CONF-841007--18

# SIMULATION OF THE TREAT-UPGRADE AUTOMATIC REACTOR CONTROL SYSTEM

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CONF-841007--18

DE85 002737

## ABSTRACT

This paper describes the design of the Automatic Reactor Control System (ARCS) for the Transient Reactor Test Facility (TREAT) Upgrade. A simulation was used to facilitate the ARCS design and to completely test and verify its operation before installation at the TREAT facility.

The ARCS is a microprocessor network based closed loop control system that provides a position demand control signal to the transient rod hydraulic drive system. There are four identical servo-hydraulic rod drives and each operates as a position control system. The ARCS updates its position demand control signal every 1 msec and its function is to control the transient rods so that the reactor follows a prescribed power-time profile (planned transient).

The Main Control Algorithm (MCA) for the ARCS is an optimal reactivity demand algorithm. At each time step, the MCA generates a set of reference reactor functions, e.g., power, period, energy, and delayed neutron power. These functions are compared to plant measurements and estimated values at each time step and are operated on by appropriate algorithms to generate the reactivity demand function. The data necessary to calculate the reference functions is supplied from a Transient Prescription Control Data Set (TPCDS). The TPCDS specifies the planned transient as a fixed number of simply connected independent power profile segments.

The developed simulation code, models the TREAT reactor kinetics, the hydraulic rod drive system, the plant measurement system, and the ARCS control processor MCA. All of the models operate as continuous systems with the exception of the MCA which operates as a discrete time system at fixed multiples of 1 msec.

The study indicates that the ARCS will meet or exceed all of its design specifications.

## INTRODUCTION

The Transient Reactor Test Facility (TREAT) is a test facility used to support the Liquid Metal Fast Breeder Reactor (LMFBR) safety program. The facility is located at the Argonne National Laboratory Test Site in Idaho. An upgrade of TREAT is due to become operational in 1985. The purpose of the TREAT Upgrade Project is to extend the test capabilities of the original TREAT reactor to more typical LMFBR accident conditions.

This paper describes the design and computer simulation of the Automatic Reactor Control System (ARCS) carried out for the TREAT Upgrade. This simulation was necessary because of the need to provide a test and verification of the ARCS design before installation. The many modifications to the reactor core and the reactivity control system meant that a new control strategy needed to be developed.

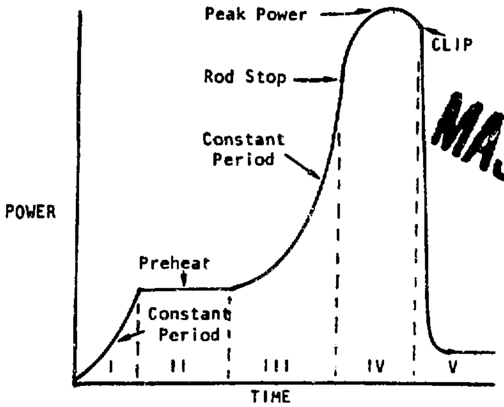
The control system includes ionization chambers, signal conditioning electronics, digital computers, MTS electronic controllers for the hydraulic positioning systems, and hydraulic pistons. There are four identical hydraulic control rod drive systems and each operates as a position control system. The rod drive systems in turn control the four transient neutron absorbing rods such that the reactor follows a predetermined power-time profile. In the transient mode TREAT operates as an adiabatic reactor.

### Control System Requirements and Constraints

The ARCS must meet the following requirements:

1. Provide a user-friendly man-machine interface to allow a user to prescribe a desired reactor power-time profile.
2. Provide a computer control signal to the four MTS closed loop position controllers for the transient rod drives.
3. Provide a computer algorithm such that the prescribed reactor power-time profile is generated under closed loop control.
4. The control algorithm shall provide smooth transitions from reactor operation on constant period to constant power and vice versa.
5. The control algorithm shall be executable at a 1 msec sample rate with an INTEL 8086/87 microprocessor.

The transient prescription defines a desired or demand reactor power-time profile. This prescription is based on an estimate of the reactor energy release required to produce the desired test fuel failure mechanism within the experimenters' test loop in the reactor.



MASTER

Figure 1. Typical TREAT Transient Power Time History

Figure 1 illustrates a typical transient prescription power-time profile. As shown, following a command for transient start, there is an initial power rise at a constant reactor period to a constant power segment (preheat) followed by a second power rise, again at a constant period, to a peak power (burst). From the experimenter's point of view, the crucial portion of the simulated accident occurs

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+The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. W-31-109-ENG-38.

about the time of the burst peak and excessive energy deposited beyond this point could act to distort the consequence of the simulated accident within the test loop. For this reason, a post-peak power clip is generally specified. The clip is achieved by rapid insertion of the transient rods.

The preheat interval is used to bring the test loop to the prototypic operating conditions that would exist in the full scale LMFBR core being simulated: the preheat interval establishes the initial conditions for the hypothetical accident. The burst interval simulates the hypothetical accident being investigated. For less demanding transients, the experimenter may optionally specify a post peak, low power segment to include decay heat consequences.

A Transient Prescription Control Data Set (TPCDS) defines to the ARCS the information necessary to generate the required power-time profile. In the actual ACRS configuration the TPCDS is generated prior to transient execution via a utility processor/control processor communication link. The TPCDS specifies both control parameter and transient data. The transient data specifies the prescription as a fixed number of independent reactor power profile segments. Each segment is connected at its end points and is described in terms of its power shape (e.g., constant period, constant power, ramp power, constant rod position, or rapid rod insertion) and conditions for segment termination. Typical conditions for which a segment may terminate include energy deposited, time, power level (from above or below), interrupt request, and extrapolation to peak energy. The interrupt termination case represents conditions in which an experimenter may request a premature segment termination.

A transient prescription to achieve the power time profile of Fig. 1 is defined by:

1. Power increase from $P_o$ on $\alpha_1$ inverse period until $P_1$ power.
2. Hold constant power at $P_1$ until $E_1$ energy.
3. Power increase on $\alpha_2$ inverse period until rod stop.
4. Rod stop is calculated based on extrapolation to achieve $E_2$ energy at peak power.
5. High speed transient rod insertion (CLIP) at T sec after peak power. An available post clip option is to hold $P_2$ power until $E_3$ energy.

Not shown in Fig. 1 is an enveloping boundary, which if crossed because of ARCS failure, leads to system scram. The scram signal is generated by a monitor computer or hardwired plant protection system (PPS).[1]

### Manual Reactor Control System (MRCS), ARCS Interface Requirements

Prior to the start of transient production, the TU-Reactor Mode switch is placed in its "Steady-State" position and the reactor is brought to the required transient initial conditions through the MRCS by manually positioning the transient rods and monitoring the reactor at critical. After the initial conditions have been established, the Mode switch is placed in the "Transient Enable position", which initiates the ARCS. The ARCS then is required to perform a number of self-diagnostic tests to assure operational readiness. If the tests are affirmative, the ARCS transmits a "Ready" status to the MRCS. At the discretion of the reactor operator a "Transient Start Command" is then issued to the ARCS which responds by producing the prescribed transient. The self-diagnostic tests necessary to place the ARCS in the operational readiness condition define the MRCS/ARCS interface requirements.

### Measurement Signal Constraints

As listed in Table I, measurements available to the ARCS are: reactor linear and log power, inverse period, and transient rod position. The data acquisition processor converts the raw measurement data (every 1 msec) to engineering units for use by the main control processor. Internal algorithms in the main control processor use the measurement data and internal data related to the prescribed reactor power-time profile to generate the rod position demand control signal. For the PPS, the energy signal is derived by direct analog integration of an ionization chamber output. The ARCS computes the required energy signal by digital integration of the linear power signal.

Table I
Measurement Signals Available to ARCS

| Measured Parameter | Sensor Type | Measurement Range |
|---|---|---|
| Linear Power | Uncompensated Ion Chamber | $10^2$ - $10^{10}$ Watts in decades |
| Log Power | Uncompensated Ion Chamber | $10^2$ - $10^{10}$ Watts |
| Inverse Period | Differentiated log signal | -0.08 to + 0.08 sec<br>-0.8 to + 0.8 sec<br>-8 to + 8 sec |
| Transient Rod Position | Position transducer | 0 - 40" |

## CONTROL ALGORITHM

### Derivation

The requirement of supplying the MTS equipment with a rod position command signal in turn requires that the main control algorithm generate a rod position demand variable. Using the results of App. A, an expression for the reactor can be written as:

$$\alpha = \beta(K_r X_r + K_f E + \rho_d)/\ell \tag{1}$$

An identical expression can be written for a demand inverse period:

$$\hat{\alpha} = \beta(K_r \hat{X}_r + K_f \hat{E} + \hat{\rho}_d)/\ell \tag{2}$$

where $\hat{\alpha}$, $\hat{x}_r$, $\hat{E}$, and $\hat{\rho}_d$ are demand variables. Combining Eqs. (1) and (2) and solving for $\hat{X}_r$ gives the Control Law

$$\hat{X}_r = X_r + \ell K_r(\hat{\alpha}-\alpha)/\beta + K_f\,(E - \hat{E})/K_r + (\rho_d - \hat{\rho}_d)/K_r \tag{3}$$

### Demand Inverse Period Algorithm (Alpha-Generator)

The demand inverse period is specified in the TPCDS for regions I and III of Figure 1. The smooth transition from regions I to II to III are accomplished by the inclusion of the Alpha-Generator shown in Fig. 2.

The Alpha Generator functions can be visualized by examining Fig. 2.

At $t=0$, $\alpha_s = \alpha_1$ and $N_{sp} = P_1$. Since $N < fN_{sp}$ then $\hat{\alpha} = \alpha_s$ and the reactor power rises on the specified inverse period $\alpha_s$. When $N > fN_{sp}$ then $\hat{\alpha} < \alpha_s$ and $\hat{\alpha}$ linearly approaches zero as N approaches

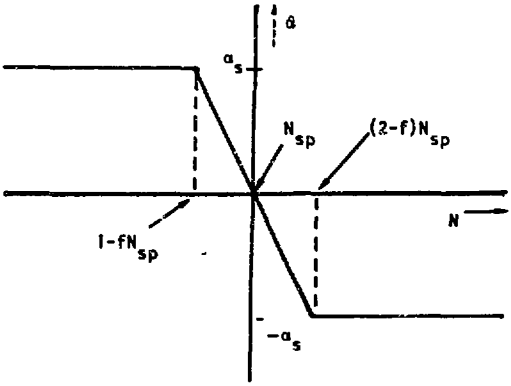

Figure 2. Alpha Generator

$N_{sp}$. At $N = N_{sp}$, $\hat{\alpha} = 0$ and reactor power is held constant at $N_{sp}$. If a perturbation were to occur and cause $N > N_{sp}$ then $\hat{\alpha} = -\alpha_s$ and the control rod position demand signal will cause $\hat{\alpha}$ to linearly approach zero and the power to approach $N_{sp}$. For region III of Fig. 1, $\alpha_s = \alpha_2$ and $N_{sp}$ is set greater than expected rod stop power, i.e., $N_{sp}$ = estimated peak power. For slower transients a value of peak power divided by f may be required for $N_{sp}$.

### Control Rod Position Algorithm

The four control rod positions are measured individually. An average rod position is computed by summing the individual rod positions and dividing the sum by four.

### Reactor Energy Algorithm

Reactor energy is calculated from the linear power measurement by using by using Trapezoidal integration.

$$E_k = E_{k-1} + (N_k + N_{k-1})T/2 \tag{4}$$

### Feedback Coefficient Algorithm

The thermal reactivity feedback coefficients ($K_f$) are computed as piece-wise linear slopes of the nonlinear energy/reactivity function shown in Table II.

Table II
Energy/Reactivity Function

| Energy (MJ) | Reactivity ($) |
|---|---|
| 0.0 | 0.0 |
| 889.4 | -1.091 |
| 2042.4 | -2.182 |
| 3410.0 | -3.273 |
| 4946.5 | -4.364 |

### Delayed Neutron Reactivity Algorithm

The reactivity contribution of the delayed neutrons is estimated by using the equations given in App. A. Table III summarizes the equations used for the reactivity algorithm.

By assuming that reactor power and demand power are constant over a sampling interval, the differential equations in Table III can be analytically integrated and algebraic state transition equations can be used to obtain updated estimates for reactivity at each sampling interval.[2] The discrete time equations for the delayed neutron reactivity algorithm are listed in Table IV.

Table III
Delayed Neutron Reactivity Algorithm

| Variable | Description | Defining Equation |
|---|---|---|
| $X_i$ | ith delayed neutron group (MW) | $\dot{X}_i = \lambda_i (N-X_i)$ |
| $\hat{X}_i$ | estimated ith delayed neutron group (MW) | $\dot{\hat{X}}_i = \lambda_i (\hat{N}-\hat{X}_i)$ |
| $\delta N$ | reactor power error (MW) | $\delta N = \hat{N} - N$ |
| $\mu_i$ | asymptotic estimate of $X_i-X_i$ (MW) | $\mu_i = \hat{X}_i-X_i$<br>$\dot{\mu}_i = \lambda_i (\delta N - \mu_i)$ |
| $\nabla\rho_d$ | estimate of delay group reactivity effect ($) | $\nabla\rho_d = \hat{\rho}_d - \rho_d$<br>$= a_i(\hat{X}_i/\hat{N} - (\hat{X}_i - \mu_i)/N)$<br>$i = 1$ to $6$ |

Table IV
Delayed Neutron Discrete Time Reactivity Algorithm

| Variable/ Parameter | | Defining Equation | Description |
|---|---|---|---|
| $\phi_{ei}$ | = | $\exp(-\lambda_i T)$ | ith estimator state transition factor |
| $\Gamma_{ei}$ | = | $1 - \phi_{ei}$ | ith estimator forcing function multiplier |
| $\mu_{ik}$ | = | $\phi_{ei}\ \mu_{ik-1} + \Gamma_{ei}\delta N_k$<br>$\mu_{io} = 0$ | ith group asymptotic estimator (MW) |
| $\hat{X}_{ik}$ | = | $\phi_{ei}\ X_{ik-1} + \Gamma_{ei}\ \hat{N}_k$<br>$X_{io} = N_o$ | ith estimated reference delay group (MW) |
| $\delta N_k$ | = | $\hat{N}_k - N_k$ | power error (MW) |
| $\Delta\rho dk$ | = | $\Sigma\, a_i(\hat{X}_i k/\hat{N}_k - (\hat{X}_{ik} - \mu_{ik})/N_k)$ | estimate of delay group reactivity ($) |
| k | | | integer denoting sample time |
| T | | | sampling interval |

Table V
Alpha-Compensator Algorithm

| Variable/ Parameter | | Defining Equation | Description |
|---|---|---|---|
| $\alpha_k$ | = | $Z_k + (\tau_1/\tau_2)\ _{mk}$ | control computer inverse period |
| $\alpha_{mk}$ | | | measured reactor inverse period after low-pass filter |
| $\tau_1$ | = | 50 msec | compensator zero |
| $\tau_2$ | = | 5 msac | compensator pole |
| $Z_k$ | = | $\phi_c Z_{k-1} + (1-\tau_1/\tau_2)*(1-\phi_c)\alpha_{mk}$ | intermediate variable in algorithm |
| $\phi_c$ | = | $\exp(-T/\tau_2)$ | compensator state transition term |

### Alpha-Compensator Algorithm

The inverse period measurement is filtered with a low pass filter to remove high-frequency noise. The filter is a first order type with a low-pass time constant of 50 msec. This time constant introduces an unacceptable measurement lag during the control transition from the transient start to the preheat flattop, resulting in the high probability of an RTS reactor trip on reactor overpower. To compensate for this measurement lag, a digital lead-lag compensator for the Alpha measurement is programmed into the Control Computer. Table V lists the compensator algorithm and its parameters.

### Power Burst Algorithm

During the preheat interval the following condition is checked:

$$E_K > E_1$$

where $E_K$ is derived from Eq. 4. If true, then $\alpha_s = \alpha_2$ and $N_{sp}$ = estimated peak power. The Alpha-Generator will cause power to increase with $\alpha_2$.

### Rod Stop Algorithm

The rod stop algorithm utilizes the definition that the slope of a curve is zero at the peak, i.e., $\alpha = 0$, at peak power with $E_{pk}$ defined as the energy at peak power. At the instant of rod stop, Eq. 12 of App. A can be used to establish the system reactivity:

$$\rho_k = \frac{\ell \alpha_k}{\beta} \qquad (5)$$

Equation 3 of App. A can be defined twice: at rod stop and at peak power. Combining these two equations and Eq. 4 yields:

$$E_{rs} = E_{pk} - (\ell\alpha/\beta - \Delta\rho)/K_f \qquad (6)$$

If $E_k > E_{rs}$ the rods are stopped, the reactivity that was available during the constant period phase is removed by the feedback energy, and the power coasts to a peak value with a corresponding desired $E_{pk}$. The term $\Delta\rho$ in Eq. 6 is included as a correction term because not all of the negative reactivity lost due to delayed neutrons is recovered at peak power.

### Power Clip Control Algorithm

The fast insertion of control rods is specified to occur at a specified time after peak power. Peak power is established by $\alpha = 0$ and $t_{pk}$ = time when $\alpha = 0$. The clip algorithms are:

If

$$t_k > t_{pk} + t_{clip} \qquad (7)$$

then

$$\hat{x}_r = 0 \qquad (8)$$

### Master Control Algorithm

Figure 3 shows in block diagram form the interrelationships of the individual algorithms enumerated above.

## SIMULATION RESULTS

The objectives of the ARCS simulation were to: 1) verify the ARCS performance to typical power-time profiles; 2) show that a 1 msec time specification can be met; 3) verify performance to the current TREAT core; and, 4) examine system sensitivity. To perform the simulation, models of the core kinetics, hydraulic transient rod drive system, and the MCA control processor were developed. Two rod drive units were modeled (one unit representing 3 identical units and the other a single unit) so that the effect of rod unit mismatches could be examined. The MCA model represents a detailed simulation of the ARCS control processor MCA, including appropriate interrupt points and measurement data conversion. Detailed models of the measurement system were also included. The model is structured so that the MCA runs at a fixed sample rate (1 msec), while the remainder of the model simulates continuous system models of the reactor core and hydraulic drive systems.

Using typical data, simulation studies were made of several key transient prescriptions. A typical prescription is the L8 event. This event calls for: a power increase from 50 W on a constant 0.1 sec period to a preheat power shelf of 240 MW; a constant power at 240 MW until a preheat energy of 1221 MJ has been obtained; followed by a 2nd power increase on a constant 0.1 sec period maintained until a rod-stop criteria is achieved; followed by a rod-hold with a consequent power roll-over to a peak power (~10,000 MW) at a prescribed energy

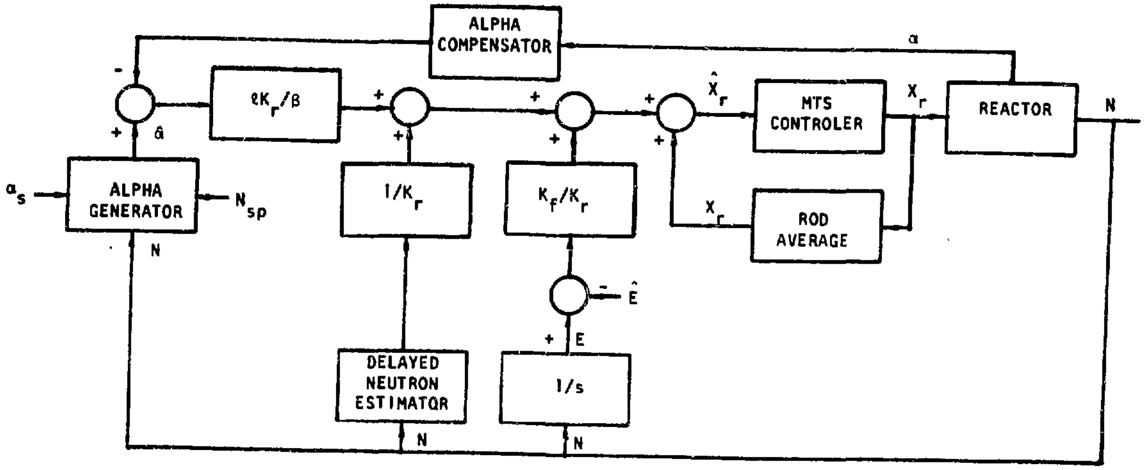

Figure 3. Master Control Algorithm

level of 2500 MJ; the event ends at 8 sec with insertion of all rods at the maximum prescribed energy. Table VI lists the simulation results for an L8 experiment. Simulation of the L8 event and other events show that the MCA is capable of maintaining the transient prescription to well within 1% of its specified value. The simulations also show that the MCA provides an event invariant control system with exceptional stability.

Table VI
Simulation Results for L-8 Experiment

| Segment | Time (sec) | Rod Pos (in) | Period (msec) | Power (MW) | Energy (MJ) |
|---|---|---|---|---|---|
| Start Transient | 1.510 | 15.78 | 100.1 | $5\times10^{-5}$ | 0.0 |
| Start Pre-Heat | 1.670 | 10.04 | | 235.8 | 48.1 |
| End Pre-Heat | 6.589 | 18.38 | | 239.0 | 1221.5 |
| Start Burst | 6.840 | 31.50 | 100.1 | 2303.6 | 1424.8 |
| Rod Stop | 6.941 | 35.17 | | 6285.0 | 1833.3 |
| Peak Power | 7.022 | 35.04 | 0.0 | 9360.0 | 2499.7 |
| Start Clip | 7.042 | 35.06 | | 9147.5 | 2685.5 |
| End Experiment | 8.000 | 0.0 | -20.0 | 106.3 | 3414.8 |

## CONCLUSIONS

The ARCS described in this paper will meet all of its design objectives. The system is realizable using the Intel 8086/87 product line and is capable of operating at higher sample rates. This is important as it allows for future real-time software expansion capabilities.

## REFERENCES

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2. W. C. Lipinski, "Optimal Digital Computer Control of Nuclear Reactors", ANL-7530, January 1969.

## APPENDIX A

### REACTOR KINETICS MODEL

The point reactor kinetics equations can be derived to provide explicit reactivity terms for control rod input, energy and delayed neutrons as follows:

$$\dot{N} = \beta \rho N/\ell \qquad (1)$$

$$\dot{X}_i = \lambda_i (N - X_i) \qquad i = 1 \text{ to } 6 \qquad (2)$$

$$\rho = \rho_r + \rho_f + \rho_d \qquad (3)$$

$$\rho_{di} = - a_i (1 - X_i/N) \qquad i = 1 \text{ to } 6 \qquad (4)$$

$$\rho_d = \Sigma \rho_{di} \qquad i = 1 \text{ to } 6 \qquad (7)$$

$$E = \int N dt \qquad (8)$$

$$\rho_f = K_f E \qquad (9)$$

$$\rho_r = K_r X_r \qquad (10)$$

$$\alpha = \dot{N}/N \qquad (11)$$

$$\alpha = \beta \rho/\ell \qquad (12)$$

In Eq. 9 $K_f$ is a function of E and in Eq. 10 $K_r$ is a function of $X_r$.

## Appendix B

### Nomenclature

| | |
|---|---|
| $\alpha$ | Inverse reactor period, $sec^{-1}$ |
| $\alpha_s$ | Setpoint inverse reactor period, $sec^{-1}$ |
| $\beta$ | Delayed neutron fraction |
| $\nabla\rho$ | Correction term for delayed neutrons at peak power, $ |
| $\lambda_i$ | Decay constant for i-th group of delayed neutrons |
| $\rho$ | Total reactivity, $ |
| $\rho_d$ | Reactivity due to delayed neutrons, $ |
| $\rho_{di}$ | Reactivity due to i-th group of delayed neutrons, $ |
| $\rho_f$ | Feedback reactivity, $ |
| $\rho_r$ | Control rod reactivity, $ |
| $a_i$ | Fraction of delayed neutrons in i-th group |
| $E$ | Reactor energy, MJ |
| $E_{pk}$ | Reactor energy at peak power, MJ |
| $E_{rs}$ | Reactor energy at rod stop, MJ |
| $f$ | Fraction of reactor power setpoint |
| $K_f$ | Temperature feedback coefficient, $/MJ |
| $K_r$ | Control rod worth, $/in |
| $\ell$ | Prompt neutron lifetime, sec |
| $N$ | Reactor power, MW |
| $N_{sp}$ | Reactor power setpoint, MW |
| $P$ | Reactor power, MW |
| $t_{clip}$ | Clip time after peak power, sec |
| $t_{pk}$ | Time at peak power, sec |
| $X_i$ | Delayed neutron power of i-th group |
| $X_r$ | Control rod position, in |

Notes:
1. Added subscript k indicates value at sample interval k.
2. Added symbol ^ above variable indicates demand variable.