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TREAT REACTOR CONTROL AND PROTECTION SYSTEM*

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ABSTRACT

The main control algorithm of the Transient Reactor Test Facility (TREAT) Automatic Reactor Control System (ARCS) resides in Read Only Memory (ROM) and only experiment specific parameters are input via keyboard entry. Prior to executing an experiment, the software and hardware of the control computer is tested by a closed loop real-time simulation. Two computers with parallel processing are used for the reactor simulation and another computer is used for simulation of the control rod system.

A monitor computer, used as a redundant diverse reactor protection channel, uses more conservative setpoints and reduces challenges to the Reactor Trip System (RTS).

The RTS consists of triplicated hardwired channels with one out of three logic. The RTS is automatically tested by a digital Dedicated Microprocessor Tester (DMT) prior to the execution of an experiment.

INTRODUCTION

The TREAT reactor [Ref. 1] has been a major transient test facility for in-pile tests in support of reactor safety research programs.

As the result of a detailed study, it was decided that the near-term optimum strategy for acquistion of additional in-pile transient testing capability was to upgrade the capabilities of the TREAT reactor.

A set of demanding functional requirements has been imposed on the upgraded facility [Ref. 2].

The necessity of meeting these demanding functional requirements in the TREAT Upgrade reactor has produced a design with a smaller margin between operating and damaging temperatures for reactor fuel assembly cladding, than is currently available in the TREAT reactor. An obvious impact on this reduced margin in temperature is the reduced time interval between initiation of a reactivity accident and progression to reactor clad damaging conditions. In other words, unless protective mechanisms detect a malfunction and intervene in time, the possibility of fuel clad damage from reactivity accidents must be considered [Refs. 3 and 4]. This paper describes the design of a multilayered reactivity accident prevention and protection system for the TREAT Upgrade reactor.

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AUTOMATIC REACTOR CONTROL SYSTEM (ARCS)

The ARCS 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 an independent position control system which receives a position command signal from the master controller. The rod drive systems in turn position 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

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 experimenter's test loop in the reactor.

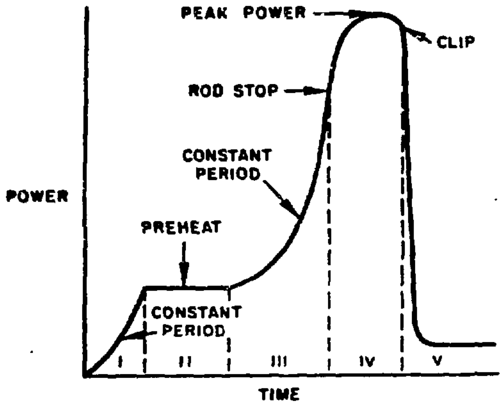

Fig. 1. Typical TREAT Transient Power Time History

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 about the time of this 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 experiment is terminated with a reactor scram.

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 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 ARCS 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 positon, 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.

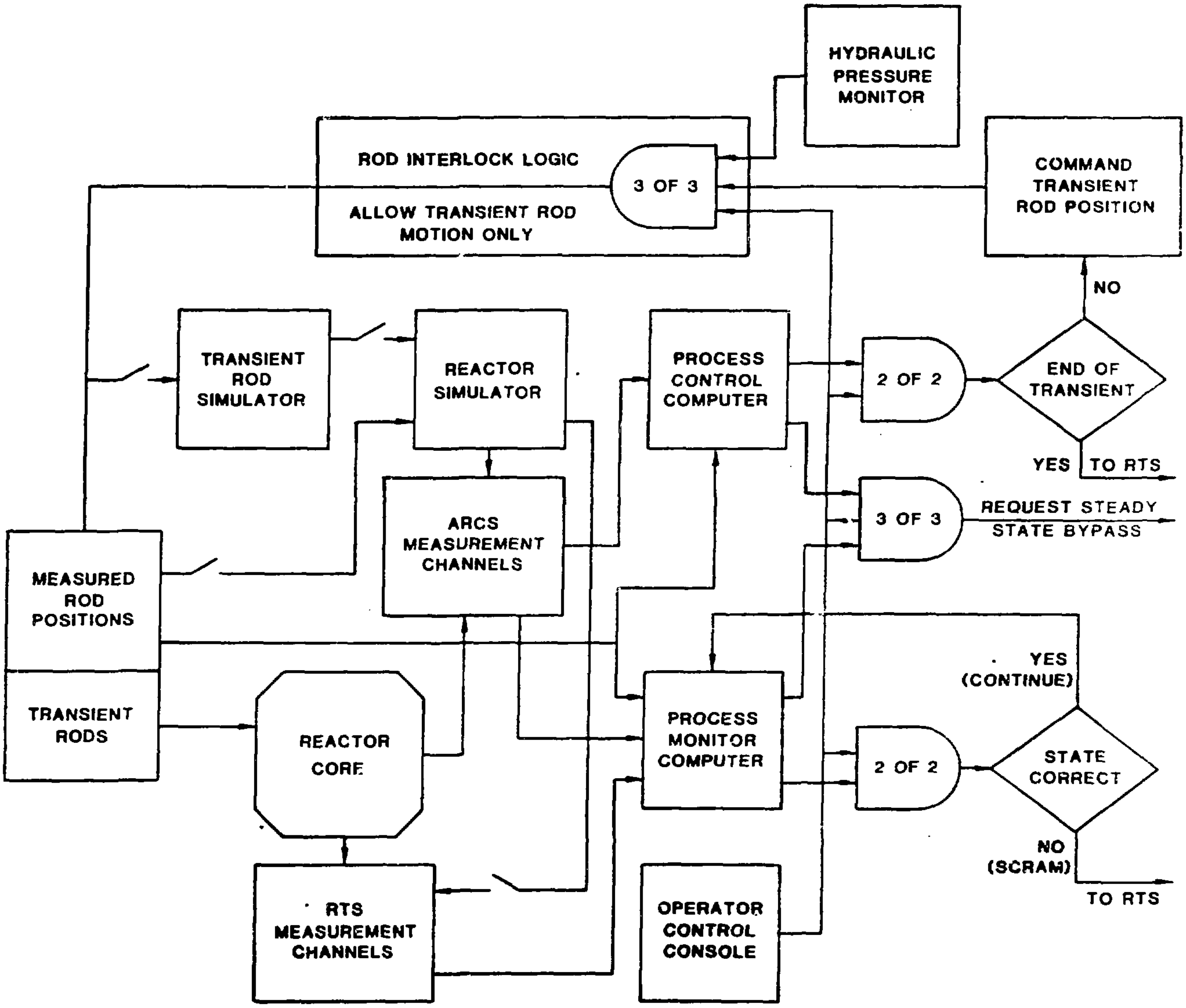

Fig. 2. Automatic Reactor Control System Block Diagram.

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. The block diagram for the ARCS is shown in Fig. 2.

MEASUREMENT SIGNAL CONSTRAINTS

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.

CONTROL ALGORITHM

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

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

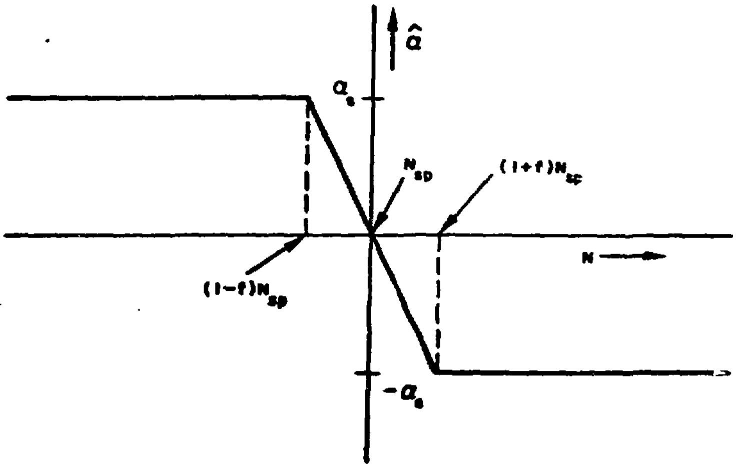

Fig. 3. Alpha Generator

DEMAND INVERSE PERIOD ALGORITHM (ALPHA-GENERATOR)

The demand inverse period is specified in the TPCDS for regions I and III of Fig. 1. The smooth transition from regions I to II and II to III are accomplished by the inclusion of the Alpha-Generator shown in Fig. 3.

The Alpha Generator functions can be visualized by examining Fig. 3. At $t = 0$, $\alpha = \alpha_s$ and $N_{sp} = P_{sp}$. Since $N < fN_{sp}$ then $\alpha = \alpha_s$ and the reactor power rises on the specified inverse period α_s. When $N > fN_{sp}$ then $\alpha < \alpha_s$ and α linearly approaches zero as N approaches N_{sp}. At $N = N_{sp}$, $\alpha = 0$ and reactor power is held constant at N_{sp}. If a perturbation would occur and cause $N > N_{sp}$ then $\alpha = -\alpha_s$ and the control rod position demand signal will cause α 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

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

FEEDBACK COEFFICIENT ALGORITHM

The thermal reactivity feedback coefficients (K_f) are computed as piece-wise linear slopes of the nonlinear energy/reactivity function [Ref. 5].

DELAYED NEUTRON REACTIVITY ALGORITHM

The reactivity contribution of the delayed neutrons is estimated by using the equations given in App. A. By assuming that reactor power and demand power are constant over a sampling interval, the differential equations can be analytically integrated and algebraic state transition equations can be used to obtain updated estimates for reactivity at each sampling interval [Ref. 5].

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.

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 α_2.

ROD STOP ALGORITHM

The rod stop algorithm utilizes the definition that the slope of a curve is zer 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. 10 of App. A can be used to establish the system reactivity:

$$\rho_k = \ell\,\alpha_k/\beta \tag{5}$$

Equation 3 of App. A can be defined twice: at rod stop and at peak power. Combinin these two equations and Eq. 5 yields:

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

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 desired time after peak power. Peak power is established by $\alpha = 0$ and t_{pk} = time when $\alpha = 0$. The clip algorithms are:

$$\text{if} \quad t_k > t_{pk} + t_{clip} \tag{7}$$

$$\text{then} \quad \hat{x}_r = 0 \tag{8}$$

SIMULATION RESULTS

The objectives of the ARCS simulation were to: 1) verify the ARCS performance t 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 three 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 interrup points and measurement data conversion. Detailed models of the measurement system were also included. The model is structured so that the Master Control Algorithm (MCA) runs at a fixed sample rate (1 msec), while the remainder of the model simulate 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 1220 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 level of 2500 MJ; the event ends at 8 sec with insertion of all rods at the maximum prescribed energy. Table I 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 I

Simulation Results for L-8 Experiment

Segment	Time (Sec)	Rod Pos (in.)	Period (msec)	Power (MW)	Energy (MJ)
Start Transient	0.0	0.0	∞	$5\text{x}10^{-5}$	0.0
Start Pre-Heat	1.670	10.04		235.8	48.1
End Pre-Heat	6.589	18.3[illegible]		239.0	1221.5
Start Burst	6.840	31.50		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	2685.6
End Experiment	8.000	0.0	-20.0	106.3	3414.8

SIMULATORS

High reliability of the ARCS software and hardware is guaranteed by performing a series of transient simulations before committing to an actual experiment. The first simulation is performed off-line on a main-frame computer using a Continuous Systems Modeling Program (CSMP) simulation of the reactor, control system dynamics, and control algorithm and experiment specific control parameters. This simulation is not performed in real-time. The second simulation is performed in real-time using specific control parameters loaded into the process control computer, and using the real-time transient rod and reactor simulators. The third simulation performed is similar to the second, except the actual hydraulic control system is included in the control loop with the reactor held subcritical by the insertion of eight rods. This step-wise verification of the selected control parameters and the associated closed loop transient performance assures that the final transient performed on the reactor will meet the experimenter's specifications without having to perform trial and error experiments on the reactor.

MONITOR COMPUTER

The reactor trip system design as originally proposed included two hard wired channels and a third redundant and diverse computer channel. Since the RTS was designed to meet a specific reliability goal, the reliability of the hard wired channels and the computer channel had to be quantified. The quantification of the computer channel reliability had to include both hardware and software. The safety review committee accepted the values presented for hardware reliability (i.e. 10^{-4} to 10^{-3} failure per 10 hour interval) but would not accept software validation and verification nor black box testing of fixed structure software (which could only accept parametric inputs over an allowable range) without a numerical reliability specification for the software. Under these conditions, a third hard wired channel was added to the RTS and the diverse computer channel was defined to be part of the ARCS. The monitor computer functions to detect errant behavior of the control system and terminates an experiment before the RTS is challenged.

The monitor computer is programmed to duplicate the RTS protective functions on period, power and energy with more conservative setpoints. In addition, the monitor computer performs interchannel comparisons of the RTS and ARCS nuclear channel outputs, and compares the relative positions of the four transient rods to verify proper performance as a bank. If deviations of nuclear channel outputs or rod bank performance are detected before the end of the preheat interval, the monitor computer sends a signal to the RTS to scram the reactor.

DEDICATED MICROPROCESSOR TESTER

The TREAT Reactor Trip System (RTS) is a multiply-redundant safety system which provides safe operation for both steady state and transient production operating modes. To insure that this complex safety system is functioning properly, a Dedicated Microprocessor Tester (DMT) has been implemented to perform a thorough checkout of the RTS prior to all TREAT operations. A quantitative reliability analysis of the RTS shows that the unreliability, that is, the probability of failure, is acceptable for a 10 hour mission time or risk interval. Consequently an automated tester is necessary to complete the RTS checkout and allow reactor operations within this restricted interval. The complete RTS checkout sequence requires 1-1/4 hours. Additionally, the DMT improves the reliability of the checkout by reducing the potential for gross human error; that is, the DMT monitors the RTS to verify that the operator responded correctly to each DMT-requested action, e.g., to press a button. Therefore the DMT both increases the efficiency of the RTS checkout and improves the reliability of the validation.

RTS DESCRIPTION

The basic function of the Reactor Trip System (RTS) is to protect the reactor facility by preventing potentially damaging uncontrolled reactivity excursions. The RTS monitors the facility for the occurrence of abnormal operating conditions by continuously comparing instrumentation signals against preset limits. Upon sensing an out-of-limits condition, the RTS initiates a reactor scram by removing the control-rod-drive latch voltages. The RTS is designed to monitor both steady state and transient production operations; bypasses are employed as needed to circumvent steady state trip circuits in the transient production mode. A comprehensive block diagram of the entire RTS is presented in an earlier paper [Ref. 6].

The RTS transient instrumentation is a triply-redundant system; each group, identified by A, B, or C, consists of Linear Power, Integrated Power or Energy, and Log/Period nuclear channels that deliver analog inputs to the Transient Input Trip Logic. The input trip logic compares these analog inputs to specified reference values which define the operational boundary for transient production. Figure 1 illustrates a typical transient with power as a function of time, but trip boundaries and associated limiting temperatures are better defined in the Power vs. Energy plane [Ref. 4]. The boundaries for the power and energy signals are displayed on the power versus energy (PE) plane in Fig. 4a, along with the trace of a typical transient; the scans indicated on the figure are discussed in Test Procedures. Two boundaries, and hence two separate trip circuits, are defined: one, the transient-dependent which is adjustable using 10-turn potentiometers on the front panel and, two, the transient-independent which is internally hard-wired. The maximum values for the transient-dependent boundary correspond to those for the transient-independent boundary; therefore, the transient-independent trip circuits serve as backup to the transient-dependent trip circuits. In addition, the transient-independent circuits include a dynamic period boundary which provides an energy-dependent period trip point. The boundaries for the dynamic period trip are displayed on the α versus energy (αE) plane in Fig. 4b.

The latched trip-status outputs from the five Input Trip Logic units, together with trip signals from the ARCS computers and manual scram buttons, are supplied to of the triplicated Ouput Trip Logic units. If one of these units sense the tripped-condition of any of its inputs, it signals the solid state relays in the corresponding Trip Unit to turn-off. Since the Trip Units are in series, turning-off the relays will remove the latch power from all 12 control rod drives, thus scramming the reactor. Additionally, two independent seismic channels will initiate a scram if the ground acceleration along any of the axes in the subpile room exceeds limits.

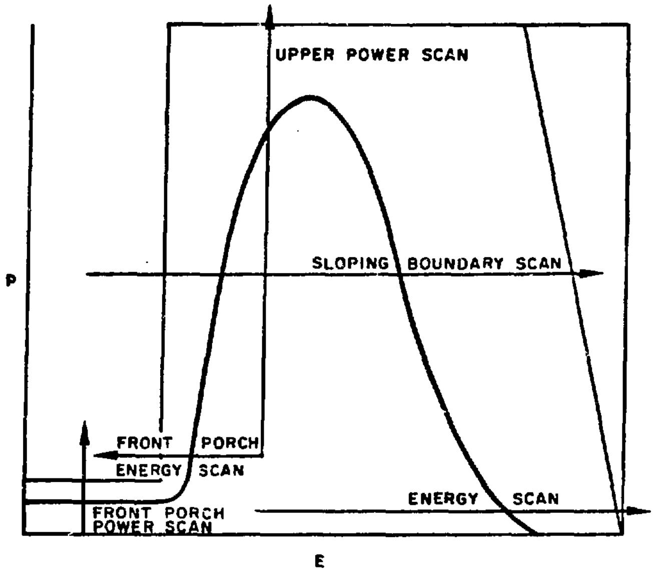

Fig. 4a. Transient-Dependent Parameters for Transient Input Trip Logic

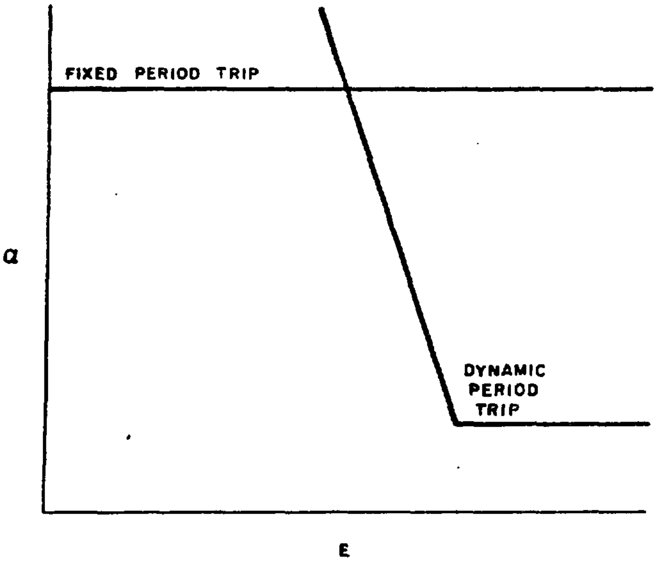

Fig. 4b. Transient-Dependent Dynamic Period Trip

DMT HARDWARE

Figure 5 is a block diagram of the DMT hardware. Since the DMT is an extension of the TREAT Upgrade Automatic Reactor Control System (ARCS), it uses commercially available hardware compatible with the ARCS. The DMT's CPU is an 8086/8087 Multibus* single board computer. Additional Multibus boards provide 216 bits of digital I/O, 64 multiplexed channels of 12-bit analog input, and 8 channels of 12-bit analog output. The DMT distribution panel is the physical interconnect between RTS/DMT cables and the DMT I/O ports. The distribution panel provides passive R-C filtering on all analog and digital inputs and interfaces RTS bi-directional analog signals with the DMT analog to digital converter (ADC) and digital to analog converters (DAC). CMOS switches controlled by DMT digital outputs are used to connect and disconnect the DMT digital to analog converters. In addition, the distribution panel provides two reference voltages used in the DMT's ADC calibration self-check.

The DMT connects to the ARCS central node computer via a serial port. The DMT uses this link to the central node to obtain printer services, to invoke ARCS initiated stimuli, and to obtain nonvolatile storage. Since the DMT is not configured with a printer, it must use the central node's line printer to generate hardcopy of test results. Text is sent via the serial port to a print task running on the central node. The DMT is required to test the RTS response to ARCS initiated stimuli such as computer trips and transient enabling signals. The DMT requests operator invocation of these ARCS initiated stimuli by sending a message via the serial port to the

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*Multibus and IRMX88 are trademarks of Intel Corp.

central node task. Finally, the DMT requires writable nonvolatile storage for core configuration dependent parameters. Since the DMT has only PROM and RAM memory, it must use the Winchester disk on the central node to store and recall core configuration dependent parameters. Again this is accomplished through communications with a central node task via the serial port.

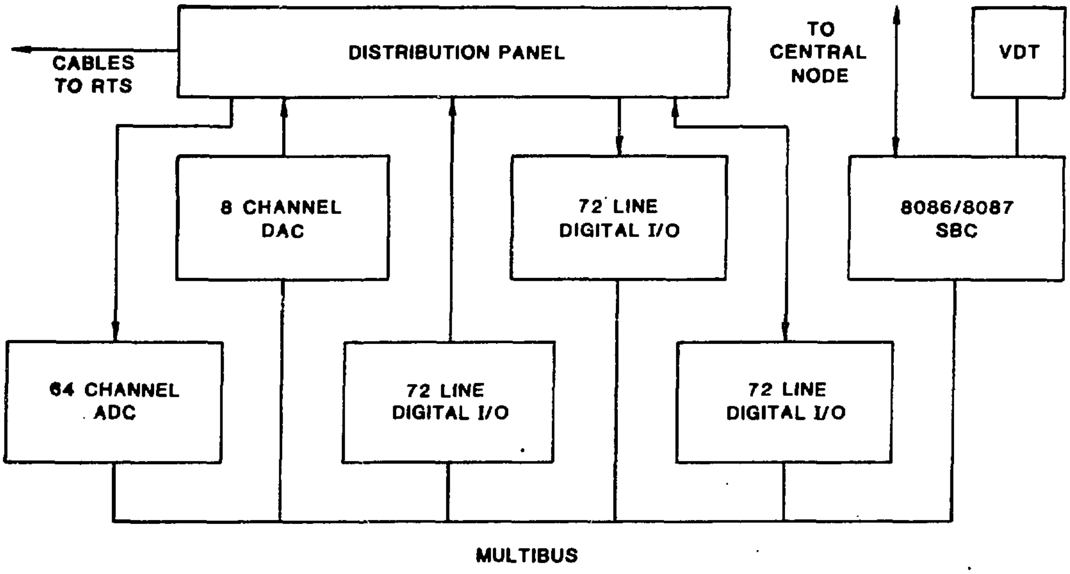

Fig. 5. DMT Block Diagram

DMT SOFTWARE

The DMT software system uses Intel's IRMX88 executive. IRMX88 is PROM-based, event-driven and multitasking. All applications code for the DMT is written in Intel's PLM86 high level compiling language. The code is generally structured into a program, subprogram and module organization. Basic functions such as analog and digital input and output are at the module level. These modules are invoked by subprograms to test individual instruments. The subprograms in turn are invoked by the DMT RTS test task which performs testing of the RTS. More complete discussion of DMT software is given in an earlier paper [Ref. 6].

DMT VERIFICATION AND VALIDATION

Since the DMT is deemed to be "safety related", a quality assurance plan for the DMT implementation was written which conforms to the requirements of ANSI/ASME standard N45.2-1977, Quality Assurance Program Requirement for Nuclear Facilities. The QA plan spawned a number of control procedures addressing areas such as hardware and software design control, software development control, system test control, document control, etc.

Software verification and validation is an integral, significant factor in the DMT software design, development and testing process. A detailed software specification down to the module level was developed and verified against DMT functional requirements. Software development began after review and acceptance of the specification. Verification during the development phase consisted of review of module and subprogram listings and testing of modules and subprograms.

DMT system testing consists of system verification, validation, reverification, and revalidation phases. The verification and validation phases was performed with the DMT's program in RAM rather than PROM to facilitate correction of any software problems. In the verification phase the DMT is required to successfully complete a test of an RTS system known to be error free. The validation phase consists of performing an error-seeded test to demonstrate the DMT's ability to detect and announce RTS failures. Approximately 300 errors were sequentially seeded in the RTS to exercise all the DMT's fault detection capabilities.

Upon successful completion of the verification and validation tests, the DMT program was committed to PROM and software configuration control commenced. The software configuration control requires the documentation of software problems in Software Problem Reports (SPRs) and the documentation of corrective actions for modifications in Software Change Orders (SCOs). An SPR identifies the nature of the problem, the conditions under which the problem manifested itself and the name and version number of the module causing the problem. After review of the SPR, an SCO is generated which specifies a software change, the purpose of the change, the module to be changed, the new module version number, the programmer to make the change, the date the change was made and the date the change was tested. The SPRs and SCOs provide an auditable trail to software changes.

After the DMT's program was transferred to PROM, the verification and validation tests were repeated from the PROM resident version (reverification and revalidation) to ensure that the transfer did not introduce errors.

CONCLUSION

The Automatic Reactor Control System (including the simulators), the Reactor Trip System, and the Dedicated Microprocessor Tester were thoroughly tested. The test results demonstrated that all design objectives were met. In March 1985 the equipment was shipped from ANL-East and installed in the cabinet housings in the I&C room at TREAT. Final installation will be performed during the shutdown scheduled to complete the upgrading of TREAT.

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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:

$$\dot{N} = \beta\ \rho N/\ell \tag{1}$$

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

$$\rho = \rho_r + \rho_f + \rho_d \tag{3}$$

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

$$\rho_d = \Sigma\ \rho_{di} \qquad i = 1 \text{ to } 6 \tag{5}$$

$$E = \int N dt \tag{6}$$

$$\rho_f = K_f E \tag{7}$$

$$\rho_r = K_r X_r \tag{8}$$

$$\alpha = \dot{N}/N \tag{9}$$

$$\alpha = \beta\ \rho/\ell \tag{10}$$

In Eq. 7 K_f is a function of E and in Eq. 8 K_r is a function of X_r.

APPENDIX B
NOMENCLATURE

α	Inverse reactor period, sec^{-1}
α_s	Setpoint inverse reactor period, sec^{-1}
β	Delayed neutron fraction
$\Delta\rho$	Correction term for delayed neutrons at peak power, \$
λ_i	Decay constant for i-th group of delayed neutrons
ρ	Total reactivity, \$
ρ_d	Reactivity due to delayed neutrons, \$
ρ_{di}	Reactivity due to i-th group of delayed neutrons, \$
ρ_f	Feedback reactivity, \$
ρ_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 set-setpoint
K_f	Temperature feedback coefficient, \$/MJ
K_r	Control rod worth, \$/in.
ℓ	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.