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REAL-TIME DYNAMIC SIMULATOR FOR THE TOPAZ II REACTOR POWER SYSTEM*

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BIOGRAPHY

Kwan S. Kwok is a Senior Member of the Technical Staff at Sandia National Laboratories. He served as the task manager responsible for systems engineering in the TOPAZ International Program. He has over 15 years of experience in the nuclear power industry, space nuclear systems, and dynamic control of power systems. He has a Ph.D. and an MS in nuclear engineering, and a BS in mechanical engineering. Dr. Kwok is currently a project manager and principal investigator in the Intelligent Systems and Robotics Center.

ABSTRACT

A dynamic simulator of the TOPAZ II reactor system has been developed for the Nuclear Electric Propulsion Space Test Program. The simulator is a self-contained IBM-PC compatible system that executes at a speed faster than real-time. The CPU is an 80486 DX2 processor operating at 66 MHz. The data acquisition system also employs an 80486 processor at 24 MHz on board. The data acquisition system is capable of providing 128 channels of analog-to-digital inputs at 1.3 MHz simultaneously, 64 channels of digital inputs at 1.6 MHz on a single channel, 64 channels of digital outputs at 1.6 MHz on a single channel, and 66 digital-to-analog channels at 1.6 MHz on a single channel. The simulator software operates in the Windows environment.

The simulator combines first-principle modeling and empirical correlations in its algorithm to attain the modeling accuracy and computational throughput that are required for real-time execution. The overall execution time of the simulator for each time step is 15 ms when no data are written to the disk, and 18 ms when nine double precision data points are written to the disk once in every time step. The simulation program has been tested and it is able to handle a step decrease of $8 worth of reactivity. It also provides simulations of fuel, emitter, collector, stainless steel, and ZrH moderator failures. Presented in this paper are the models used in the calculations, a sample simulation session, and a discussion of the performance and limitations of the simulator. The simulator has been found to provide realistic real-time dynamic response of the TOPAZ II reactor system under both normal and casualty conditions.

INTRODUCTION

A simulator of the TOPAZ II reactor system has been designed, constructed, and tested for use in the Nuclear Electric Propulsion (NEP) Space Test Program (Kwok 1994a). Its hardware and software have been entirely designed, developed, and fabricated in the United States. The work reported herein is derived directly from the knowledge gained in the joint U.S.-Russian space nuclear technology program. The simulator provides a realistic representation of the dynamic response of the Russian TOPAZ II power system, and serves as a system on which new ideas can be tested and tried prior to commitment for hardware testing.

The TOPAZ II Reactor System Real-time Dynamic Simulator is designed primarily to facilitate the development and qualification of the TOPAZ II reactor control unit (RCU). The dynamic characteristics of the simulator are therefore represented explicitly in the models. It combines first-principle modeling and empirical correlations in its algorithm to attain the modeling accuracy and computational throughput that are required for real-time execution (Kwok 1993). In addition to being a test system for the RCU, it serves as a training tool for both TOPAZ II operators and control system designers by providing users with hands-on experience that simulates the actual dynamic response of the TOPAZ II power system. The strong feedback mechanisms inherent in the TOPAZ II design are apparent during a simulation session. In addition, the simulator can be put under severe operating conditions, which may otherwise be impossible or extremely difficult to perform in a mock-up or preoperational test in which hardware is involved. Examples are a continuous drum withdrawal or an ejection of the reflector while operating at full power.

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This paper provides an overview of the hardware, software, and the modeling and characteristics of the TOPAZ II simulator, which is described in detail elsewhere (Kwok 1993). It begins with an outline of the design requirements, followed by an overview of the TOPAZ II reactor system. A description of the overall simulator system and specifications for the computer and the data acquisition system follow. The paper then describes the models employed in the simulator. The neutronic model includes a section on the treatment of the neutron source strength at shutdown. Included in the discussion are the kinetics parameters and equations for reactivity feedback calculations that are used in the simulator. Also discussed is the user interface, which provides the user with program control and access to the simulator. Next, a sample simulation session is given, in which major events for observation, proper techniques in reactor control, and expected response of the TOPAZ II are highlighted. This is followed by a discussion on the performance response and limitations of the simulator.

DESIGN REQUIREMENTS

The primary purpose of the simulator is to support the development process of the RCU. The reactor control unit is a critical component for operation of the TOPAZ II power system while in orbit. Its development requires a high-performance simulator that can provide an update of the reactor and its associated systems once every few hundredths of a second. The cycle update time imposed on the simulator must be less than the maximum cycle time allowed on the RCU, which in turn must be less than or equal to 100 ms, when allowable overshoot on the power level is taken into consideration. The cycle update time of the simulator must be less than one half that of the RCU in order for the simulator to appear as a continuous real-time system to the RCU.

The design goal of the TOPAZ II Reactor System Real-time Dynamic Simulator is "to provide a real-time dynamic simulator capability for the TOPAZ II Instrumentation and Control Task. The simulator is to be used initially as a development tool for the Reactor Control Unit."

Specific requirements are that the dynamic simulator must:

1. be capable of interfacing with the instrumentation and actuators that are a part of the TOPAZ II reactor system,
2. be capable of interfacing with the RCU,
3. be capable of interfacing with several external systems simultaneously,
4. be easily portable between test facilities and experimental sites,
5. be able to share files and data in formats and media associated with personal computer software and utilities,
6. meet the intent and conditions imposed by applicable federal, state, and local codes, regulations, orders, and requirements,
7. meet usual industry standards and prudent engineering practice, and
8. be flexible enough to meet future, as-yet undefined, requirements and constraints in a timely manner.

DESCRIPTION OF TOPAZ II REACTOR SYSTEM AND SIMULATOR

The TOPAZ II reactor is a liquid-metal cooled, zirconium-hydride moderated, beryllium-reflected epithermal reactor designed for operation in space (Polansky et al. 1993). It is fueled by thirty-seven highly enriched thermionic fuel elements (TFEs), which are loaded with UO_2 pellets that have a central hole for venting fission gases into space.

The three safety drums and nine control drums consist of beryllium and a layer of boron for reactor control. The integral worth of the three safety drums is \$2.0 total and the integral worth of the nine control drums is \$5.3 total (E.C. Glushkov, personal communication, February 1993). The safety drums operate at a fixed rotational speed of 22.5°/s, whereas the nine control drums operate at a variable rotational speed of up to 1.4°/s. The total reactivity worth of all twelve drums is \$6.8, owing to shadowing effects from adjacent drums (E.C. Glushkov, personal communication, June 1993). The safety drums are designed to be driven from the full-in position to the full-out position only once, because their motors are not shielded from the reactor radiation, and will cease operation a few hours after full power operation of the reactor. The control drum drive motor is mounted behind a lithium-hydride and stainless steel shield and remains operational throughout the lifetime of the reactor. The safety drums, control drums, and radial reflector are held together by metal straps with fusible links. In the event of an emergency, these metal straps would either be released through an electrical signal, or melted and released by the heat generated from reentry. Release of the metal straps will allow the twelve reflector panels to disassemble and separate the three safety drums, nine control drums, and radial reflector from the reactor, causing the reactor to shut down. Once released, the action becomes irreversible.

The RCU provides primary control of the TOPAZ II reactor power level in accordance with the programmed control laws based upon the measured reactor power level and its divergence from the desired power level. It monitors key values, such as neutron flux levels, primary coolant temperature, electrical output, and position of control drums, and determines the control action that affects rotation of the control drums. It performs (1) startup of the reactor from source levels to critical, (2) power increase from critical to point of adding heat, (3) heat-up in the power range, (4) stabilization of power at the desired level, (5) compensation for both long-term and short-term reactivity feedback.

Polansky et al. (1993) provide a more detailed description of the actual TOPAZ II power system and Kwok (1994b) overviews the models included in the TOPAZ II reactor system simulator. The automatic control system is not completely represented in the simulator because development of the RCU is in progress. It is represented by an automatic proportional-integral-derivative (PID) controller, which is able to hold the reactor power constant, change power up to about 25% without changing the set point, or change power by sliding the set point of the controller (Kwok 1993). Furthermore, the model of the control drums in the simulator does not include the gear back-lash effect. It was estimated to be small; however, it requires 6-8 s for the effect to vanish, a time lag that may be important to the overall dynamic response of the TOPAZ II. Luppov et al. (1994) discuss the dynamic modeling of the control drum drive system.

DESCRIPTION OF HARDWARE

The computer system used in the TOPAZ II simulator is an 80486DX2-66MHz IBM-PC compatible system built into an industrial-grade rack-mountable enclosure (Kwok 1993). The mother board, graphics board, sound board, disk controllers, hard disk drive, floppy disk drives, and power supply are installed in a rack-mounted enclosure. The enclosure has an extra fan installed near the front panel for a larger heat removal capability. The extra fan allows the new high-performance CPU chips to run cooler, which may be a highly desirable feature if the 486 processor is upgraded later.

The computer system has an Intel 66 MHz 80486DX2 microprocessor with 256K static RAM cache (25 ns), 16 MB dynamic RAM (70 ns SIMMs) expandable to 64 MB, 1.2 MB 5.25" and 1.44 MB 3.5" Epson diskette drives, 340 MB Western Digital IDE (13 ms), 17 MB DTR with 128K multisegmented cache buffer, local-bus IDE interface, ATI Ultra Pro VESA local-bus with 1 MB VRAM, 15" CrystalScan 1572FS color monitor, Phoenix BIOS, clock/calendar, eight 16-bit ISA slots, two with 32-bit VESA local-bus slots, one parallel and two serial ports, Gateway 2000 124-key AnyKey keyboard, Windows Sound system, DOS 5.0, Microsoft Windows 3.1, Microsoft mouse, and Labtec CS-180 speaker system.

The data acquisition system is manufactured by Microstar Laboratories. The central driving unit is the DAP 3200e/102 data acquisition processor (DAP), with its own Intel 80486 24-MHz processor and 4 MB of RAM on board. The hardware system provides 128 channels of analog-to-digital (A/D) inputs at 1.3 MHz simultaneously, 64 channels of digital inputs at 1.6 MHz on a single channel, 64 channels of digital outputs at 1.6 MHz on a single channel, and 66 digital-to-analog channels at 1.6 MHz on a single channel. An aggregate output rate of 1.6 million updates per second is shared among the analog outputs and up to sixteen digital outputs. Analog outputs can be updated at the same rate that analog inputs are sampled, and at the same time.

The on-board 80486 processor gives the DAP 3200e exceptional real-time response, and the larger 4-MB on-board memory option allows the DAP 3200e to handle complex tasks. Task latency is less than 0.5 ms. In addition, the DAP 3200e includes its own multitasking real-time operating system, DAPL 4.0. Therefore, it can handle all the critical aspects of a data acquisition and control system, and all its associated analog and digital I/O, while leaving the processor on the 80486DX2-66MHz system free to handle the demands of the Windows operating system and user interface.

The built-in dual 512-word, high-speed FIFO buffers allow the DAP 3200e to bypass DMA hardware, and run the ISA bus in the host computer at its maximum speed. An optimized communications protocol that is shared between the DAPL and the driver residing on the PC platform ensures gap-free data transfer with no errors.

MODELS

The TOPAZ II power system employs a small and compact core, in which neutronic responses of the reactor are tightly coupled. The neutron flux shape of a tightly coupled reactor does not change significantly in a transient. The changes that occur in the reactor may be described by treating the entire core as a "point."

Point Kinetics Model

The neutronic model is a space-independent point kinetics model with a distributed neutron source. The equations describing the response of the reactor are (Henry 1975):

$$\frac{dT(t)}{dt} = \frac{\left[\rho(t) - \overline{\beta}\right]}{\ell^*} T(t) + \sum_{i=1}^{N} \lambda_i C_i(t) + Q(t), \text{ and}$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\ell^*} T(t) - \lambda_i C_i(t), \quad for \quad i = 1, N$$

where $T(t)$ is the amplitude function and is a weighted integral of all neutrons present in the reactor. Other symbols are defined as:

$\rho(t)$ = net reactivity,

$\overline{\beta}$ = effective delayed neutron fraction,

ℓ^* = prompt neutron lifetime,

λ_i = decay constant for the ith precursor group,

$C_i(t)$ = concentration of the ith precursor group normalized to the initial power,

$Q(t)$ = effective neutron source strength,

β_i = fractional yield of the ith group of delayed neutrons,

N = number of groups of delayed neutrons, including photoneutrons, and

t = time expressed in seconds.

Six groups of delayed neutrons are used in the neutronic model. The effective delayed neutron fraction is 0.008 and the prompt neutron lifetime is 2 x 10^{-5} s. The respective kinetics parameters are shown in Table 1.

TABLE 1. Reactor Kinetics Parameters*

Parameter	**Value**
Group 1 Delayed Neutron Fraction, β_1	3.040 x 10^{-4}
Group 2 Delayed Neutron Fraction, β_2	1.704 x 10^{-3}
Group 3 Delayed Neutron Fraction, β_3	1.504 x 10^{-3}
Group 4 Delayed Neutron Fraction, β_4	3.256 x 10^{-3}
Group 5 Delayed Neutron Fraction, β_5	1.024 x 10^{-3}
Group 6 Delayed Neutron Fraction, β_6	2.080 x 10^{-4}
Group 1 Delayed Neutron Precursor Decay Constant, λ_1 [s^{-1}]	0.0127
Group 2 Delayed Neutron Precursor Decay Constant, λ_2 [s^{-1}]	0.0317
Group 3 Delayed Neutron Precursor Decay Constant, λ_3 [s^{-1}]	0.1160
Group 4 Delayed Neutron Precursor Decay Constant, λ_4 [s^{-1}]	0.3110
Group 5 Delayed Neutron Precursor Decay Constant, λ_5 [s^{-1}]	1.3970
Group 6 Delayed Neutron Precursor Decay Constant, λ_6 [s^{-1}]	3.8720

* Supplied by E.C. Glushkov, personal communication, February 1993.

Integral worth of the control drums in $\Delta K / K$ is given by the following equation (E.C. Glushkov, personal communication, June 1993):

$$\rho(\theta) = 6.89\times10^{-13}\theta^5 - 2.33\times10^{-10}\theta^4 + 3.28\times10^{-9}\theta^3 + 4.57\times10^{-6}\theta^2 - 5.88\times10^{-5}\theta + 1.74\times10^{-4}$$

where:

$\rho(\theta)$ = integral reactivity worth of the nine control drums, and

θ = angular position of the main control drum expressed in degrees.

The model first determines the change in reactivity caused by the change in position of the safety drums, control drums, and the radial reflector. It then combines this reactivity change with reactivity feedback caused by the temperature changes that occur in the moderator, reflector, core plates, UO_2 fuel, and TFE electrodes.

SHUTDOWN NEUTRON SOURCE STRENGTH

The shutdown neutron source level is a direct result of spontaneous fission. These source neutrons will undergo subcritical multiplication and will reach a steady-state level in the reactor. The power level at shutdown depends on the number of source neutrons from spontaneous fission and the shutdown reactivity of the reactor. The two point kinetics equations can be solved for the steady-state condition at shutdown by setting the *d/dt* terms to zero and solving for the source term.

The *Nuclear Engineering Handbook* lists the rate of spontaneous fission for U-235 as 3.1×10^{-4} fissions/g/s (Etherington 1958). The TOPAZ II reactor may have a fuel loading as high as 27 kg of U-235, which results in a neutron source strength of 8.37 fissions/s. The shutdown reactivity of the TOPAZ II is -$6.21, which corresponds to a shutdown K_{eff} of 0.95267. The steady-state neutron population caused by subcritial multiplication further increases the source level to a fission rate of 177 fissions/s at shutdown. There are about 3×10^{10} fissions/s/W (Henry 1975). This gives 6 nW as the shutdown power level, which corresponds to an effective neutron source level of 1.46×10^{-5} W/s. This shutdown source strength is used in the evaluation of the first point kinetics equation during execution of the simulation program.

REACTIVITY FEEDBACK

Reactivity feedback caused by temperature changes in the ZrH moderator, Be reflector, reactor core support plates, UO_2 fuel, and TFE electrodes has been determined under isothermal conditions up to a temperature of 1000 K (Gunther 1990). Linear extrapolation is used in the correlation for the UO_2 fuel because the temperature in the fuel exceeds 1000 K during normal operation (El-Genk et al. 1993). The following are mathematical expressions for reactivity feedback effects as a function of temperature in the moderator, reflector, TFE electrodes, core support plates, and fuel (Gunther 1990):

Zirconium-Hydride Moderator:

$$\Delta\rho_m(\Delta K / K) =$$

$$(T_m - T_0)\left[-8.22 \times 10^{-16}(T_m - T_0)^4 + 1.60 \times 10^{-12}(T_m - T_0)^3 - 1.11 \times 10^{-9}(T_m - T_0)^2 + 2.92 \times 10^{-7}(T_m - T_0) + 1.76 \times 10^{-5}\right]$$

where:

$\Delta\rho_m(\Delta K / K)$ = change of reactivity in the moderator in $\Delta K / K$,

T_m = temperature of the moderator, and

T_0 = initial temperature of the moderator, given as 300 K.

UO_2 Fuel:

$$\Delta\rho_f(\Delta K / K) = 1.2 \times 10^{-5}(T_f - T_0) - 1.38 \times 10^{-2}\left\{\left(\frac{T_f}{T_0}\right)^{\frac{1}{2}} - 1\right\} \quad for \quad T_f < 800\,K,$$

and

$$\Delta\rho_f(\Delta K / K) = -1 \times 10^{-3} - 2.2 \times 10^{-4}(T_f - T_0) \quad for \quad T_f > 800\,K,$$

where:

$\Delta\rho_f(\Delta K / K)$ = change of reactivity in the UO_2 fuel in $\Delta K / K$,

T_f = temperature of the UO_2 fuel, and

T_0 = initial temperature of the UO_2 fuel, given as 300 K.

Beryllium Reflector:

$$\Delta\rho_r(\Delta K / K) = 3.8 \times 10^{-3}\left\{1 - \left(\frac{T_0}{T_r}\right)^{\frac{1}{2}}\right\}$$

where:

$\Delta\rho_r(\Delta K / K)$ = change of reactivity in the reflector in $\Delta K / K$,

T_r = temperature of the reflector, and

T_0 = initial temperature of the reflector, given as 300 K.

Core Support Plates:

$$\Delta\rho_{cp}(\Delta K / K) = -2.22 \times 10^{-6}(T_{cp} - T_0)$$

where:

$\Delta\rho_{cp}(\Delta K / K)$ = change of reactivity in the core support plates in $\Delta K / K$,

T_{cp} = temperature of the core support plates, and

T_0 = initial temperature of the core support plates, given as 300 K.

TFE Electrodes:

$$\Delta\rho_e(\Delta K / K) = 8.52\times10^{-4} - 4.26\times10^{-4}\left\{\left(\frac{T_e}{T_0}\right)^{\frac{1}{2}} + \left(\frac{T_c}{T_0}\right)^{\frac{1}{2}}\right\}$$

where:

$\Delta\rho_e(\Delta K / K)$	=	change of reactivity in the TFE electrodes in $\Delta K / K$,
T_e	=	temperature of the emitter,
T_c	=	temperature of the collector, and
T_0	=	initial temperature of the TFE electrodes, given as 300 K.

Thermal Models

Thermal systems in the TOPAZ II reactor power system closely follow a typical response of a first-order dynamic system. Review of the data taken during the thermionic system evaluation test (TSET) shows that each thermal system exhibits an equivalent time constant and an asymptotic final value. This kind of behavior is also noted in the development of the Thermionic Transient Analysis Model (TITAM) at the University of New Mexico (El-Genk et al. 1993).

Each thermal model has a final temperature that is directly proportional to the reactor power. This is the asymptotic value that the system will approach after four or more time constants. Using results from both TSET and TITAM, a time constant that determines the overall system response is calculated. Both the time constant and the final temperature can be fine-tuned to calibrate the system response, if so desired.

Under casualty conditions, high temperatures may cause structural failures in the systems. The thermal models in the simulator monitor critical components for excessively high temperatures. These critical components are (1) the UO_2 fuel, (2) the molybdenum emitter, (3) the molybdenum collector, (4) the stainless steel in the primary coolant system, and (5) the reflector. A warning message will be displayed on the screen if the temperature in any of these components equals or exceeds the respective melting temperature.

USER INTERFACE

This section describes the connections between the data acquisition system and external equipment. There are fifty-nine sets of connections that require interfacing, including six analog inputs, twenty-nine analog outputs, thirteen digital inputs, and eleven digital outputs. The user controls the simulator through the user control panel (Kwok 1993).

Interfacing the RCU to the simulator is similar to interfacing the user control panel to the simulator. The RCU must collect data and issue control signals in the same way the user control panel does. Therefore, most of the controls and indicators on the user control panel will no longer be functional when the RCU is connected to the simulator. For this reason, some of the status indicators on the user control panel are duplicated on the screen display.

The RCU can determine the status of the TOPAZ II power system by acquiring data through direct connections to the twenty-nine analog output channels. A cable can be used to interface the RCU to the simulator in the same manner as that of the simulation control panel. Doing so will provide the RCU access to all the status indicators, vent valves, release relays, and the control drum drive and safety drum drive motors. The two ion chambers provide outputs to the analog output boards. The analog input channel ADC0 interprets the value of the input voltage as a fraction of full speed for the control drum drive motor. That is, 0 V is full speed in, 2.5 V is full stop, and 5 V is full speed out. This analog input channel provides direct speed control of the nine control drums.

SAMPLE SIMULATION SESSION

In an actual startup of the TOPAZ II power system, there are many neutronic, thermal, mechanical, and electrical limits that must be observed The simulator models the important events and provides warning messages if temperature limits are exceeded.

A typical reactor startup for the TOPAZ II power system begins with withdrawing the safety drums one at a time. The user should allow sufficient time between the withdrawal of each safety drum in order for subcritical multiplication to take place. Build-up of subcritical neutrons can be observed by monitoring the rate of increase of the reactor power level. The control drums are then withdrawn in a stepwise manner until the main drum reaches 154°. Again, the stepwise approach is used to allow a sufficient neutron population to build up as a result of a source in a subcritical reactor prior to attaining criticality. This is important for proper operation of the nuclear instrumentation at source levels. The operator will test whether the reactor is critical during the stepwise withdrawal of the control drums by observing the "prompt" and "delayed" responses of the reactor during and after the drum movement. The reactor is critical when a steady period (a spontaneous exponential increase) is maintained following the initial prompt effects caused by drum motions. Once the reactor is critical, the control drums are driven inward to 145° and held there. When the power reaches the point of adding heat, approximately 5 kW, the operator should limit the power increase at a rate of no more than 600 W/s until

35 kW. The thermal covers should be ejected shortly after passing this point. The rate of power increase should be decreased to no more than 80 W/s after 35 kW. When the power approaches the desired level, 115 kW, the control drums should be carefully adjusted to maintain a steady power level. At this time, particular attention must be paid to the overall positive feedback mechanisms inherent in the TOPAZ II power system. The operator must constantly adjust the control drums inward to counteract the positive reactivity caused by the temperature increase in the moderator and the reflector. At this point, the operator can set and engage the automatic controller. A good set of numbers to use is to set the gain multiplier at 5, P at or near 4, I at or near 0.2, and D at or near 0.1. This allows a fairly high gain for proportional adjustment, a somewhat small integral compensation for prolonged lagging effects, and a small compensation based on the rate of change of the error. The operator can now "vent" the cesium and increase the work section output of the thermionic system by pushing a button. Once the thermionic system output is stabilized and the proper EM pump voltage has been verified, the startup battery electrolyte should be vented. The EM pump voltage can be monitored on channel 10 of the analog output boards.

The automatic controller will regulate the reactor power at the set point, while the temperature changes in the different systems cause reactivity effects in the reactor. The control drums will eventually be driven to about 90° after the reactor system as a whole reaches thermal equilibrium.

A final evolution the operator can simulate is that of a reflector ejection. This will shut down and change the state of the reactor to below the initial shutdown condition. The operator initiates the reflector ejection by pushing the REFLECTOR RELEASE 1 and REFLECTOR RELEASE 2 buttons. The operator will observe an initial prompt drop caused by the elimination of the short-lived prompt neutrons. This factor of 50 decrease will occur instantaneously, followed by a rapid decrease to a factor of 100 below the initial power level in a matter of seconds. This is followed by a classical decrease of the reactor power, limited by the rate of decay of the longest delayed-neutron precursor group that has a half-life of 55 s. The resultant reactor period is -80 s. The operator can easily observe this by using a stopwatch to confirm that the time it takes the reactor power to decrease by a factor of 2.7 is indeed 80 s.

PERFORMANCE AND LIMITATIONS

The overall execution time of the simulator for each time step is 15 ms when no data are being written to the disk, and 18 ms when nine double precision data points are written to the disk once every time step. If necessary, execution time can be further improved by updating the screen and writing to the disk at a frequency less than once every time step.

In each time step, neutronic integration is performed with an integration time step size of 0.5 ms. Convergence is usually accomplished in about 20 iterations. This combination of integration time step size and number of integration steps is optimized for an average cycle time of 20 ms or less. However, for more severe transients, numerical instabilities can be avoided by decreasing the integration time step size, while proportionally increasing the number of integration steps. For example, a 0.1-ms integration time step size is used with 100 integration steps. A finer integration time step size may be applicable if the average time step size is decreased by reducing the frequency of the screen update.

During a simulation session of a reactor startup and steady-state operation, the simulator depicts the effects of prompt and delayed neutrons correctly. That is, when control drum motions are initiated, the neutron power increase will be dominated by the prompt neutron life-time when drum motion is present. The initial surge of prompt neutrons will eventually cease, once drum motion has stopped, and the delayed neutron precursor concentrations come to an equilibrium.

When the reactor power is above the point of adding heat, the simulator properly introduces reactivity feedback caused by the heating up of the moderator, reflector, fuel, electrodes, and core plates. The strong positive delayed effect of the moderator is evident when the control drums are "turned in" at a substantial rate in order to compensate for the positive temperature feedback. The control drums are initially at about 130° when the reactor reaches criticality. The drums are normally shimmed to about 90° when the reactor reaches thermal equilibrium.

The neutronics calculation in the simulator is based on a first principle, whereas the thermal models and the thermionics model are based on empirical correlations. Recalibration of these dynamic models should be performed when new data become available. The neutronic calculations are integrated with a time step size of 0.5 ms. Numerical instabilities may be experienced if excessive reactivity is inserted in one step. The simulation program has been tested and it is able to handle a step decrease of $8 worth of reactivity.

Reactivity worth of the control drums and safety drums exhibits effects caused by shadowing. The simulator now handles this nonlinear effect by reducing the worth of each safety drum from $0.67 to $0.50. This is the reason for a possible very slow startup with one safety drum fully inserted.

The model of the control drums does not include the gear backlash effect (Luppov et al.1994). The effect was estimated to be small; however, it requires 6-8 s for the effect to vanish. This time lag may be important to the overall dynamic response of the TOPAZ II. It should be investigated and a sensitivity study performed on the simulator.

CONCLUSIONS

The TOPAZ II Reactor System Real-time Dynamic Simulator has been completed in accordance with the design requirements developed for supporting the RCU development effort, and has provided realistic simulation of the dynamic response of the TOPAZ II reactor system. The overall execution time of the simulator for each time step is 15 ms when no data are written to the disk, and 18 ms when nine double precision data points are written to the disk once in every time step. The simulation program has been tested and it is able to handle a step decrease of $8 worth of reactivity. It also provides simulations of fuel, emitter, collector, stainless steel, and ZrH moderator failures.

Although the simulator has been developed primarily to facilitate the development and qualification of the RCU, manual control of the simulator has provided TOPAZ operators, control system designers, and model developers significant insight into the control characteristics of the TOPAZ II reactor system. It has provided the necessary performance throughput for the RCU development effort. In addition, its dynamic characteristics can be adjusted by the user, if so desired. The latest technology in digital equipment is employed by the simulator, resulting in a system that is versatile and expandable for meeting future requirements.

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