equations of motion, is followed by a solution of the basic equation set for all equations, and ends with a stabilizer step for the mass and energy equations. For this ordering, the SETS finite-difference equations for Eqs. (1)-(3) are

STABILIZER EQUATION OF MOTION

$$(\tilde{V}^{n+1}_{j+1/2} - V^{n}_{j+1/2})/\Delta t + V^{n}_{j+1/2}\nabla_{j+1/2}\tilde{V}^{n+1}$$
$$+ \beta(\tilde{V}^{n+1}_{j+1/2} - V^{n}_{j+1/2})\nabla_{j+1/2}\tilde{V}^{n}$$
$$+ \frac{1}{\langle\rho\rangle^{n}_{j+1/2}\Delta x_{j+1/2}}(P^{n}_{j+1} - P^{n}_{j})$$
$$+ K^{n}_{j+1/2}(2\tilde{V}^{n+1}_{j+1/2} - V^{n}_{j+1/2})\,V^{n}_{j+1/2} = 0 \quad . \qquad (7)$$

where

$$\beta = 0, \quad \nabla_{j+1/2}\tilde{V}^{n} < 0$$
$$= 1, \quad \nabla_{j+1/2}\tilde{V}^{n} > 0 \quad ;$$

BASIC EQUATIONS

$$(V^{n+1}_{j+1/2} - V^{n}_{j+1/2})/\Delta t + V^{n}_{j+1/2}\nabla_{j+1/2}\tilde{V}^{n+1}$$
$$+ \beta(V^{n+1}_{j+1/2} - V^{n}_{j+1/2})\nabla_{j+1/2}\tilde{V}^{n} + \frac{1}{\langle\rho\rangle^{n}_{j+1/2}\Delta x_{j+1/2}}(\tilde{P}^{n+1}_{j+1} - \tilde{P}^{n+1}_{j})$$
$$+ K^{n}_{j+1/2}(2V^{n+1}_{j+1/2} - V^{n}_{j+1/2})\,V^{n}_{j+1/2} = 0 \quad ; \qquad (8)$$

$$(\tilde{\rho}^{n+1}_{j} - \rho^{n}_{j})/\Delta t + \nabla_{j}\cdot(\rho^{n}V^{n+1}) = 0 \quad ; \qquad (9)$$

$$(\tilde{\rho}_j^{n+1}\tilde{e}_j^{n+1} - \rho_j^n e_j^n)/\Delta t + \nabla_j \cdot (\rho^n e^n V^{n+1})$$

$$+ \tilde{p}_j^{n+1}\nabla_j \cdot (V^{n+1}) - \bar{h}_j^n (T_{wj}^n - \tilde{T}_j^{n+1}) = 0 \quad ; \tag{10}$$

and

STABILIZER MASS AND ENERGY EQUATIONS

$$(\rho_j^{n+1} - \rho_j^n)/\Delta t + \nabla_j \cdot (\rho^{n+1} V^{n+1}) = 0 \quad ; \tag{11}$$

$$(\rho_j^{n+1} e_j^{n+1} - \rho_j^n e_j^n)/\Delta t + \nabla_j \cdot (\rho^{n+1} e^{n+1} V^{n+1})$$

$$+ \tilde{p}_j^{n+1}\nabla_j \cdot (V^{n+1}) - \bar{h}_j^n (T_{wj}^n - \tilde{T}_j^{n+1}) = 0 \quad . \tag{12}$$

A tilde above a variable indicates that it is the result of an intermediate step and is not the final value for the time step.

The material Courant stability limit is eliminated by the treatment of the terms $V\nabla V$, $\nabla \cdot \rho V$, and $\nabla \cdot \rho e V$ during the two steps. Additional robustness has been obtained with the particular form for the friction terms and the use of nonzero values of β in the $V\nabla V$ terms. These special terms for friction and $V\nabla V$ are obtained by linearizing similar terms that are fully implicit in velocity ($K_{j+1/2}^n V_{j+1/2}^{n+1} |V_{j+1/2}^{n+1}|$ and $V_{j+1/2}^{n+1} \nabla_{j+1/2} V^{n+1}$).

Equation (7) simply represents a linear system in the unknown $\tilde{V}^{n+1}$ and is solved first. Next, the coupled nonlinear system given by Eqs. (8)-(10) is solved. In practice, this is accomplished by a Newton iteration in which the linearized equations are reduced to a linear system involving only pressure variations. Once these equations are solved, V^{n+1} is known; hence, Eqs. (11) and (12) are simple linear systems, with unknowns ρ_j^{n+1} and $\rho_j^{n+1} e_j^{n+1}$, respectively.

The most significant change when the SETS method is adapted to two-phase flow is the addition of predictor motion equations for the liquid and vapor.

These equations are used to provide a better interfacial drag force in the stabilizer motion equations.

The extension of the SETS method to multidimensional flow is straightforward except for the equation of motion.[7] We found that the stabilizer equation of motion may be replaced by separate equations for the velocity components: that is, the coupling among the different velocity components from the cross-derivative expressions in the momentum flux terms of these equations may be treated explicitly.

The five- or seven-point, finite-difference approximation used in the various convective terms of the multidimensional SETS formulation results in several large, sparse, banded matrices of the order of the number of hydrodynamic cells. Fast solution of these matrices is crucial to achieving fast run times for TRAC-NPA.

The stability of the multidimensional SETS formulation was tested by running a number of different two- and three-dimensional flow problems until steady state was achieved with the maximum time step fixed at the material Courant limit and again with the maximum time step allowed to increase arbitrarily. In all cases studied, the steady states were maintained at the highest Courant number tested, that is, 40,000.

III. TRAC CHARACTERISTICS

TRAC is a transient, Eulerian finite-difference, two-field, multimaterial-component, thermal-hydraulics code. Some of its distinguishing characteristics[1] are summarized in the following paragraphs.

The thermal-hydraulic equations describe the transfer of mass, energy, and momentum between the steam-water phases and the interaction of these phases with the heat flow from system structures. Additional continuity equations are available for modeling a noncondensable as part of the gas field and a solute that moves with the liquid. Because the interactions are dependent on the flow topology, a flow-regime-dependent constitutive equation package has been incorporated into the code.

TRAC incorporates a detailed heat-transfer analysis capability for both the vessel and the loop components. Included is a two-dimensional treatment of fuel-rod heat conduction with dynamic fine-mesh rezoning to resolve both bottom flood and falling-film quench fronts. The heat transfer from the fuel rods and other system structures is calculated using flow-regime-dependent heat-transfer coefficients obtained from a generalized boiling curve based on local conditions.

TRAC is completely modular by physical component. The components in a calculation are specified through input data; available components allow the user to model virtually any PWR design or experimental configuration. This gives TRAC great versatility in the possible range of applications. TRAC component modules currently include accumulators, pipes, plena, pressurizers, pu[illegible] team generators, tees, turbines, valves, and vessels with associated internals (downcomer, lower plenum, core, upper plenum, etc.). There is also a general capability for modeling plant-control systems, trips, and operator interactions.

TRAC also is modular by function; that is, the major aspects of the calculations are performed in separate modules. For example, the basic one- or three-dimensional hydrodynamics solution algorithm, the wall-temperature field solution algorithm, the heat-transfer-coefficient selection, and other functions are performed in separate sets of routines that are accessed by the appropriate component modules.

IV. THE NUCLEAR PLANT ANALYZER

The development of a faster running version of TRAC can have significant economic value simply because of TRAC's widespread use. Even a 10% improvement in run time can save hundreds of thousands of dollars per year in computer costs. However, there are more important consequences of the fact that TRAC can be run in real-time. For the first time, interactive best-estimate engineering simulation will be possible.

We have coupled TRAC-NPA to an interactive graphics executive to create a Nuclear Plant Analyzer (NPA). A block diagram of the NPA software structure is shown in Fig. 1. The NPA provides interactive control of TRAC together with selectable color-screen display of results at run time or in playback mode. Display choices include a schematic with a color-coded representation of a selected system variable presented on a TRAC-noding diagram and a set of time-history (x-y) plots.

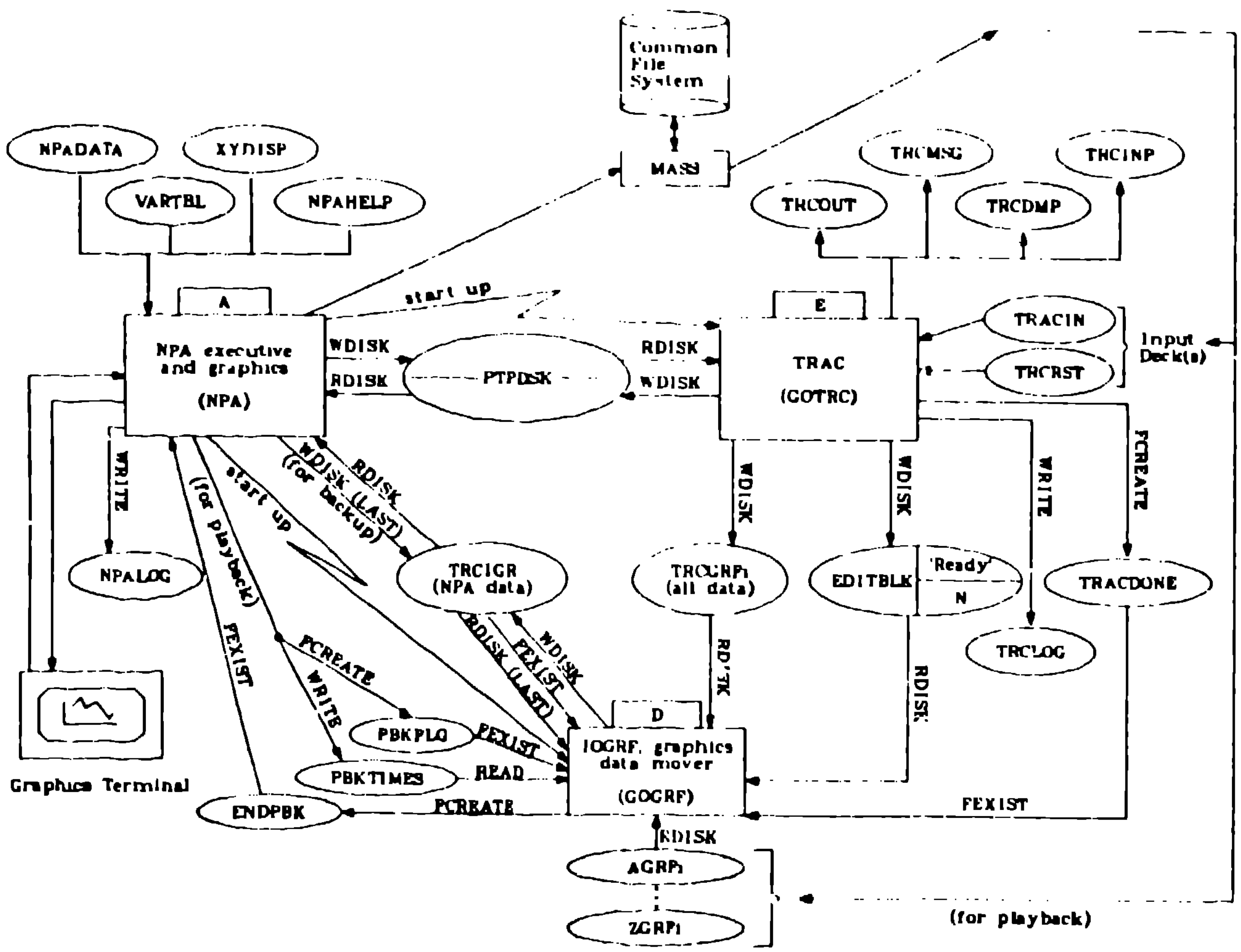

Fig. 1.
A block diagram of the NPA software structure.

There are a number of NPA objectives. The NPA makes TRAC much more accessible to untrained users. The NPA is intended to handle all interaction with the computing environment. However, it also enhances the effectiveness of the experienced analyst by facilitating input-deck preparation and debugging and by displaying results quickly in a variety of ways. For both types of users, there will be increased comprehension of results including ease of "what if" studies by permitting interactive running of transients with operator intervention. The NPA also will allow computational results to be exchanged between sites and replayed.

V. CONCLUSION

Coupling the TRAC-NPA code, which employs the SETS Courant limit violating numerics in both one-dimensional and three-dimensional hydrodynamic components, with an interactive graphics executive provides a powerful new tool for reactor safety applications.

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