CHARACTERISTICS AND CONTROL RESPONSE OF THE TOPAZ II REACTOR SYSTEM REAL-TIME DYNAMIC SIMULATOR

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Abstract

A dynamic simulator of the TOPAZ II reactor system has been developed for the Nuclear Electric Propulsion Space Test Program. The simulator combines first-principle modeling and empirical correlations in its algorithm to attain the modeling accuracy and computational through-put that are required for real-time execution. The overall execution time of the simulator for each time step is 15 ms when no data is 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 dynamic simulator of the TOPAZ II reactor system has been designed, constructed, and tested for the Nuclear Electric Propulsion (NEP) Space Test Program (Kwok 1994). The TOPAZ II Reactor System Real-time Dynamic Simulator is designed primarily for use as a test system for the development and qualification of the TOPAZ II Reactor Control Unit (RCU). It combines first-principle modeling and empirical correlations in its algorithm to attain the modeling accuracy and computational through-put 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. Additionally, the simulator can be put under severe operating conditions, which may otherwise be impossible or extremely difficult to perform in a mock-up or pre-operational test in which hardware is involved. Examples are a continuous drum withdrawal or an ejection of the reflector while operating at full power.

This paper discusses the modeling and characteristics of the TOPAZ II Reactor System Real-time Dynamic Simulator. First, the paper provides a description of the models employed in the simulator. The neutronic model includes a section on the treatment of the neutron source strength at shutdown. Also included are the kinetics parameters and equations for reactivity feedback calculations that are used in 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. It follows with a discussion on the performance response and limitations of the simulator.

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):

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

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\ell^*} T(t) - \lambda_i C_i(t), \text{ for } i = 1, N \quad (2)$$

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,
- $\bar{\beta}$ = effective delayed neutron fraction,
- ℓ^* = prompt neutron lifetime,
- λ_i = decay constant for the i th precursor group,
- $C_i(t)$ = concentration of the i th precursor group normalized to the initial power,
- $Q(t)$ = effective neutron source strength,
- β_i = fractional yield of the i th 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 2×10^{-5} s. The respective kinetics parameters are shown in Table 1 (Glushkov 1993a).

TABLE 1. Reactor Kinetics Parameters.

Parameter	Value
Group 1 Delayed Neutron Fraction, β_1	3.040×10^{-4}
Group 2 Delayed Neutron Fraction, β_2	1.704×10^{-3}
Group 3 Delayed Neutron Fraction, β_3	1.504×10^{-3}
Group 4 Delayed Neutron Fraction, β_4	3.256×10^{-3}
Group 5 Delayed Neutron Fraction, β_5	1.024×10^{-3}
Group 6 Delayed Neutron Fraction, β_6	2.080×10^{-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

Integral worth of the control drums in $\Delta K/K$ is given by the following equation (Glushkov 1993b):

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

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. Equations (1) and (2) 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 subcritical 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 Equation (1) 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 on 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:

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

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:

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

and

$$\Delta \rho_f (\Delta K / K) = -1 \times 10^{-3} - 2.2 \times 10^{-4} (T_f - T_0), \quad \text{for } T_f > 800 \text{ K}, \quad (6)$$

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:

$$\Delta \rho_r (\Delta K / K) = 3.8 \times 10^{-3} \left\{ 1 - \left(\frac{T_0}{T_r} \right)^2 \right\} \quad (7)$$

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:

$$\Delta\rho_{cp} (\Delta K / K) = -2.22 \times 10^{-6} (T_{cp} - T_0) \quad (8)$$

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:

$$\Delta\rho_e (\Delta K / K) = 8.52 \times 10^{-4} - 4.26 \times 10^{-4} \left\{ \left(\frac{T_e}{T_0} \right)^{\frac{1}{2}} + \left(\frac{T_c}{T_0} \right)^{\frac{1}{2}} \right\} \quad (9)$$

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.

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 step-wise manner until the main drum reaches 154° . Again, the step-wise 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 step-wise 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 seconds. The resultant reactor period is -80 s. The operator can easily observe this by using a stop watch 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 is 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. Finer integration time step size may be applicable if the average time step size were decreased through reduction of screen update frequency.

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 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 becomes available. The neutronic calculations are integrated with a time step size of .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 exhibit effects caused by shadowing. The simulator now handles this non-linear 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 back-lash effect (Luppov et al.1993). The effect was estimated to be small; however, it requires six to eight seconds 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 is 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.

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References

- El-Genk, M.S., H. Xue, and D. Paramonov (1993) "Start-up Simulation of a Thermionic Space Nuclear Reactor System," in *Proceedings of the 10th Symposium on Space Nuclear Power Systems*, CONF-930103, M.S. El-Genk and M.D. Hoover, eds., American Institute of Physics, New York, NY.
- Etherington, H. ed. (1958) *Nuclear Engineering Handbook*, McGraw-Hill Book Co., New York., NY 1958.
- Glushkov, E.C. (1993a) Personal Communications, INERTEK, Moscow, Russia, February 1993.
- Glushkov, E.C. (1993b) Personal Communications, New Mexico Engineering Research Institute, Albuquerque, NM, June 1993.
- Gunther, N.G. (1990) Characteristics of the Soviet TOPAZ II Space Power System, Report SPI-52-1, Space Power Inc., San Jose, CA.
- Henry, A.F. (1975) *Nuclear Reactor Analysis*, MIT Press, Cambridge, MA 1975.
- Kwok, K.S. (1993) TOPAZ II Reactor System Real-time Dynamic Simulator - User's Guide and Reference Manual, SAND93-2725, Sandia National Laboratories, Albuquerque, NM, in preparation.
- Kwok, K.S. (1994) "Design and Construction of the TOPAZ II Reactor System Real-time Dynamic Simulator," *Proceedings of the 11th Symposium on Space Nuclear Power Systems*, CONF-94101, M.S. El-Genk ed., American Institute of Physics, New York.
- Luppov, A.N., K.N. Prikot, G.A. Lisochkin, V.V. Skorlygin, and K.S. Kwok (1994) "Control Drum Drive Mechanism and Regulation Characteristics of the TOPAZ II Reactor," *Proceedings of the 11th Symposium on Space Nuclear Power Systems*, CONF-94101, M.S. El-Genk ed., American Institute of Physics, New York.

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