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HYBRID SIMULATION IN FFTF SYSTEM CONCEPTUAL DESIGN*

A. L. Gunby and Grant A. Worth

Battelle Northwest

INTRODUCTION

The Fast Flux Test Facility (FFTF) will be the primary test facility for fast reactor fuels in the USAEC Liquid Metal Fast Breeder Reactor (LMFBR) development program. As such, the FFTF must provide high plant availability for fuel and material tests in high energy neutron fluxes and high sodium temperatures typical of future LMFBRs.

Battelle Northwest (BNW) has been pursuing conceptual design of the FFTF with the broad objectives of (1) defining the overall configuration of the plant, such as the reactor type, the number of heat transport loops, and the types of components in each loop, and (2) defining those problem areas which require further study as the project moves into preliminary design, such as thermal transients in the heat transport loops resulting from equipment failure. Early in conceptual design, the need for simulation of the reactor and heat transport systems was recognized for both the preceding broad objectives. Hybrid simulation was to be used for fast, inexpensive scoping work for FFTF components and for long-term studies of process control, while all-digital simulation was to be used for detailed calculations and for checking the hybrid.

This paper presents the development of useful models for hybrid simulation of the FFTF reactor and process system and discusses the use of the models throughout conceptual design. Simulation details are discussed where appropriate and plans for future work are outlined.

SUMMARY

At the start of FFTF conceptual design, hybrid simulation was chosen as the most promising method of performing time-consuming control studies and real-time simulation for plant checkout and operator training. A hybrid computer was purchased for eventual installation in the FFTF plant, and simulation models of the reactor and process systems were developed for the equipment. During the conceptual design phase, the hybrid simulation proved useful at several points during its development, notably (1) in providing scoping information for early component conceptual studies, (2) in providing conservative, "worst-case" values for thermal transients, and (3) in providing preliminary evaluation of plant control schemes. Model simplifications have been made to fit the simulation on the equipment, with each model portion checked against a detailed all-digital simulation.

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Model development will continue as simulation techniques allow expansion and sophistication of models. An approach now in use on the FFTF hybrid (modular programming) allows greater model detail where it is needed by programming system components (e.g., vessel, heat exchanger) and system functions (e.g., plant protection system) as separate entities on the digital side. Detail in one part of the simulation is provided by sacrificing detail in another, less-needed part.

SYSTEM DESCRIPTION

The FFTF reactor and heat transport system for the current conceptual design is shown schematically in Figure 1. Several basic features have changed during conceptual design, notably a change from 4 loops to 3, and a change of cold leg primary pumps to the hot leg. The overall layout remains the same, however, with the reactor cooled by three primary sodium loops, each primary loop transporting heat through an intermediate heat exchanger (IHx) to a secondary sodium loop which, in turn, loses its heat in an air-cooled dump heat exchanger (DHX). Throughout conceptual design, component designs have changed, with the hybrid simulation easily accommodating these changes. Current conceptual design of components favors the following: (a) 10-pass crossflow DHX, (b) 1660-tube, counterflow, Fermi-type IHX, (c) Fermi-type sodium pumps. Pump drives will be either the wound-rotor motor type or the electro-magnetic clutch type with a constant speed motor.

The reactor core consists of 70 to 80 driver fuel elements in a vertical array, each containing 217-pin subassemblies of $\text{UO}_2\text{-PuO}_2$ fuel and cooled by sodium. Sodium also passes around the tubes, having leaked past tube-grid plate seal for the purpose of hydraulic balance. Around the core region is the radial reflector, which generates about 5% of the reactor heat and is cooled by an equivalent sodium flow. Finally, inlet and outlet plena accept and mix their respective input flows to provide core inlet and vessel outlet sodium, respectively.

MODEL DEVELOPMENT AND USE

MODEL DEVELOPMENT

Hybrid computer models of the FFTF reactor and heat transport system were developed in relation to the need for transient results and also to available equipment. Several distinct phases of development are evident, though they overlapped considerably during design. During the first phase of this development, utilization of the hybrid had to be minimal, as the machine was new and software was still being developed. Conceptual design during this period required "scoping" information for thermal transients, i.e., data on how thermal transients at various points in the proposed FFTF system would be affected by changes in design data or operating conditions. For example, the effect of outlet plenum mixing volume on thermal transients at the vessel outlet nozzles is one input (among many) needed to estimate the desired vessel size. Throughout this phase, models remained fairly simple, with simplifications made in the conservative direction. Only one coolant circuit was modeled.

The second phase of modeling increased the utilization of the hybrid capability. A second coolant circuit was added and portions of the system model were made more sophisticated. During this period of conceptual design, the simulation was used for defining "worst-case" thermal transients (those transients resulting from a set of extreme circumstances) at key points in the process system. Worst-case transients were then used to develop testing objectives in the component development program. For example, thermal shock tests for the primary pumps (in the hot leg) must consider the worst-case conditions of full core ΔT , high-performance fuel, and imperfect outlet plenum mixing.

FIGURE 1 SCHEMATIC DIAGRAM OF FFTF REACTOR AND HEAT TRANSPORT SYSTEM

The third phase considered control aspects. Process control simulators were added to the overall simulation and a plant protection system was simulated. These improvements allowed the study of control configurations for the reactor and process system, in particular, system responses to reactor power perturbations. Models for each phase are discussed in the following sections.

PHASE 1 MODEL

Overall Description

During this period, the analog portion of the hybrid simulation was emphasized since the analog-digital interfacing was being completed and familiar analog techniques were dependable. The only portions of the simulation designated for digital simulation were the coolant transport delays and some selected function generators. A single coolant circuit was modeled; thus, transient behavior of all circuits was assumed to be identical. Figure 2 shows the simulated system with the division between analog and digital simulation.

Component Model Descriptions

Equipment limitations on the analog side forced an early evaluation of desired model complexity. Two basic considerations were kept in view during this effort: (1) sodium outlet temperature from the modeled component is the parameter of interest; internal temperatures (e.g., nodal temperatures) are not of primary concern, and (2) due to the preliminary nature of conceptual design, accuracies on the order of $\pm 5\%$ for thermal transients are acceptable. Models were made as complex as necessary with the understanding that as design progresses and greater detail is needed, the models would be made more sophisticated. A complete description of the Phase 1 models may be found in Reference 1.⁽¹⁾

Reactor Vessel: Neutron kinetics were simulated with three delayed groups, as in the method of Albrecht and Metelmann.⁽²⁾ An algebraic expression for neutron dynamics was used, to eliminate the need for extremely high-gain analog integration. Heat generation due to fission product decays was separated from the total power generation and also represented by three decay terms. Reactivity feedbacks included linear terms for sodium and core expansion (based on average sodium temperature), and for core bowing (based on core ΔT), as well as a logarithmic term for Doppler (based on average fuel temperature). Inlet and outlet plenum models assumed perfect mixing throughout the plenum volume, with heat transfer to steel structures in the region being represented by a single node for each plenum.

Heat transfer within the core was divided in three parts by three coolant streams: fuel coolant, leakage, and radial reflector coolant. The radial reflector region was modeled by a single node as though heat were generated directly in the coolant. Simulation parameters were chosen to account for the stored heat in the reflector and to approximate the time constant of coolant temperature response to power changes. Leakage coolant acquires heat from the fuel coolant through the reactor tubes, and was also simulated by a single axial node. The core itself was simulated by two lumped nodes representing fuel and coolant. This simplification was acceptable based on comparisons with a detailed digital FFTF core model (4 axial nodes, 3 fuel nodes plus clad and coolant radially) as shown in Figure 3. For a core scram with full flow, the agreement in tube and vessel outlet temperature transients was good. For a combined power and flow scram, the tube outlet temperatures deviated somewhat but the damping of the outlet plenum provided good agreement at the vessel outlet.

Sodium Systems: Sodium hydraulics were simulated by assuming the Darcy-Weisbach flow vs head loss relation, with an exponent of 1.8. Pump and motor

FIGURE 2. SIMULATED FFTF REACTOR AND HEAT TRANSPORT SYSTEM, PHASE ONE.

FIGURE 3. VESSEL MODEL COMPARISON, OUTLET TEMPERATURE TRANSIENT.

dynamics were simulated with speed control by an eddy-current clutch. Although pipe bends do not follow the above relationship and the reactor is hydraulically complex, comparison to a more detailed hydraulic model (accounting for bends, entrance and exit losses) for a typical primary flow coastdown showed good agreement (Figure 4).

Transport delays were the main contribution of the digital capability to the hybrid simulation. Pure delays were assumed as a conservative approach, since stored heat in the piping will tend to dampen thermal transients moving down the pipe.

IXH: The IHX was simulated as a counterflow exchanger divided into 4 nodal segments. Comparisons to models with 1, 2, 3, 6, and 8 nodes were performed which demonstrated the adequacy of the 4-node approach. Finite difference approximations for the partial differential equations were used, using central difference expressions at the first computed temperature of each coolant stream, and three-point backward expressions elsewhere (i.e., backward with respect to flow direction). The heat transfer coefficient was analog-simulated as being flow and temperature dependent. Stored heat in the tube metal was equally divided between tube and shell sodium. Transient studies showed less than 1% deviation from models using a separate metal node.

DHX: In spite of its crossflow design, the DHX was simulated as a counterflow device, an assumption which improves with the number of tube passes across the air flow direction. Preliminary model investigations indicated that three nodes would be sufficient axial complexity. Figure 5 shows the relative responses to loss of air flow for the 3-node hybrid model compared to an 18-node crossflow DHX model. Heat storage in the finned tubing was lumped with that for the sodium. This practice assumes that the metal temperature behaves substantially like the sodium temperature. The assumption is still under study at this time. Again, finite difference approximations for the standard partial differential equations were employed, with central difference expressions at the first computed temperature of each coolant stream, and three-point backward expressions elsewhere. The heat transfer coefficient was simulated on the analog side as a function of both coolant flows and temperature.

Use of the Model

The single coolant circuit model was used for "scoping" conceptual design studies for system components. Thermal transients as functions of operating parameters (power, ΔT) and of design data were determined for use as inputs to thermal stress studies of vessel, pump, IHX and DHX. With the expected scope of thermal transients defined, preliminary analysis of specific component concepts could proceed for the purpose of determining concepts most likely to succeed.

For example, Figure 6 shows vessel outlet temperature transient rates as a function of vessel outlet plenum volume for a power scram with full flow. A representative mixed oxide core was assumed. These results were used as inputs to vessel design studies which examined such problems as nozzle spacing, and needs for thermal barriers. The hybrid was able to generate this information quickly and inexpensively.

PHASE 2 MODEL

The single coolant circuit simulation was expanded during this phase to include a second coolant circuit, with each circuit capable of simulating one, two, or three of the actual circuits. As shown in Figure 7, one circuit is primarily analog-simulated, while the other is digital. The component models used in each coolant circuit (analog or digital) are identical. Heat transfer

FIGURE 4. FLOW MODEL COMPARISON: PRIMARY FLOW DECAY FOR LOSS OF PUMP MOTOR

FIGURE 5. DHX SODIUM OUTLET RESPONSE TO LOSS OF AIR FLOW, FULL SODIUM FLOW.

FIGURE 6. EFFECT OF OUTLET PLENUM MIXING ON VESSEL OUTLET THERMAL TRANSIENT DUE TO POWER SCRAM, FULL FLOW.

FIGURE 7 FFTF SYSTEM HYBRID SIMULATION, PHASE TWO

coefficients for the IHXs and DHXs were shifted to the digital side as functions of the appropriate temperatures and flows.

Expansion of the model to the multicircuit status was accomplished without simplifications in model complexity. Indeed, several additions to the models were made. In the reactor model, the fuel was divided into three radial nodes of equal volume, resulting in a better match to the detailed core model for reactor tube outlet temperature responses to combined power and flow scrams. Further, flow-dependent mixing plena were added at the inlet and outlet of each IHX and DHX (total of twelve).

Use of the Model

This stage of model development was an interim between the single-circuit model and the goal of a multicircuit model with control simulation. During this time, the need arose for defining conservative, "worst-case" transients for component development and testing. A combination of circumstances designed to produce the most severe thermal transients was selected, including high-performance fuel, poor plenum mixing, high power and core ΔT , and low pump inertias. The hybrid simulation easily assimilated the changes and produced the required thermal transients. An example is shown in Figure 8, comparing the worst-case primary hot leg transient to the transient resulting from expected initial design data.

PHASE 3 MODEL

Model Modifications

During this phase of model development, control loops and a protection system were added to the simulation. Analog simulators of proportional-plus-reset controllers were used, separate from the analog console of the hybrid. Switching arrangements allowed a wide variety of process control loops to be formed. Reactor control simulation was based on a reactivity-neutron flux loop which moved a simulated control rod when the flux signal moved outside a pre-set deadband. A plant protection system was simulated on the digital portion with the capability of looking at any computed variable, comparing it to a setpoint, and initiating control or protective action in any desired sequence, i.e., power setback, controlled shutdown, and reactor scram.

Use of the Model

Several plant control systems were studied to examine concept feasibility. Response of the total system to anticipated perturbations (power, flow) was measured, with the process control system programmed to maintain a particular test objective. For example, Figure 9 shows the results of a reactor setback from 400 MW_t to 300 MW_t with constant sodium flows. Airflow at the DHX is controlled by a proportional-plus-reset controller with a setpoint adjustment as a function of power level, in order to maintain reactor inlet temperature constant. As power decreases, airflow drops to raise secondary cold leg temperature and hold primary cold leg temperature within ± 10 °F. Work of this type is just beginning and will continue through the next design phases. Further model improvements will be made enabling more detailed control studies.

SIMULATION FEATURES

COMPUTER DESCRIPTION

The hybrid computer system used in the reactor simulation was developed by interfacing a Beckman Model 2133 analog computer (about 170 amplifiers) with a Digital Equipment Corporation (DEC) PDP-7 digital computer (8K core memory). The interface consists of a 24-channel multiplexer, an analog-to-digital

FIGURE 8. COMPARISON-"WORST CASE" TO INITIAL EXPECTED TRANSIENT AT VESSEL OUTLET FOR POWER SCRAM WITH FULL FLOW

FIGURE 9. PRELIMINARY CONTROL STUDY: SYSTEM RESPONSE TO POWER SETBACK, CONSTANT SODIUM FLOWS.

converter and 24 digital-to-analog converters. Digital control of analog functions is provided through control interfacing.⁽³⁾

The software system used in digital programming is a combination of greatly modified DEC Basic Software System programs and several programs developed independently at BNW. DEC's basic assembler and debugging program (DDT) were modified to make them compatible with a hybrid computer system. BNW software includes magnetic tape editor and loading programs and provides selective core dump capabilities (to magnetic tape).

The actual language used in programming is a "dialect" of DEC's assembly language and is called SIMPL-1 (Simulation Implementing Machine Programming Language - Version 1).⁽⁴⁾ The technique is essentially "subroutine programming" in that a subroutine library is available for integration, transport time delays, function generation, and all basic mathematical operations such as multiplication, division, and taking of logarithms. The language provides the capability of doing digital programming with an analog approach, i.e., direct conversion from block diagrams with "black boxes" for integration and other mathematical operations.

Fixed-point arithmetic is used along with analog scaling techniques within the digital program. This was easily done since the entire simulation had originally been scaled for an analog computer. The efficiency of assembly language programming combined with the speed of fixed point arithmetic operations provides the capability of operating the entire simulation in ten times real-time, i.e., ten times as fast as the actual process would operate. Ten times real-time will be referred to as problem-time in this paper. The high speed operation has proven beneficial in performing long-term control studies.

SIMULATION TECHNIQUES

The division of labor between the analog and digital portions of the hybrid computer has been established primarily on the basis of high gain operations functioning better on the analog computer. If the entire simulation (Phase 3 Model) were placed on an analog computer, 320 amplifiers, 60 integrators, 55 multipliers, 25 function generators, over 250 potentiometers, and at least 20 differential relays would be needed, as well as 8 variable time delays. The hybrid simulation of Phase 3 uses 120 amplifiers, 36 integrators, 30 multipliers, and 130 potentiometers. The digital computer provides the rest of the capability.

Main Simulation Program

The digital program is broken up into about 20 subprograms, each of which can be entered at a varying rate. The overall frame-time of the digital computer program is about 16.5 milliseconds which corresponds to 0.165 seconds problem time; however, many variables are updated three, four, or even five times during this single cycle. The frequency of iteration can be varied for each subprogram individually to provide stable output signals from each. For example, high gain integrations, such as pump motor speed, require a higher iteration rate than flow integrations to maintain stability.

The simulation itself occupies about 5,000 of the available 8,000 core memory locations on the PDP-7. Of the remaining 3,000 memory locations, about 1,000 are used by an on-line monitoring program, Dynamic Keyboard Monitor (DKM). This program provides the capability of making on-line decisions to initiate control actions or transients, or to alter controller setpoints or safety trip points. This is done by way of the teletype while the computer is in compute mode without returning to initial conditions, and will provide the basis for future operator training. In addition, DKM makes possible the

changing of instructions during operation of the simulation, providing a powerful debugging tool.

DKM also allows commands to be given to selectively load any of several support programs from magnetic tape into the remaining portion of memory (2,000 locations). These programs (discussed below) can be loaded relocatably and are loaded on an interrupt level so as to not disturb the operation of the simulation. Once they are loaded, DKM can be used to transfer control and initiate program action by these programs.

Simulation Support Programs

Several support programs share a buffer zone in memory. They are loaded when needed and replaced by other programs upon completing their functions. The first of these automatically sets potentiometers on the analog computer. This provides for easily changing parameter values or initial conditions when a new study is to be performed.

A separate program is also used for monitoring steady-state conditions. It stores the steady-state values of all integrators for use as initial condition settings at a later time. This includes digital and analog variables.

To assist in determining whether the simulation is operating correctly, several programs can be loaded to monitor steady-state conditions and calculate energy balances throughout the simulated system. Heat balances are calculated for the vessel, IHX, and DHX including percent error deviation for each component.

When the simulation is operating, the buffer zone of memory is used for a simulated protection system replacing the preoperational support programs mentioned above. This program monitors any number of variables comparing their values to pre-set trip points. If a trip point is reached, action is automatically taken as specified by the user. This program is used not only for protective functions but also provides the user with the capability of initiating accident conditions. This prevents the necessity of patching special relays and integrators on the analog patch board merely to initiate a particular transient.

During a transient condition a user-specified number of variables can be monitored and their values can be stored in preselected time increments. These values can be automatically printed out together with a heading describing the transient.

Special Simulation Techniques

The digital programming in the FFTF Simulation emphasizes special techniques to maximize computer efficiency. As an example, function generation (table lookup) methods developed for multiple input functions are readily available but are time-consuming (e.g., 290 microseconds for two input functions). A time savings of 30 to 65% has been achieved by breaking these functions into single-variable functions with their outputs being handled algebraically to produce the desired function. Having the programmer spend more time in developing an efficient program is desirable since the plant simulation provides faster-than-real-time operation and since it is to be used for several years.

Other special techniques developed by BNW include several special purpose subroutines. The digital portion of the simulation performs about thirty low-to-medium gain integrations. These integrations are performed by a subroutine which utilizes asynchronous rectangular integration techniques. Normalized mathematical operations are used within the subroutine to provide a maximum

degree of accuracy. Truncation errors are greatly decreased by accumulating an eighteen bit remainder term from one sample time to another and using it to update the output. The subroutine provides the capability of using an input multiplier with the integration, much the same as gains are used on analog integrators. The amount of computer time needed for one sample time for a single integration is about 65 microseconds.

It is felt that the use of rectangular integration is justified in that all FFTF system models using digital integrations had previously been programmed on the analog computer. These include models of the pump, hydraulics, the IHX, and the DHX. No significant differences were detected in the results of the two approaches.

Another special subroutine being used in the simulation is one which simulates variable flow transport time delays. Coolant pipes can be divided into a large number (several hundred if desired) of nodes and the rate at which temperature transients pass from one node to the next is determined as a function of flow rate. The subroutine requires between 70 and 90 microseconds for each entry regardless of how many nodes the pipe is divided into. In the simulation these time delays have been updated ten times per second, problem time (100 times per second real-time).

RECENT DEVELOPMENTS

COMPUTING EQUIPMENT

The FFTF Simulation has recently been transferred to a new hybrid computer facility consisting of an AD-4 (Applied Dynamics) analog computer and a DEC PDP-9 digital computer. The analog computer is solid-state and is equipped with a digital logic patchboard while the PDP-9 has two 8K memory banks with the capability of easily expanding to three or four. Cycle time for the PDP-9 is 1.0 microseconds compared to 1.75 microseconds for the PDP-7; however, because of slower hardware arithmetic operations (multiply and divide) there is little speed advantage with the new computer. An interface similar to the one already described is used in linking the two computers together.

A modified version of DEC's Advanced Software System is used for all digital programming. The language used is a version of DEC's assembly language with many BNW-developed macros which have been included as a part of DEC's Macro Assembler. This approach has been used in place of many subroutines used in programming on the original simulation because of the extra operating speed gained and because the larger core memory is available.

SIMULATION TECHNIQUES

As the design of the FFTF progresses beyond the conceptual stages, the need for more complexity in the hybrid model arises. A solution to this problem would be a programming technique which would allow adding complexity to portions of the system which are of major interest and simplifications to other, less important portions. Ideally, the programming would be such that changes could be easily made and any portion of the system could be expanded.

This capability was provided by a "modular" programming approach. The digital program was separated into several programs or modules which can be loaded and operated independently of one another. They communicate only with a master program which defines all system variables that are used by more than one program module. Each program module represents a separate component of the plant simulation, such as an IHX, a DHX, coolant pipes, hydraulics, and reactor kinetics. If a study of only one component is needed then only that one component module needs to be loaded into memory.

Modulizing of the Phase 3 model is now complete and it is possible to make studies of more complex system components without having to edit, assemble, load, and debug a single overall program describing the entire simulation. A single module can be modified and combined with the rest of the simulation during the loading process. Detailed models of particular components can be developed separately and studied at the expense of less important, simplified models elsewhere in the system. In this approach, the analog computer serves as a separate module.

The utility of the modular programming will be evident in continuing plant control studies (Phase 3 Model) and in performing pipe rupture studies which will require a widely different model. The pipe rupture studies will be pursued with a complex reactor model and a complex primary coolant loop and pump model. Modeling of secondary loops and DHXs will be rudimentary or nonexistent. These studies, with an all-digital approach, are now in progress and consume from fifty to several hundred times the problem time in the computing process. Hybrid studies will yield great computing cost savings.

CONCLUSIONS

Experience with the FFTF hybrid simulation leads to the following basic conclusion: using a structured assembly language which gives the programmer the capability of applying well-known analog computer techniques (i.e., "black boxes" for multiplication, division, and integration) to a digital program, a relatively small computer system can be used efficiently in large scale studies. This can provide the following advantages:

- 1) Large systems can be simulated, often in faster-than-real-time operation.
- 2) Powerful man-machine interaction capabilities can be provided in a manner not at all possible on large, expensive computer systems.
- 3) Large cost savings can be achieved. The same overall FFTF simulation, if simulated with conventional digital programming techniques, would cost at least 100 times as much to run as it does on the hybrid computer.

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