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Development of Transient-Reactor Analysis Code (TRAC) for Real-Time Applications

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Abstract

This is the final report of a six-month, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Nuclear-plant training simulators employ simplified one-dimensional thermal-hydraulics codes because of the demands to run in real time and with limited computing power. The objective of this project was to investigate the feasibility of using the advanced Transient-Reactor Analysis Code (TRAC) in a simulator to increase the fidelity of a simulator. Many issues need to be addressed to take such a complex code from a batch engineering environment to a real-time environment. Working with simulator vendor, GSE, we investigated the technical issues relating to integrating TRAC into a real-time environment. We also modified a nuclear power plant model for simulator purposes and investigated its performance in real time.

1. Background and Research Objectives

Traditionally, nuclear-plant training simulators have employed simplified, one-dimensional (1D) thermal-hydraulics codes because of the demands to run in real time and with limited computing power. There has always been a desire to increase the flexibility of such training systems and to increase the fidelity of models in the simulators. Although the Transient-Reactor Analysis Code (TRAC), the state-of-the-art code for two-phase transient thermal-hydraulics systems analysis, with its three-dimensional (3D) thermal hydraulics coupled to 3D heat transfer and neutron kinetics, is the most advanced code for such applications, many issues need to be addressed to take such a complex code from a batch engineering environment to a real-time environment.

For engineering purposes, the main driver is accuracy of the computation. One must

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use sufficient spatial detail (nodding) and sufficient temporal detail (timesteps) to capture the behavior of complex two-phase phenomena accurately. The challenge that pushes the state-of-the-art is in asking that the detailed transient 3D, two-phase, thermal-hydraulic analysis be performed in real-time, lock-step with other real-time software during each timestep, and to keep running over the full duration of a transient for a wide variety of transients.

The objective of this project was to investigate the feasibility of using TRAC in a simulator. One facet was investigating the computer science aspects of integrating a batch engineering code in a real-time environment including timing, data flow, and control of actions in TRAC with respect to other parts of a real-time system. A second facet was investigating the numerical methods to use to have the physical models run smoothly, continuously, and accurately in real time. A third facet was investigating the actual runtime performance of TRAC in a real-time mode using an actual engineering plant model for a selection of transients. The outcome of this project was to determine the technical capabilities and limitations of TRAC in a real-time environment and to develop a plan to take TRAC fully into real-time simulation.

2. Importance to LANL's Science and Technology Base and National R&D Needs

This project fits with two Los Alamos core competencies: (1) modeling, simulation, and high-performance computing (MSHPC), and (2) analysis and assessment. TRAC is the only United States code that has 3D models for thermal hydraulics, reactor kinetics, heat conductors, and high-resolution solute tracking coupled together. Therefore, this tool would provide the highest fidelity calculations and, at the same time, would gain consistency between engineering analysis and real-time simulation.

One of the 1996–1998 Laboratory tactical goals is in the MSHPC core competency, which has the stated strategic direction: "Create the world's best computing to help solve critical problems in science and technology through predictive modeling and simulation." Below are two examples of how running TRAC in real time or even faster than real time will help address national technology efforts and the Department of Energy mission to provide safe, nuclear power for civilian and military uses. [TRAC is used by Knolls Atomic Power Laboratory (KAPL) for the design and safety analysis of nuclear power plants for the Navy. In the future KAPL would like to extend the use of TRAC for all of its real-time applications.]

Emergency management organizations at nuclear power plants and at the Nuclear Regulatory Commission (NRC) dream of having a high-fidelity simulation tool—first, to help

investigate an incident; second, to be constantly tracking the state of the plant; and third, in faster-than-real time to help manage the incident (e. g., to examine actions to control long-term cooling).

Another real-time application consists of a thermal-hydraulic driver for electrical engineers who test and develop instrumentation and control (I&C) systems. Again, the ability to develop a better I&C system is dependent on the fidelity of complex, nonlinear interactions among the coupled thermal-hydraulic, heat-transfer, reactor kinetics, and control system models.

3. Scientific Approach and Accomplishments

We worked extensively with GSE Systems, Inc. (GSE), of Columbia, Maryland. GSE is the foremost vendor of nuclear and fossil power plant and chemical process simulation systems in the US and has the largest installed base of power plant simulators in the world, covering every type of power plant. Los Alamos provided the expertise about TRAC, while GSE provided the expertise about real-time systems. Our efforts concentrated on (1) real-time software design techniques to integrate TRAC into a real-time simulator and (2) engineering plant models modified for use in a simulator.

Los Alamos provided GSE with a license to use TRAC, and GSE provided Los Alamos with proprietary information about their real-time software systems and hardware configurations. Together we investigated the software techniques needed to move TRAC from a batch-oriented engineering analysis to a real-time simulation environment. As a real-time code, TRAC must become a seamless part of real-time systems. We determined the division of the numerical and modeling engine in TRAC from its input/output (I/O) functions. I/O functions would be integrated with the overall simulator I/O modules. We defined the interfaces between the TRAC data structure and a common simulator database. We determined that the graphical user interface for TRAC would be a useful additional screen for the simulator and that certain TRAC output information would be routed through and integrated with other simulator displays. We investigated concepts for placing TRAC under a real-time executive controller for timestep, logic states, and I/O.

At an early stage of the investigation, we were able to learn enough to write an informal discussion paper on the real-time applications of TRAC. Together, LANL and GSE outlined technical issues related to taking a batch code into real time and taking a staged approach for developing what we would call TRAC-RT. We envisioned the following five stages.

I. Proof of Concept. In the first stage we would take the ideas and concepts developed during the LDRD project and demonstrate existing real-time capabilities and limitations by actually interfacing TRAC with a full-plant simulator in a simple way and running certain plant scenarios.

II. Initial TRAC Simulator. We would define a limited prescribed mode for TRAC in real time and build a developmental simulator. We would integrate TRAC into a modern simulator graphical user interface for dynamic and logic/control testing and verification. We would develop sufficient real-time improvements to eliminate the major limitations discovered in Phase I and to qualify TRAC-RT for limited simulator use.

III. Modernized TRAC Simulator. We would replace the current version of TRAC with a new modernized version, which uses Fortran 90 and modern streamlined data structures, taking advantage of large computer memory to make TRAC far more efficient computationally and effective in its use of data storage and transfer in a real-time multiprocessing computing environment. (The modernized version of TRAC is being produced under a separate project for KAPL and the NRC.) We would incorporate Stage II real-time improvements into the modernized version of TRAC and qualify it for limited simulator use. We would continue improving TRAC-RT performance for real time.

IV. General TRAC Simulator. We would define a general operating envelope for TRAC in real time to create a full-scope training and engineering simulator. We would optimize TRAC performance for real-time simulation over the entire operating envelope. We would develop general real-time improvements necessary to qualify TRAC-RT for the general operating envelope required by the NRC and KAPL.

V. Advanced TRAC Simulator. We would add the following new capabilities for TRAC in real time: (a) 3D conduction, 3D kinetics, and 3D high-resolution solute tracking; (b) third fluid field for droplets or bubbles; (c) stratification and wave tracking; and (d) balance of plant (BOP) models. This would produce a simulator with the same capabilities as in the engineering version (batch-mode) of TRAC and create a new world standard for simulators—the equivalent of the best engineering tools, and capabilities that far exceed today's simulators.

Los Alamos and GSE sent an informal discussion paper about TRAC-RT to the NRC and KAPL and held meetings with them about the proposed project. The paper, "Real Time Applications of TRAC," written by George Niederauer of Los Alamos and Oussama Ashy of GSE, contained "Part I. Issues Related to Real-Time TRAC," and "Part II. Proof of Concept." Part II is a proposal to perform Stage I.

Los Alamos investigated the existing real-time capabilities and limitations of TRAC. Los Alamos has a full engineering model of the H. B. Robinson-2 (HBR) power plant, a Westinghouse three-loop design, and GSE has an on-site full-scope simulator of the same plant, which uses their simplified 1D thermal-hydraulic code. Los Alamos and GSE staff met to determine the needs for a simulator model using TRAC. Los Alamos then modified its HBR plant model for a typical simulator nodalization for current generation simulators. (Of course, in the future, the goal is to provide the same detailed engineering nodalization for real-time applications as

well, but this requires both software development as well as advances in the speed of workstation computers.)

Together with GSE, Los Alamos determined the breakpoints in the nodalization, which would divide the TRAC engineering model into the TRAC simulator model and the GSE BOP model. In a simulator application, the TRAC plant model would consist of only the primary reactor coolant system components and would not include the feedwater and steam lines. The reason is that the TRAC code would be used as a thermal-hydraulic module for the primary coolant system only and would receive response of the feedwater and steam lines from another simulator module. (In an advanced TRAC simulator, these lines would also be modeled by TRAC rather than a GSE BOP model.)

Los Alamos and GSE identified an evaluation test matrix and selected the following four transients to cover a typical range of common simulator operations.

1. Partial Loss of Primary Flow (referred to as the pump trip transient). The partial loss of primary flow is the result of a trip of the reactor coolant system (RCS) pump in one loop. For this calculation, loop-1 pump is assumed to trip. A reactor trip occurs on low flow in the affected loop followed by closure of the main turbine stop valve and termination of feedwater. The unaffected RCS pumps continue to operate at normal speed. The transient continues for several hundred seconds to a quasi-steady no-load condition at decay power, full flow in the unaffected loops, and reverse flow in the affected loop.

2. Steam-Generator Overfeed Transient (referred to as the overfeed transient). The steam-generator overfeed transient results from loss of control of the feedwater system to one steam generator. For this calculation, the loop-1 feedwater control valve is assumed to fail open. Following loss of control, the feedwater system to that steam generator begins to fill the secondary at maximum flow. A reactor trip signal is generated by high secondary level, and results in control rod insertion, closure of the main turbine stop valve, and termination of feedwater. The transient continues for several hundred seconds to a quasi-steady condition at decay power and full flow in the primary system.

3. Loss of Main Feedwater Flow (LOFW). The LOFW is caused by a simultaneous trip of all feedwater pumps and affects all steam generators. Following loss of all feedwater, low inventory conditions in the steam generator secondary loops generate a reactor trip signal, which causes control rod insertion, closure of the main turbine stop valve, and termination of feedwater (redundant). As with the overfeed transient, the transient continues for several hundred seconds to a quasi-steady condition with the reactor at decay power levels and full RCS flow.

4. Steam Generator Tube Rupture (SGTR). The SGTR transient results from the rupture of one or more steam-generator tubes and leads to a slow depressurization of the primary system. For this calculation, one tube in a loop-2 steam generator is assumed to rupture. The reactor trip signal results from low primary system pressure and causes control rod insertion, main turbine stop valve closure, and termination of feedwater. As with the other transients, the calculation will continue for several hundred seconds to quasi-steady conditions with the reactor at decay power levels and full RCS flow.

We specified appropriate initial and boundary conditions for the transients. A steady-state calculation was performed with the renoded plant model. All four transients start from normal operating conditions of full power, full flow, and normal pressure. The normal systems for controlling the steam dump valves, primary inventory, and primary pressure are available for controlling the transient behavior.

Each of the transients was calculated out to 600 s with a maximum timestep size of 0.25 s. The maximum timestep size is the desired timestep size for real-time simulation applications. Because of the reaction time of operators, simulators must refresh all of the screens every 0.25 s. Each of the four transients was run by TRAC in a single, continuous calculation from beginning to end. Thus, TRAC met two of the three criteria for runtime: (1) running continuously without need for restart and (2) calculating each and every timestep with a maximum of timestep size of 0.25 s. The third criterion is to calculate the timestep a little faster than in real time to provide time for transfer of data between TRAC and other real-time software in the simulator. For this, TRAC must complete its timestep calculation in 0.9 of the real-timestep duration. Meeting this criterion depends on the computational efficiency of TRAC and the computer on which it is run.

TRAC would be run on either a dedicated processor in a multiprocessor workstation or on its own dedicated workstation. Timing calculations were performed on four different workstation platforms: a Sun Sparc 20, an HP 9000, a Sun Ultra, and an IBM RS 6000. An overall ratio of CPU time to problem time for the steady-state and four transient calculations was calculated for each platform, then extrapolated for the same cases with the feedwater and steam lines removed. With the current version of TRAC and current generation of workstations, only the IBM RS 6000 met this criterion, calculating transients in 0.85 of the real-timestep duration.

Vendors of simulators prefer other workstations such as the multiprocessor Silicon Graphics, Inc. (SGI) workstations and IBM-compatible personal computers running the NT system software on Pentium chips made by Intel. The current version of TRAC is not available on either of these machines; however, the modernized version of TRAC converted to Fortran 90 will be machine independent. Modernized TRAC should be available in late 1997. Also, the computing power of computers is increasing at a rapid rate, so that the power of other computers

besides the IBM RS 6000 should soon be capable of running the simulation problems discussed in this report in the required time.

Each TRAC calculation proceeded at the maximum timestep of 0.25 s throughout the major part of the transient for each of the four scenarios. During each scenario there was a time when the calculation proceeded at less than the maximum timestep. In each case, the reduced timestep was associated with the rapid change of power and flow conditions in the plant model, specifically following reactor trip and steam-generator secondary-side feedwater and steam line trips. Also, smaller timesteps were used during the initial part of the transient in the transition from the steady-state calculation. We identified these as areas where runtime could be improved. Some preliminary work was done to investigate what causes the small timesteps and to identify ways to increase the timesteps. An informal report, "A Renoded HBR-2 Plant Model for Real-Time Plant Simulator Applications," about investigating the runtime characteristics of a simulator model was written by Jim Lime and Thad Knight of Los Alamos.

In summary we investigated the potential for moving TRAC from a batch-oriented engineering analysis environment to a real-time simulator environment and demonstrated the potential for real-time calculations that meet simulator requirements. We developed a discussion paper and proposals to move this area of study from an LDRD project to one funded by sponsors such as KAPL and the NRC. We were successful in meeting the objectives of the LDRD project, which were to investigate and demonstrate the feasibility of using TRAC in a simulator.