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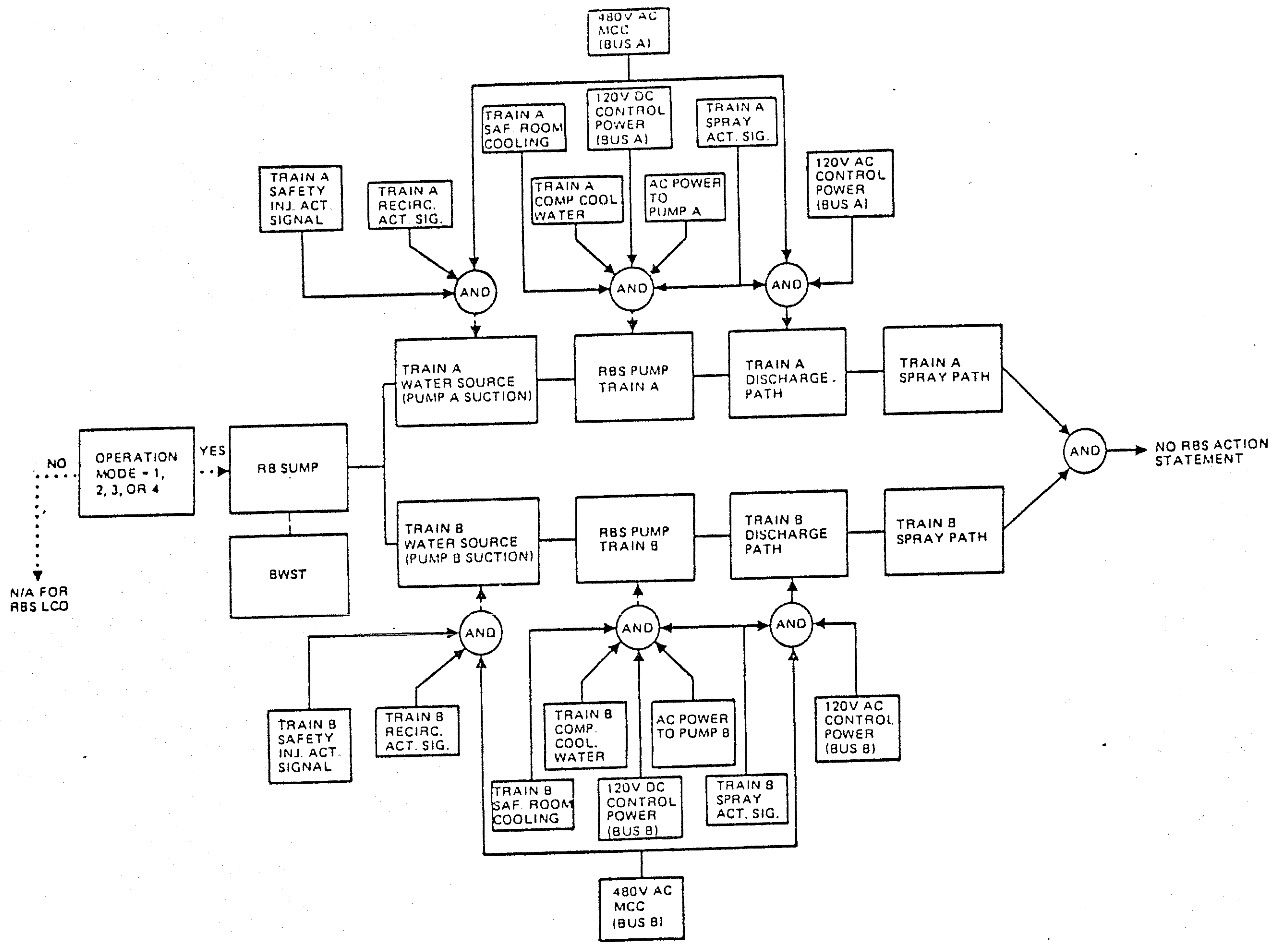

Fig. 1. Example block diagram of reactor building spray system.

him which LCO action statements apply as a result of the component status change. The documentation describes the plant system models, the applicable LCOs. In addition, this report provides a detailed description of the computerized component data files and the logic model files, as well as instructions on how to use the MTSECS. Included in the operating instructions is information on input of component status changes, execution of LCO evaluations, and interpretation of output instruction. Hence, with this report, the plant operating staff is prepared to use MTSECS without continuing need for outside support.

The MTSECS makes operator's decisions on technical specifications compliance more accurate and timely. This allows the operator to put more time and attention on monitoring other aspects of the plant's safety and performance rather than on making decisions about technical specification compliance.

3. Digital Computer Control of a Nuclear Reactor, *J. Bernard, A. Ray, D. Lanning (MIT)*

This paper describes a digital algorithm that changes power on the 5-MW(th) MIT research reactor. The Massachusetts Institute of Technology and the Charles Stark Draper Laboratory have undertaken a program to demonstrate signal validation techniques for real-time fault diagnosis, information display, and sensor calibration in nuclear plants.[1] In addition, methods for the real-time measurement of reactivity and the direct digital control of reactor power are being investigated.

There has been little application of direct digital control to reactors in the United States. Frogner attributes this to the regulatory position that credit not be taken for the positive performance of an automated control system but an allowance be made for potential malfunctions. Also, the design of safety systems has overshadowed that of controllers.[2] Discussions with industry officials have revealed other reasons including concern that computers might enable nonlicensed individuals, (e.g., load-dispatchers) to initiate power changes and that existing control methods are considered adequate.

Direct digital control does offer many potential improvements such as:

1. The integration of interacting analog control laws into a well-designed digital algorithm. This might reduce the incidence of feed pump pressure/steam generator level malfunctions.
2. The ability to monitor and strictly limit reactivity.
3. The detection and control of xenon oscillations.
4. Improved core power distribution control.
5. Calculation, display, and control of parameters such as subcooling margin and NPSH that are not directly measurable.

6. Enabling the licensed operator to monitor the plant without having to manipulate it. Nuclear power, unlike airlines or the chemical industry, still requires that operators do both.

A description of the MIT research reactor is given elsewhere.[1] An existing controller was replaced by a digital controller using validated signals. Its algorithm, which adjusts power by positioning a regulating rod whose integral worth is 0.17% $\Delta K/K$, is unique in several respects. First, it determines reactivity on line via either a balance or inverse kinetics. Second, it incorporates reactivity feedback. Third, overshoots are prevented by restricting reactivity so that reactor period can always be made infinite by stopping rod motion. This is a vital safety feature since the rate of change of power depends on both the rod motion ($d\rho/dt$) and rod height above the critical position (ρ). Finite rod speeds and position-dependent rod worths may make it impossible to instantly negate reactivity. Thus, even with the direction of rod motion reversed, power could still rise if sufficient positive reactivity were still present. The relations between power (P), period (τ), and reactivity (ρ) are given by:

$$P(t) = P(0)\exp(t/\tau) \quad (1)$$

$$\tau = (\bar{\beta} - \rho)/(\lambda\rho + d\rho/dt) \; , \quad (2)$$

where $\bar{\beta}$ is the effective delayed-neutron fraction and λ is the time-dependent effective one-group decay constant.

Safety dictates that $(\bar{\beta} - \rho)$ be kept positive. So, period can be rapidly made infinite if reactivity is restricted so that:

$$\rho \leqslant |d\rho/dt|/\lambda \; . \quad (3)$$

The algorithm therefore restricts reactivity according to the relation:

$$[\rho - \dot{\rho}/\lambda]/\dot{\rho} \leqslant \tau \ln(P_f/P) \; . \quad (4)$$

The equation compares the time remaining to attain full power (P_f) with the time required to eliminate whatever reactivity is present beyond the controllable amount as specified by Eq. (3). The one-group decay constant, λ, is updated in real-time using an analytic reactor model.

The algorithm contains separate safety and instruction sections. The former ensures that power, period (transient and steady), and reactivity are as prescribed. The latter correlates predetermined control actions, which have been evaluated off-line for safety and which correspond to the directives provided to licensed operators, with the reactor's power and period. Safety section signals supercede all others.

Figure 1 shows two experimental runs in which power was lowered from 4 to 1 MW, held constant for several

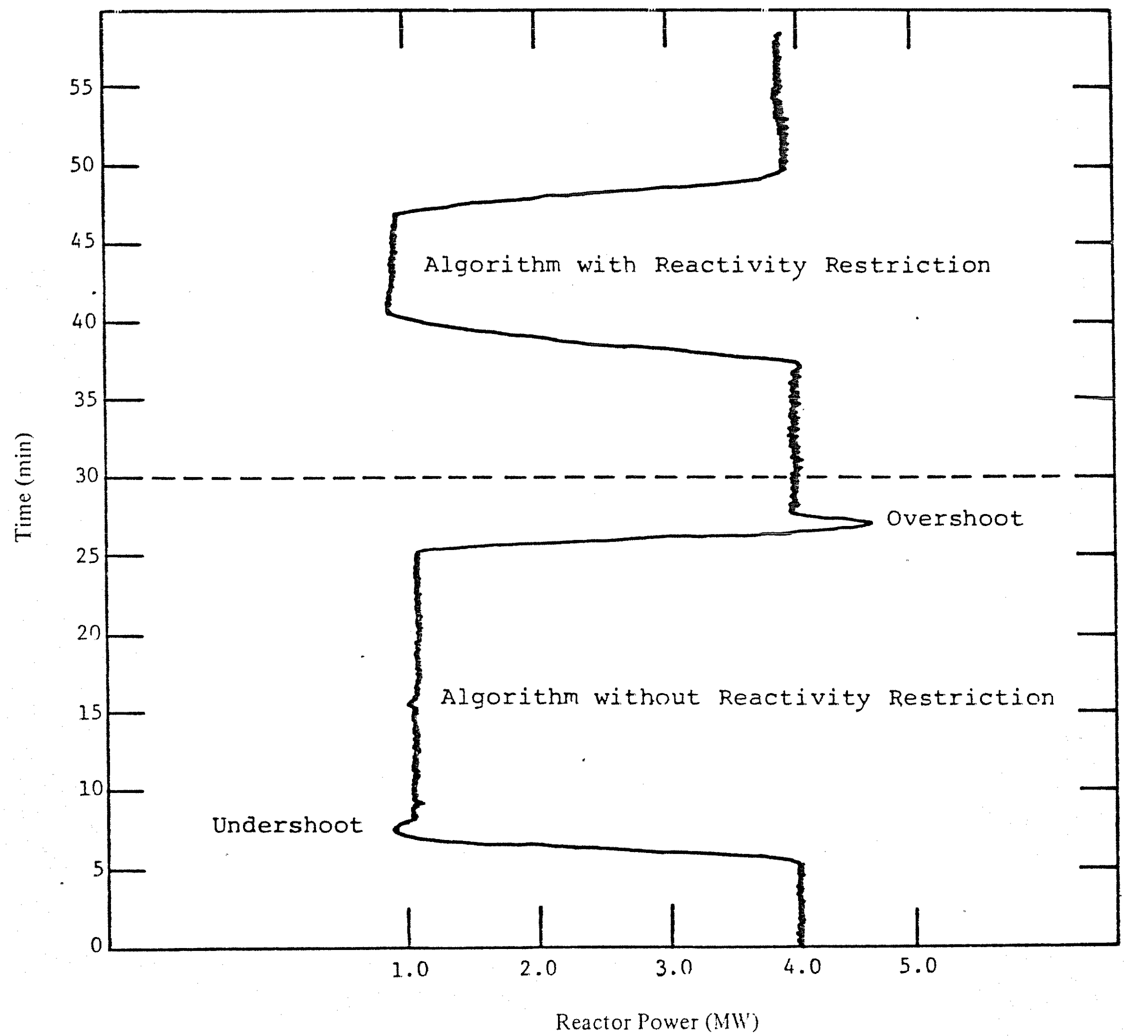

Fig. 1. Reactor power transients under direct digital control.

minutes, and then returned to 4 MW. First, the response of a controller designed without the reactivity restriction given by Eq. (4) is depicted. There is an undershoot at 1 MW and a substantial overshoot at 4 MW. Second, the response of a controller with that restriction is shown. There is neither an under- nor overshoot. (*Note*: The slight slopes observable in the traces at steady state result from changes in primary coolant temperature which affect the leakage flux to the neutron sensors. This will soon be corrected.)

Safety features associated with the hardware are discussed elsewhere.[1] Those associated with software will be reported later.

Ultimately, it is hoped to demonstrate total direct digital control, including startups, of the MITR-II. If the safety and advantages of this approach can be shown on a research reactor, then it might be possible to extend the use of digital control techniques to commercial nuclear plants.

1. A. RAY and J. BERNARD, "On-Line Signal Validation and Feedback Control in a Nuclear Reactor," 5th Power Plant Dynamics, Control and Testing Symposium, Knoxville, Tenn., March 1983.

2. B. FROGNER and H. S. RAO, "Control of Nuclear Power Plants," *IEEE Trans. Automatic Control*, **AC-23**, *3*, 405 (June 1978).

4. Design of an Automatic Control Rod Drive System for Transient Power Testing at EBR-II, *L. J. Christensen (ANL-Idaho)*

A computer-controlled automatic control rod drive system (ACRDS) was designed and operated in EBR-II during reactor runs 121 and 122. The ACRDS was operated in a "checkout" mode during run 121 using a low worth control rod. During run 122 a high worth control rod was used to perform overpower transient tests as part of the LMFBR oxide fuels transient testing program.[1] The testing program required an increase in power of 4 MW/s, a hold time of 12 min and a power decrease of 4 MW/s. During run 122, 13 power transients were performed.

The ACRDS design featured two operating modes: (a) a manual mode where the reactor operator controlled the rod movement using the existing raise-lower switches, and (b) an automatic mode where a computer generated the error signal to the controller that operated the dc rod drive motor. The control system is shown in Fig. 1. The ACRDS was used on only one of the eight control rods with the other seven operated in manual mode. The ACRDS replaced the existing single-speed drive motor with a servocontrolled dc motor.

Manual mode was the preferred operating mode from a safety standpoint due to its slower speed. Abnormal conditions sensed in automatic mode would trip the system back to manual mode. Even in manual mode, interlocks prevented rod insertion unless the reactor power was <16% or the rod had previously been inserted to 8 in. The ACRDS could be removed in manual mode at any time since this was the less reactive condition.

In manual mode the control rod speed was the same as the other control rods. The manual controller output voltage was limited and clamped so rod speed could not exceed the normal 0.083 in./s.

Automatic mode was severely restricted both by procedure and by hardware and software interlocks. Nine conditions were required to be fulfilled before the automatic permissive circuit was active. Two interlocks were associated with the computer: (a) one was a software check that verified all parameters were within expected limits, and (b) a circuit that checked to ascertain the software was cycling through the main program. One interlock was activated by power level and one by the position of the ACRDS control rod. The others were associated with rod operation.

In automatic mode, the velocity demand signal was generated by comparing the power feedback signal with the power demand trace stored by the computer. The computer algorithm calculated the velocity error signal required. The motor was operated in automatic mode from stop to nearly maximum control speed and would move the $0.83 control rod at rates up to ±1.2 in./s. This provided sufficient reactivity insertion rate to quickly achieve and maintain the 4 MW/s change in power. The fast acceleration and deceleration times, <200 ms, and ample velocity provided a system that could change power rapidly. Very little power overshoot or undershoot existed by the design, as shown in Fig. 2.

A 16-bit microcomputer with 128 K RAM, 8 D/A channels, 8 A/D channels, and hardware multiply-divide was used. The subroutines occupied <64 K of the memory. The computer system had a printer and CRT terminal. The printer was used to print, for verification, the control parameters for the transient to be run. The CRT terminal was used to input and output information to the operator prior to and after the transient. The computer I/O handler required too much time to run in real time during a transient and could not graph the progress of the transient.

The use of a dc motor in a servo-feedback system created safety problems since the dc motor is not inherently speed limited. Both controllers were modified internally so the voltage to the motor, and therefore the speed, was limited to values supported by safety analysis. The dc servocontroller-motor system had the feature of constant torque and therefore constant acceleration. The 460-oz-in. motor accelerated the control rod to control velocity in 200 ms.

Software development consisted of several stages.[2] In a mockup ACRDS test assembly, the transfer function of the ACRDS rod, drive motor, and gearing was measured using a white noise source. EBR-II dynamic parameters and control rod worths permitted a preliminary controller algorithm design. Final controller design and simulated tests were conducted on a hybrid computer. Parallel to this effort, an EBR-II dynamics and rod worth simulator (portable analog device) was fabricated allowing preliminary algorithm testing on the ACRDS control computer with a mockup control rod. Final transient simulations were performed with the control rod installed in the reactor.

Operational and safety interlocks and trips were provided to assure operation within the approved safety envelope. The safety criteria required that (a) a single failure would not insert reactivity faster than 12 ¢/s, and (b) that sodium boiling temperatures could not be reached. The first criterion was achieved by limiting the voltage output of the controller and velocity check by the computer. The second was met by software and hardware interlocks on rod position that would cause the ACRDS to trip to the slow manual mode. Additional interlocks were provided to prevent unauthorized use of the ACRDS in automatic mode and to limit rod movement.

During reactor startup the ACRDS rod was fully inserted using manual mode. Prior to performing a transient, the ACRDS was lowered to its starting position and the system placed in automatic mode.

To get into automatic mode required all interlocks to be satisfied, a transient permissive key was issued by the shift supervisor and the transient software was loaded into the computer. The transient software was considered a controlled document and was issued by approved procedure.

The power was then held constant by the computer-controlled system until the "transient start" pushbutton was depressed that started the transient sequence. A typical transient is shown in Fig. 2 with the rod movement shown in