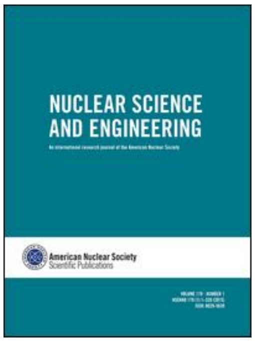

Nuclear Science and Engineering

ISSN: 0029-5639 (Print) 1943-748X (Online) Journal homepage: https://www.tandfonline.com/loi/unse20

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To cite this article: John A. Bernard & David D. Lanning (1992) Considerations in the Design and Implementation of Control Laws for the Digital Operation of Research Reactors, Nuclear Science and Engineering, 110:4, 425-444, DOI: 10.13182/NSE92-A23916

To link to this article: https://doi.org/10.13182/NSE92-A23916

Published online: 12 May 2017.

NUCLEAR SCIENCE AND ENGINEERING: **110**, 425–444 (1992)

Considerations in the Design and Implementation of Control Laws for the Digital Operation of Research Reactors

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Received October 8, 1990
Accepted August 29, 1991

Abstract—*Factors relevant to the design and implementation of digital controllers for research reactors are discussed with emphasis on the rationale for incorporating a system model in the control law. For this purpose, proportional-integral-derivative and period-generated control are compared. The latter is a model-based technique that achieves excellent trajectory tracking of nonlinear systems. It does this by combining feedback and feedforward control action in a manner that cancels the effects of the system's dynamics on the controller's performance. Model-based control is also superior in that it permits replication of some of the functions that humans perform when exercising control. In particular, models can be used to predict expected plant response and thereby facilitate diagnosis. The importance of validated signals, supervisory algorithms, properly designed man-machine interfaces, and automated diagnostics are discussed in relation to control law implementation. In addition, a summary is provided of reactor dynamics as related to control, and arguments are presented in support of using the rate of change of reactivity as the actuator signal. Experimental results obtained from trials of digital controllers on both the 5-MW(thermal) Massachusetts Institute of Technology Research Reactor and the Annular Core Research Reactor that is operated by Sandia National Laboratories are included.*

I. INTRODUCTION

Research reactors are multipurpose facilities that provide sources of neutron and, in some cases, gamma radiation for use in the basic and applied sciences, education, materials research, medicine, earth and planetary studies, neutron activation analysis, engineering, and many other disciplines. For example, major research projects currently in progress at the 5-MW(thermal) Massachusetts Institute of Technology Research Reactor (MITR-II) include the evaluation of the radioisotope ^{165}Dy for the nonsurgical treatment of rheumatoid arthritis, the study of coolant chemistries with the objective of reducing radiation exposure from activated corrosion products, the use of neutron activation analysis to identify sources of airborne pollutants (acid deposition), the possible identification of earthquake-prone geologic formations by using track-etch techniques to assess microcracks, the development of neutron capture therapies for the treatment of deep-seated brain tumors such as glioblastoma multiforme, and the radiation-hardness testing of electronic devices for use in space travel.[1–3] This wide range of activities necessitates frequent adjustments of a research reactor's power. Given this need for flexible operation and the present availability of sophisticated yet low-cost, real-time computing equipment, the operators of research reactors are increasingly considering conversion of their facilities to digital control.

Digital systems are very different from the analog controllers with which most research reactors were equipped when they were built some 15 to 35 yr ago. To fully appreciate this difference, it is necessary to have some understanding of how humans achieve control. Four tasks are involved. These are planning, prediction, implementation, and assessment.[4,5] Planning entails first noting the operational objectives, then determining the current plant state, and finally identifying the most efficient means for achieving the objectives given the confines of approved procedures. A specific sequence of control actions is then chosen based on the operator's experience and understanding of the plant. For example, a skilled operator would know whether or not withdrawal of a control device by a certain distance would result in an acceptable rate of rise of power. Adjustments to the chosen control signal are made only if it appears that the response of the plant will not be as projected. Thus, an operator's ability to anticipate or predict plant behavior is of the utmost importance. Implementation of the selected control action may require the simultaneous application of signals to several plant subsystems. This process is already often entirely automated via electromechanical means. The last of the four tasks is assessment, and it is the most complex. Operators must ascertain that the required control action is being implemented. If all proceeds as anticipated, there is no difficulty. But if that is not the case, the operator must determine why. Is his or her understanding of the plant's behavior deficient? Or has some component failed, and, if so, which one? Assessment is generally only done well by experienced personnel.

Analog devices are basically an extension of a human's capability to implement a control action. Such equipment may provide either steady-state or transient control. But, in each case, a licensed reactor operator is performing the planning, prediction, and assessment functions. For example, an operator might use an analog controller to conduct a transient by programming a decade box to move the reactor's control devices. The responsibility of decision remains with the operator. The decade box is merely a tool. Digital technology differs in that the software can be designed to provide the equivalent of most of the control functions that are normally performed by a human. For example, numerical models could be used for prediction and techniques such as signal validation for assessment. The decision to utilize digital technology for process control therefore brings with it a number of questions. Is it possible to design a digital controller that will replicate each of the functions now performed by a human? If not, which tasks should be assigned to the machine, and how can one be certain that licensed operators will understand and recognize the machine's limitations? These and related questions are now being debated within the nuclear, chemical, and aerospace communities. This paper addresses one part of this debate by enumerating issues concerning the design and implementation of closed-loop laws for the trajectory control of power in research reactors.

The specific objectives of this paper are to (a) review reactor dynamics with emphasis on factors that affect system control, (b) summarize the rationale for formulating reactor control laws in terms of the rate of change of reactivity, (c) describe and assess both proportional-integral-derivative (PID) and period-generated control laws, (d) delineate the benefits that can be achieved by incorporating a system model in a control law, and (e) enumerate factors relevant to the implementation of a closed-loop control law including signal validation, supervisory control, automated diagnosis, and the man-machine interface.

II. REACTOR DYNAMICS

Figure 1 illustrates the aspects of the fission process that bear on reactor control. Of significance is that there are three parallel but separate mechanisms for the production of neutrons. Prompt neutrons appear directly following the fission event and have lifetimes that are quite short, typically 100 μs. Delayed neutrons are produced following the decay by beta-particle emission of fission products that are referred to as "precursors." The delay in the appearance of a delayed neutron relative to the fission event is the result of the precursor half-life. There are six recognized groups of precursors with half-lives ranging from 0.23 to 55 s. The average value is 12.2 s. The third mechanism for neutron production is the interaction of fission product gamma rays with certain moderating materials, most notably heavy water and beryllium. Called photoneutrons, their appearance is delayed relative to the fission event because of the time required for the fission products to undergo radioactive decay and emit the needed gamma rays. In the ensuing discussion, the term "delayed" includes both those from precursors and photoneutrons.

The process shown in Fig. 1 is described in quantitative terms by the space-independent kinetics equations. Those equations constitute a suitable model for research reactors because the small, compact cores that power those reactors do not exhibit spatial dependencies under conditions of normal operation. The space-independent kinetics equations can be combined through differentiation and substitution to obtain the dynamic period equation, which gives the instantaneous reactor period as a function of the rate of change of reactivity, the reactivity, and the rate of redistribution of the delayed neutron precursors.[6] This relation is particularly useful in the design of tracking controllers for nuclear reactors because it explicitly represents each of the parameters that can affect the rate at which a reactor's neutronic power will increase or decrease.

The instantaneous reactor period $\tau(t)$ is defined as $\tau(t) = 1/\omega(t)$, where

$$\dot{T}(t) \equiv \omega(t)T(t) \tag{1}$$

and $T(t)$ denotes the amplitude function, which is a weighted integral of all neutrons present in the reactor. In the discussions on controller design that follow, the

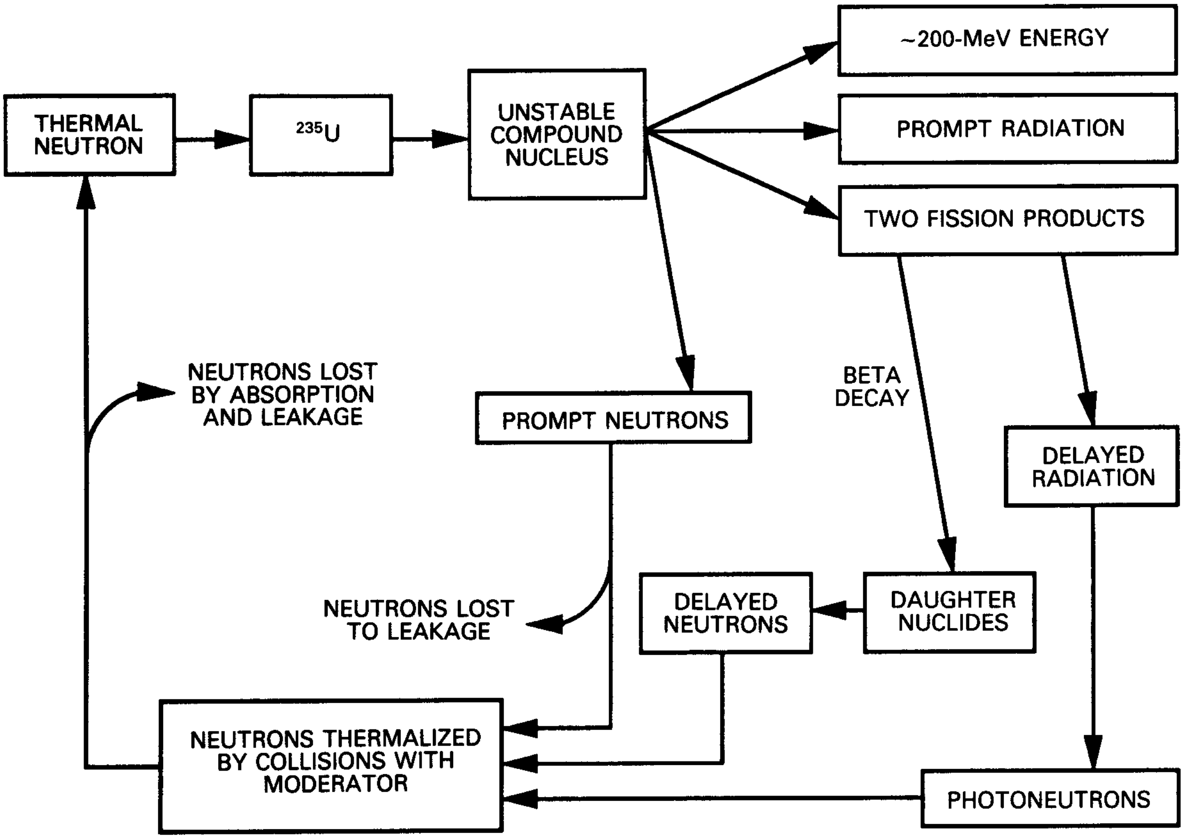

Fig. 1. Fission process showing prompt, delayed, and photoneutron production.

amplitude function is approximated as the reactor neutronic power $n(t)$. Thus,

$$\tau(t) = n(t)/\dot{n}(t) \ . \tag{2}$$

The dynamic period equation may be written in either a standard or alternate form. The two are mathematically equivalent, but the alternate is the easier to program. It is as follows:

$$\tau(t) = \frac{[\bar{\beta} - \rho(t)] + l^*\left[\dfrac{\dot{\omega}(t)}{\omega(t)} + \omega(t) + \lambda'_e(t)\right]}{\dot{\rho}(t) + \lambda'_e(t)\rho(t) + \sum \bar{\beta}_i[\lambda_i - \lambda'_e(t)]} \ , \tag{3}$$

where the alternate, effective, multigroup decay parameter is defined as

$$\lambda'_e(t) \equiv \sum \lambda_i^2 C_i(t) / \sum \lambda_i C_i(t) \quad \text{for } i = 1, N \ , \tag{4}$$

and where

$\bar{\beta}$ = effective delayed neutron fraction

$\rho(t)$ = net reactivity

l^* = prompt neutron lifetime

$\dot{\omega}(t)$ = rate of change of the inverse of the dynamic reactor period

$\omega(t)$ = inverse of the dynamic reactor period

$\dot{\rho}(t)$ = rate of change of the net reactivity

$\bar{\beta}_i$ = effective fractional yield of the i'th group of delayed neutrons

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

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

Adjustments of power in research reactors are achieved by withdrawing a control device so as to insert positive reactivity and thereby place the reactor on a period, with period defined as the power level divided by the rate of change of power. Having established a period, the power is allowed to rise. Once the power level approaches the desired value, the control device is gradually returned to its original position to reduce the reactivity to zero and to level the power without overshoot. The crucial aspect of the control process is that the lengthening of the reactor period must be initiated before attaining the specified power level. Such anticipatory actions are necessary because the rate at which reactivity can be removed is finite, particularly when rods are used at normal speeds. Hence, if changes in the reactor power are to be achieved both efficiently and without challenge to the safety system, some method must be available by which the proper time for initiation of the reactivity removal process can be reliably predicted. Licensed operators are sufficiently experienced so that they can make the appropriate judgments. The implementation of digital technology requires that the equivalent capability be developed in software. Doing so is not easy because of the nonlinear, time-delayed nature of reactor dynamics. In particular, allowance must be made for the following:

1. The instantaneous reactor period is a function of the rate of change of reactivity, the reactivity, and the rate of redistribution of the delayed neutron precursors. This means that the period observed at any given moment in a reactor will depend on both the distance that a control device has been moved beyond the critical position and the rate at which that device is being moved.

2. The dynamic response of a reactor is determined by that of its prompt and delayed neutron populations. Prompt neutrons appear simultaneously with the fission event and are therefore a function of the current power level. Delayed neutrons appear some time after the fission event and are therefore a function of the power history. This dependence on the power history means that delayed neutrons will not be in equilibrium with the observed power during a transient. Hence, upon attaining a desired power level, the delayed neutrons will continue to rise, and an overshoot will occur unless the controller is capable of reducing the prompt neutron population at a rate sufficient to offset the still rising delayed neutron population.

3. The relation between power and reactivity is nonlinear. Also, nonlinear reactivity feedback effects result from the changes in the fuel and moderator temperature that occur during power adjustments.

4. The differential reactivity worth of the control devices is a strong function of the axial flux profile. Hence, the rate at which a controller can insert and remove reactivity varies nonlinearly with the position of the device. In general, this rate will be a maximum at the core midplane and be quite low in the upper portion of the core.

Figures 2 and 3 illustrate the difficulties that can arise if the foregoing factors are ignored. Shown are results from demonstrations conducted on the MITR-II in 1983 and 1984. The control law consisted of a directive to withdraw a control rod at constant speed until a desired power level was attained. In addition, a minimum allowed period was specified. The period limit was selected so that the controller functioned quite well under normal operating conditions. In particular, it would raise the reactor's neutronic power to

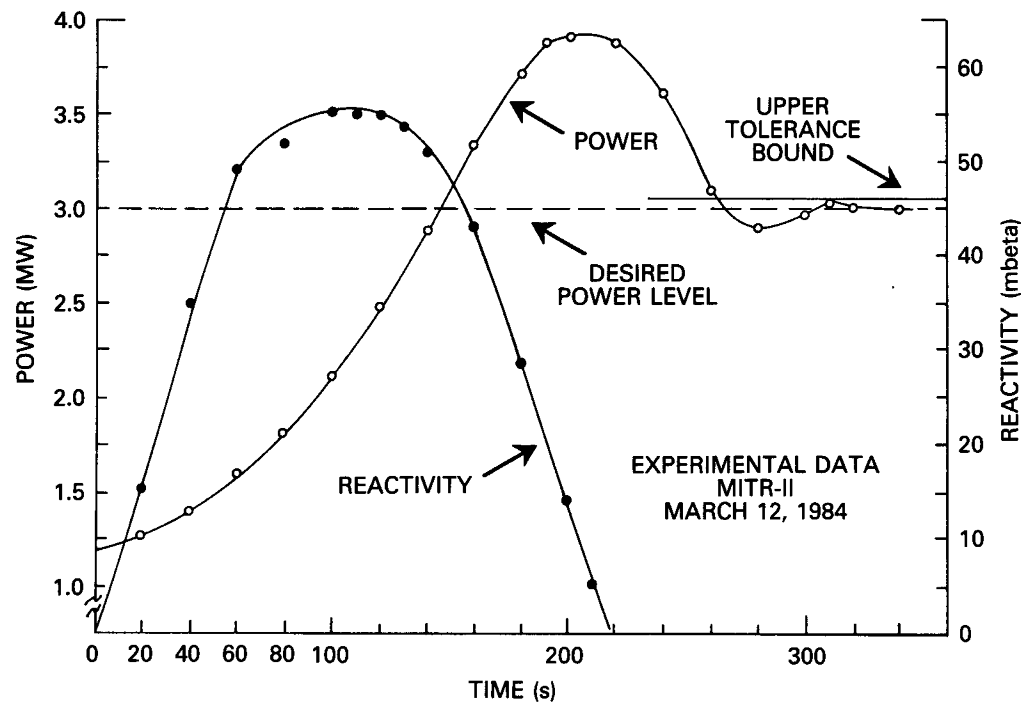

Fig. 2. Failure of controller to recognize need to limit reactivity insertion results in power overshoot.

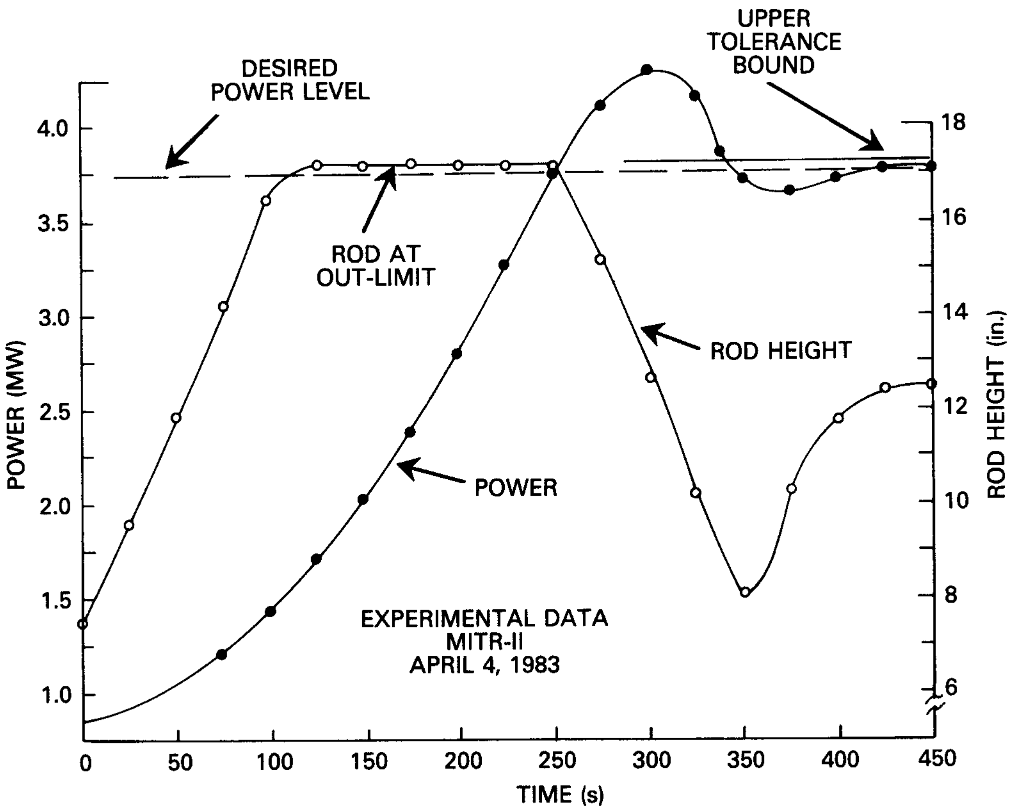

Fig. 3. Failure of controller to restrict rod withdrawal in region of low differential worth results in power overshoot.

the desired value and hold it at that value. However, this controller did not track a specified power profile. Rather, the resulting trajectory was a function of the initial position and the predetermined speed of the control device. Tests also showed that this controller was incapable of performing properly under off-normal conditions. Figure 2 shows a power increase in which a period shorter than the one for which the controller had been designed was allowed. The controller inserted the necessary reactivity but, upon attaining the specified power level, could not remove reactivity with sufficient speed to preclude an overshoot. Delayed neutrons were rising at a rate faster than the prompt ones could be decreased. This experiment demonstrated the inflexibility that results from the failure to incorporate knowledge of the system dynamics. In this case, the controller was "tuned" to a specific set of conditions and gave unsatisfactory results when those conditions were altered. Figure 3 shows a power increase for which the normal period was required, but the control device was initially positioned where its differential reactivity worth was low. The controller fully withdrew the rod in order to insert enough reactivity and then could not halt the transient because the rod was so far withdrawn as to have no strength. An overshoot resulted. Such a scenario could occur during a xenon transient, and something like this did occur at Chernobyl. Model-based control can preclude such difficulties.[a]

III. SELECTION OF THE RATE OF CHANGE OF REACTIVITY AS THE ACTUATOR SIGNAL

The control laws described in the following material are formulated in terms of the rate of change of reactivity. This means that the signal sent to the actuator is the speed at which the control device should be moved. This choice contrasts with the traditional approach to the design of controllers for nuclear reactors, which is to specify a control action in terms of the magnitude of the reactivity. Use of this latter practice means that the signal sent to the actuator is the desired position of the control device. There are a number of reasons for selecting the rate of change of reactivity as the actuator signal. First, specification of the appropriate rate of reactivity change means that both the

[a]The foregoing experiments were carefully controlled tests. Limits on power and period for the MITR-II were never exceeded. Only those established for the individual tests were violated, and these were set below those associated with the reactor.

direction and speed of the control device are uniquely determined. In contrast, if only the reactivity were specified, then the desired final position of the control device would be known, but the speed at which the device should be moved to attain that position would be undetermined. Second, as is evident from the dynamic period equation, the response of a reactor depends on both the magnitude and the rate of change of the reactivity. Failure to allow for the latter means that sudden variations will occur in the rate at which power is being raised whenever rod motion is started or stopped. Third, a major requirement in the design of controllers for safety-constrained processes such as nuclear reactors is that it be possible to alter the control signal on demand and thereby have an immediate effect on the process in question. Reactivity does not fulfill this requirement because it is a function of the distance that a control rod has been moved beyond the critical position, and adjustments in a device's position can only be made over a finite interval. In contrast, the rate of change of reactivity can be immediately altered by merely initiating movement of a control device. Moreover, a wide range of rates of change is achievable through the use of variable-speed stepper motors. Fourth, the rate of change of reactivity corresponds to the effect of a changing prompt neutron population while the reactivity itself reflects other effects including changing delayed neutron precursor populations and changing distributions of delayed neutron precursors within the defined groups. Precursor populations are a function of the power history and therefore cannot be altered on demand. In contrast, the prompt neutron population is essentially a function of only the current power level and is therefore immediately controllable. Hence, if an immediate change is required in a reactor period, an adjustment should be made in the rate of change of reactivity rather than in the reactivity itself.

In summary, the reason for using the rate of change of reactivity as the signal to the actuator is that it is itself directly controllable and, upon being changed, it will have an immediate effect on the course of the transient. Additional information has been given previously.[7–10]

IV. CONTROL LAW DESIGN

The Massachusetts Institute of Technology (MIT) has been engaged since the late 1970s in a program to develop and demonstrate advanced concepts for the control of research, space, and power reactors. A distinguishing feature of this program has been its commitment to experiment. New control concepts are tested first by simulation and then under conditions of closed-loop digital control on either the MITR-II or the Annular Core Research Reactor (ACRR) that is operated by Sandia National Laboratories (SNL). A concise review of the MIT program is given in Ref. 7, and detailed results are given in Refs. 8 through 11. The discussion here focuses on the design of PID and period-generated laws for the trajectory control of research reactor power. The emphasis is on the treatment of nonlinear behavior. These two laws were chosen for comparison because they represent opposing philosophies concerning the design of closed-loop digital controllers. At issue is whether or not a system model should be incorporated in the control law.

IV.A. Proportional-Integral-Derivative Control

The PID mode of control is the most commonly used method for the automation of process systems. It is also the simplest because it considers the system dynamics to be a "black box." No use is made of numerical models. The first step in designing a PID controller is to define an error signal as the difference between the demanded and measured outputs of the process. Multiplication of that error by a constant (the system gain) results in a proportional controller. Thus,

$$e(t) \equiv n_d(t) - n(t) \tag{5}$$

and

$$u(t) = k_p e(t) \ , \tag{6}$$

where

$n_d(t)$ = demanded (or reference) reactor power level

$n(t)$ = measured reactor power level

$e(t)$ = error signal

$u(t)$ = signal to the actuator

k_p = proportional gain constant.

Figure 4 depicts the process. Unless the gain can be made quite large (in theory, it would have to be infinite), proportional controllers will exhibit offsets in that the observed power will not be fully driven to the reference value. This situation can be rectified through the addition of integral action. By doing so, any difference between the demanded and measured outputs will eventually accumulate to the point where it forces the system response to the specified value. Unfortunately, integral action can induce oscillations as the system converges about the setpoint. These can be mitigated by the addition of an anticipatory or derivative term that is a function of the rate of change of the error. The resulting controller is of the form

$$u(t) = k_p e(t) + k_i \int e(t)\,dt + k_v \dot{e}(t) \ , \tag{7}$$

where k_i and k_v are the gain constants for the integral and derivative terms.

Proportional-integral-derivative control is well

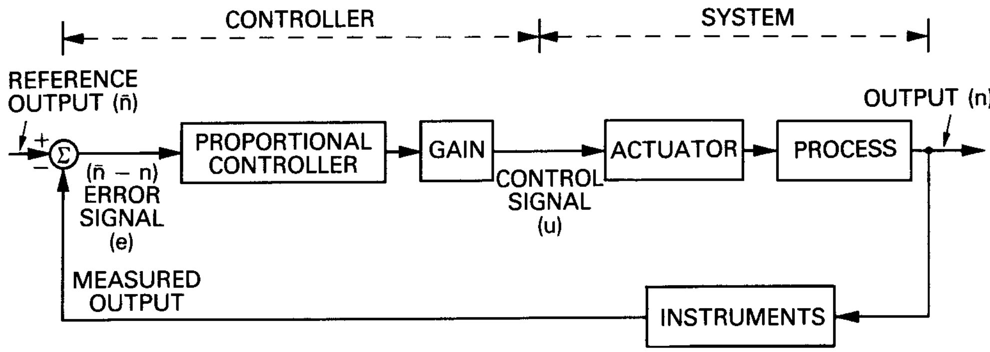

Fig. 4. Proportional control.

suited to maintaining a system parameter at some steady-state value and, as a result, is the control method employed by most analog devices. It can be modified to track a demanded trajectory by specifying both a demanded power and a demanded rate of rise of power. In this case, it becomes

$$\dot{\rho}_c(t) = k_p[n_d(t) - n(t)] - k_v[\dot{n}_d(t) - \dot{n}(t)] \quad , \quad (8)$$

where $\dot{\rho}_c(t)$ is the rate of change of reactivity that will be required from the actuator.[b] Figure 5 illustrates the approach. Control laws based on Eq. (8) have been extensively evaluated for robot movement, and while the approach is widely used, certain limitations have been noted.[12,13] These include the following:

1. The technique will cause the system to move to the desired end point, but it will not result in highly accurate tracking of a specified trajectory. Accomplishment of the latter requires incorporation of a system model in the control law.

2. There are physical limits to the speed at which an actuator can respond. This means that the gains cannot be made arbitrarily large as might be desired to rapidly overcome perturbations.

3. Even if achievable, the use of high gains to offset poor performance may be unsafe because high gains will amplify modeling errors, inaccuracies in parameter estimates, and noise. Doing so may also lead to instability.

Both PID and proportional-derivative control have been evaluated experimentally on the MITR-II. To the foregoing list, one should add that the values of the controller gains cannot be treated as constants for nonlinear systems. A set of gains chosen to properly execute one type of transient can result in poor performance for another. Other drawbacks to this mode of control are that the selection of the gains is empirical (and hence time-consuming) and that there is no theoretical basis for determining system stability.

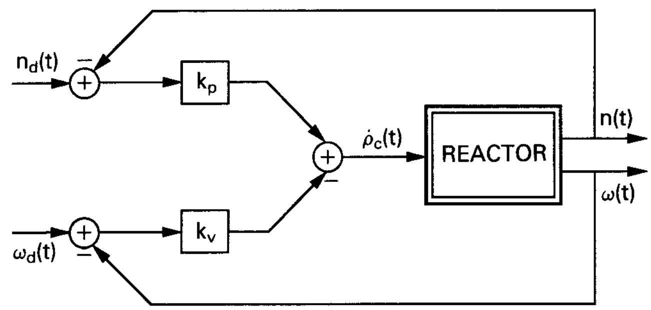

Fig. 5. Proportional-derivative control for trajectory tracking.

Figure 6 shows the results of a test of proportional-derivative control on the MITR-II. The controller was tuned to raise the reactor's power from 1.0 to 1.5 MW, and except for a small overshoot, it did this properly. However, its performance was less satisfactory when used for other types of maneuvers. This raises two concerns. First, proportional-derivative control does perform quite well when used to conduct the specific transients for which its gains have been calibrated. Might this observation not cause a reactor operator, who has little knowledge of control theory, to place undue reliance on the controller and attempt its use for other types of transients? Second, the performance of proportional-derivative controllers can be enhanced by increasing the speed of the control device that serves as the actuator. Doing so enables the controller to offset both disturbances and nonlinear effects more quickly. Yet, is this practice desirable? Repeated movement of a control device at high speed may induce wear, and if failure were to occur during transient conditions, the consequences could have safety ramifications.

[b]The minus sign in Eq. (8) is appropriate because the purpose in adding the velocity term is to dampen the speed of response, thereby reducing the likelihood of an overshoot.

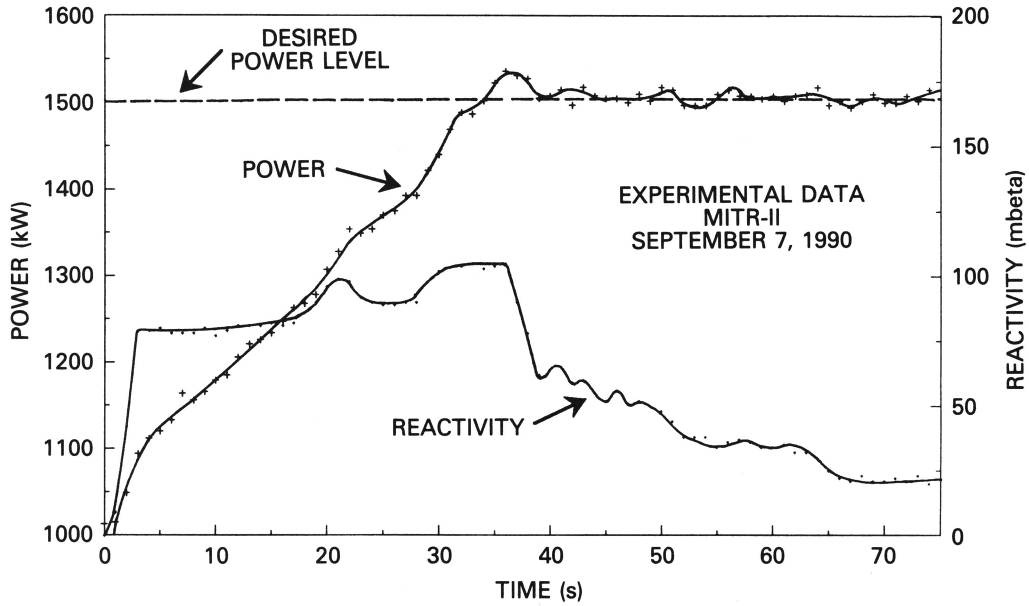

Fig. 6. Demonstration of proportional-derivative control.

IV.B. Period-Generated Control

Period-generated control is a model-based technique that was developed at the MIT Nuclear Reactor Laboratory in conjunction with SNL for the purpose of adjusting nuclear reactor power in a very rapid yet safe manner.[9,10,14] One possible application is the control of the spacecraft reactors that will be used to propel manned expeditions to Mars. The technique has since been extended to nonnuclear systems and is now being studied as a general-purpose method for the trajectory control of systems for which a demanded rate is to be observed.[15] The most well-known examples of period-generated control are the MIT-SNL Period-Generated Minimum Time Control Laws, which have been extensively demonstrated on both the MITR-II and the ACRR. Derivations of these laws were previously given.[14] The intent here is to demonstrate the utility of the model-based, period-generated approach for the trajectory tracking of nonlinear systems.

It is desired that the reactor neutronic power conform to a certain trajectory. Accordingly, some measure of the rate of rise of the power is needed. A logical choice is the inverse of the reactor period, which is defined as

$$\omega(t) \equiv \dot{n}(t)/n(t) \ . \tag{9}$$

The objective of the control method is to determine a demanded inverse period, compute the rate of change of reactivity (the actuator signal) needed to generate that inverse period, and then apply the calculated rate of reactivity change to the actual system. Doing so should cause the reactor's power to rise or fall on the desired trajectory. Hence, the first step in the implementation of period-generated control is to define an error signal in terms of the demanded and observed power levels. The conventional approach would be to take the difference between those two quantities. However, superior performance is achieved if the error signal is expressed as

$$e(t) = \ln[n_d(t + j\Delta t)/n(t)] \ , \tag{10}$$

where

$n_d(t)$ = demanded trajectory

$n(t)$ = observed trajectory

j = positive integer.

A Taylor series expansion of this logarithmic expression reveals the rationale for selecting this particular arithmetic form for the error signal:

$$\begin{aligned} e(t) &= \ln[n_d(t + j\Delta t)] - \ln[n_d(t)] \\ &\quad + \ln[n_d(t)] - \ln[n(t)] \\ &\approx \ln[n_d(t)] + j\Delta t \frac{d}{dt}\{\ln[n_d(t)]\} \\ &\quad - \ln[n_d(t)] + \ln[n_d(t)] - \ln[n(t)] \\ &= j\Delta t \frac{d}{dt}\{\ln[n_d(t)]\} + \ln[n_d(t)/n(t)] \\ &= j\Delta t\,\omega_t(t) + \ln[n_d(t)/n(t)] \ , \end{aligned} \tag{11}$$

where $\omega_t(t)$ is the inverse period that corresponds to the power trajectory $n_d(t)$. Thus, the error signal used in period-generated control is the sum of a feedforward action from the inverse period associated with the demanded trajectory, and a proportional action from the quotient of the demanded and observed system outputs. The former defines the system path. The latter provides corrective action against deviations. It has been shown that the value of j should be at least 2 to ensure stability against oscillations.[16]

The second step in the application of period-generated control is to define a demanded period in terms of the error signal. Thus,

$$\omega_d(t) = \left[e(t) + (1/T_i)\int e(t)\,dt + T_d\dot{e}(t)\right]\Big/ j\Delta t \ , \tag{12}$$

where T_i and T_d are the integral and derivative times. Equation (12) is a conventional PID feedback expression. The quantity $\omega_d(t)$ is the inverse period that will either maintain the system on the demanded trajectory or, should a deviation exist, restore it to that trajectory. That is, $\omega_d(t)$ equals $\omega_t(t)$ when the observed power is on the demanded trajectory. Otherwise, the two differ with $\omega_d(t)$ driving the system to the demanded trajectory.

The third step in the application of period-generated control to a reactor is to obtain an appropriate model and thereby relate the demanded period to the actuator signal, which is the required rate of change of reactivity. The needed expression is readily obtained by rearranging terms in the dynamic period equation. Doing so yields the following:

$$\begin{aligned}\dot{\rho}_c(t) &= [\bar{\beta} - \hat{\rho}(t)]\omega_d(t) - \hat{\lambda}'_e(t)\hat{\rho}(t) \\ &\quad - \sum \bar{\beta}_i[\lambda_i - \hat{\lambda}'_e(t)] - \hat{\dot{\rho}}_f(t) \\ &\quad + l^*\dot{\omega}(t) + l^*\{[\omega_d(t)]^2 + \hat{\lambda}'_e(t)\omega_d(t)\} \ ,\end{aligned} \tag{13}$$

where the symbol $\dot{\rho}_f$ denotes the rate of change of reactivity associated with temperature-induced feedback from the reactor's fuel and coolant. Equation (13) is a system model, and the parameters contained therein are estimates. This is indicated symbolically through use of the superscript caret.

The next issue is the treatment of the quantity $\dot{\omega}(t)$, which represents the system acceleration. For most transients, it is acceptable to make the prompt-jump approximation and set the quantity l^*, which is the prompt neutron lifetime, to zero. Under such conditions, acceleration effects can be neglected. However, if trajectories with periods of a few seconds or less are to be tracked, then allowance must be made for system acceleration. This is achieved using the following relation:

$$\dot{\omega}(t) = [\omega_d(t) - \omega(t)]/k\Delta t \ , \tag{14}$$

where

Δt = time step

k = number of time steps over which it is desired that the system attain the specified trajectory.

The quantity k should be chosen to be small because the objective of period-generated control is to cause the controlled parameter to begin rising (or falling) quickly at the demanded rate. For this to occur, the acceleration term must rapidly die out. However, as a practical matter, there is a lower limit to the value of k. Should it be made too small, $\dot{\omega}(t)$ will be quite large, and an excessive rate of change of reactivity will be needed for transient initiation.

The demanded power trajectory can now be realized by applying the quantity $\dot{\rho}_c$ to the actual system. Thus, the observed inverse period is as follows:

$$\begin{aligned}\omega(t) &= [\bar{\beta} - \rho(t)]^{-1} \\ &\quad \times \Big(\dot{\rho}_c(t) + \dot{\rho}_f(t) + \lambda'_e\rho(t) + \sum \bar{\beta}_i[\lambda_i - \lambda'_e(t)] \\ &\quad - l^*\{\dot{\omega}(t) + [\omega(t)]^2 + \lambda'_e(t)\omega(t)\}\Big) \ .\end{aligned} \tag{15}$$

The sequence of calculations is as follows. First, the demanded trajectory and the time allowed for its attainment are specified. This allows determination of $n_d(t)$ and k. Next, measurement of the actual power level allows calculation of the error signal and estimation of the demanded inverse period from Eqs. (10) and (12). The reactivity and the effective multigroup decay parameter are then determined via either measurement or calculation or a combination thereof. Substitution of $\omega_d(t)$ into Eq. (13) and then substituting Eq. (14) for $\dot{\omega}(t)$ gives the rate at which the reactivity should be changed during the next time step in order to cause the reactor's power to move to the desired trajectory. Once on that trajectory, the acceleration term will in theory become zero. As a practical matter, it will remain finite, acting as a source of feedback to correct for minor deviations in the tracking of the specified path. Repetition of the sequence of calculations yields the rate of change of reactivity needed to move the system output along the desired trajectory. Once $n(t)$ attains a new desired steady-state value, the quantity $\omega_d(t)$ is set to zero, and the rate of change of the reactivity needed to halt the transient is generated. The acceleration term will be nonzero at this time.

Shown in Fig. 7 are the power and reactivity profiles obtained during a trial of period-generated control on the MITR-II. Also, the strip-chart recording of this transient is shown as an inset. The reactor's power was increased from 1 to 2 MW under conditions of closed-loop digital control using a variable-speed stepper motor to adjust the net reactivity. The specified period was 100 s. The transient was completed at the expected time of 69 s, and the shape of the power profile was exponential. Also of interest is the steep slope of the reactivity profile during both transient initiation

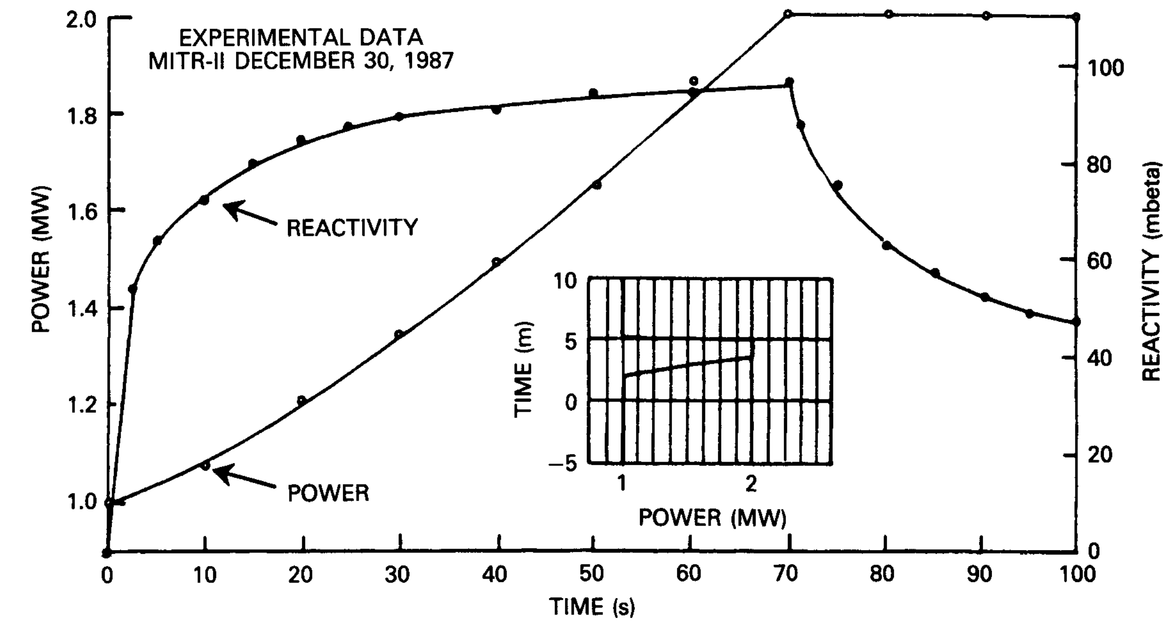

Fig. 7. Closed-loop power increase from 1 to 2 MW using MIT-SNL Period-Generated Minimum Time Control Law on a 100-s period.

and termination. This occurred because the reactor's period was in effect being stepped from infinity (steady state) to 100 s and, upon transient completion, from 100 s back to infinity. Adjustments of the prompt neutron population, which are indicated by the rate of change of reactivity, were being used to drive the transient.

Figure 8 shows the power and reactivity profiles obtained during a trial of period-generated control on the ACRR. The power was increased by three orders of magnitude, from 0.49 to 490 kW, on a demanded period of 3.0 s with the reactor initially subcritical by 800 mbeta (80 ¢).[c] Again, note the rapid rates of change of reactivity needed for both transient initiation and termination. The tracking performance achieved in both of the foregoing demonstrations was excellent. Of significance is that both the MITR-II and the ACRR tests were performed with essentially the same software. Yet, the two reactors are very different. The MITR-II uses fully enriched ^{235}U fuel and forced circulation. The ACRR uses 20% enriched $BeO\text{-}UO_2$ fuel and operates under adiabatic conditions. Use of the same software to conduct power transients on these two very different reactors demonstrates the generic nature of period-generated control.

V. RATIONALE FOR MODEL-BASED CONTROL LAWS

What accounts for the superior tracking capability of period-generated control as compared with the direct use of proportional-derivative action? The most significant difference between the two methods is that the period-generated approach incorporates a model of the system dynamics. While this does make the technique's implementation more complex, it also results in substantial benefits. In particular, major advantages to period-generated control are that it is applicable to nonlinear systems and that, in the case of rate-constrained systems, the resulting control action approaches time-optimal behavior. The basis of these attributes is discussed here.

V.A. Nonlinear Control

The period-generated approach achieves proper control of nonlinear systems through the use of a model of the process dynamics. Specifically, a feedback signal (the demanded inverse period) is computed from a comparison of the demanded and observed values of the system output. This signal is then input to an inverse dynamics model of the process that is being controlled. The solution is a form of feedforward control in the sense that the output of the inverse dynamics calculation is the actuator signal, which, upon

[c]Reactivity is a fraction and therefore is dimensionless. Nevertheless, several systems of "units" are in use. The one used here is to define a reactivity equal to a reactor's delayed neutron fraction as 1 Beta. This unit is further divided into mbeta with 1000 mbeta equaling 1 Beta. Another widely used system of reactivity units is dollars and cents. 1 Beta equals 1 \$ or 100 ¢. Hence, 1 ¢ equals 10 mbeta.

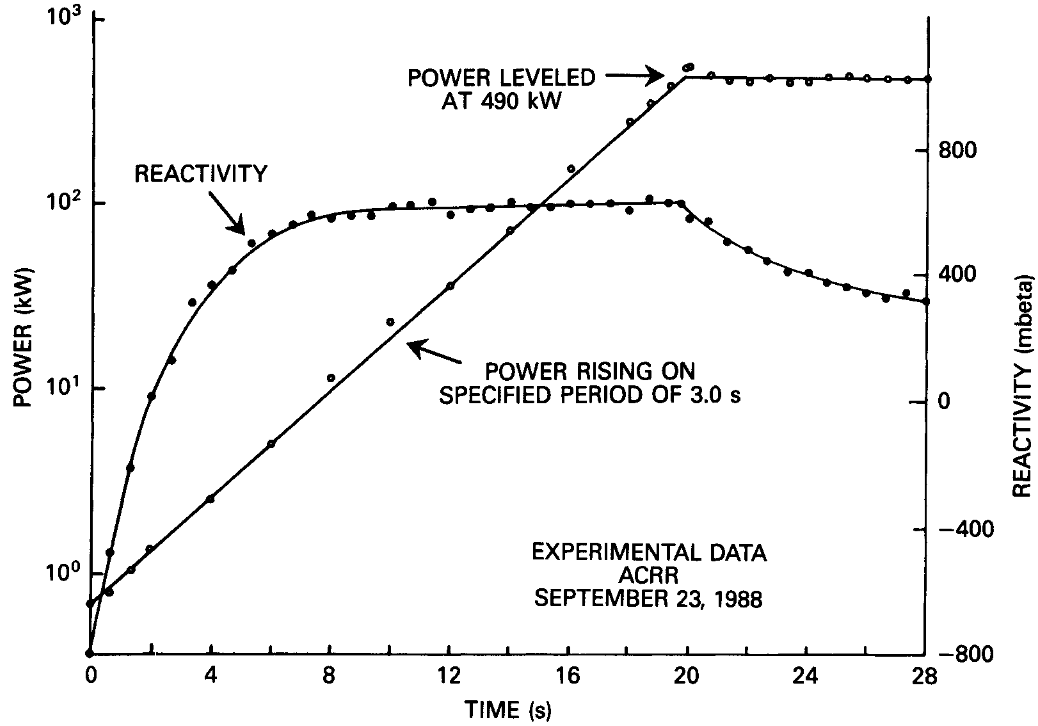

Fig. 8. Automated power increase of three orders of magnitude using the MIT-SNL Period-Generated Minimum Time Control Law with the reactor initially subcritical.

application to the actual process, will cause the system output to track the demanded trajectory. The merits of the approach are best illustrated by example.

Denote the quantities $(\bar{\beta} - \rho)$ and $\{\lambda_e' \rho + \sum \bar{\beta}_i [\lambda_i - \lambda_e'(t)]\}$ by the symbols R and r, respectively. A *functional* description of period-generated control can be written as

$$e(t) = \ln[n_d(t + j\Delta t)/n(t)] \ , \tag{16}$$

$$\omega_d(t) = \left[e(t) + (1/T_i)\int e(t)\,dt + T_d \dot{e}(t)\right]\Big/ j\Delta t \ , \tag{17}$$

$$\dot{\rho}_c(t) = \hat{R}(t)\omega_d(t) - \hat{r}(t) + [\omega_d(t) - \omega(t)]/k\Delta t \ , \tag{18}$$

and

$$\omega(t) = [R(t)]^{-1}[\dot{\rho}(t) + r(t) - \dot{\omega}(t)] \ , \tag{19}$$

where for clarity of illustration, the prompt neutron lifetime has been taken as unity and several terms of small order have been omitted. The superscript caret denotes an estimated quantity. Figure 9 is a block diagram illustrating the salient features of period-generated control. Equations (16) and (17) define, as previously discussed, the error signal and the demanded inverse period. Equation (18) is the system model. It is referred to as an "inverse dynamics calculation" because it is used to compute the actuator signal from the demanded inverse period. Equation (19) denotes the actual process. Substitution of $\dot{\rho}_c(t)$ for $\dot{\rho}(t)$ into Eq. (19) results in the feedforward control action. Doing so yields the following:

$$\begin{aligned}\omega(t) &= [R(t)]^{-1}\{\hat{R}(t)\omega_d(t) - \hat{r}(t) \\ &\qquad + [\omega_d(t) - \omega(t)]/k\Delta t + r(t) - \dot{\omega}(t)\} \\ &= [R(t)]^{-1}\hat{R}(t)\omega_d(t) - [\hat{R}(t)]^{-1}[\hat{r}(t) - r(t)] \\ &\qquad + [R(t)]^{-1}\{[\omega_d(t) - \omega(t)]/k\Delta t - \dot{\omega}(t)\} \ .\end{aligned} \tag{20}$$

If the quantities $\hat{R}$ and $\hat{r}$ are accurate, then the combination of the inverse dynamics calculation and the feedforward action will result in the canceling of the system dynamics. Thus,

$$\begin{aligned}\omega(t) &= \omega_d(t) + [R(t)]^{-1} \\ &\qquad \times \{[\omega_d(t) - \omega(t)]/k\Delta t - \dot{\omega}(t)\} \ .\end{aligned} \tag{21}$$

It is evident from Eq. (21) that once the acceleration term has been driven to zero, the actual and demanded inverse periods will be equal. This behavior is the strength of the period-generated approach and is of special importance for the trajectory control of nonlinear systems. In particular, the result of the cancellation is that Eq. (17), which is the standard PID

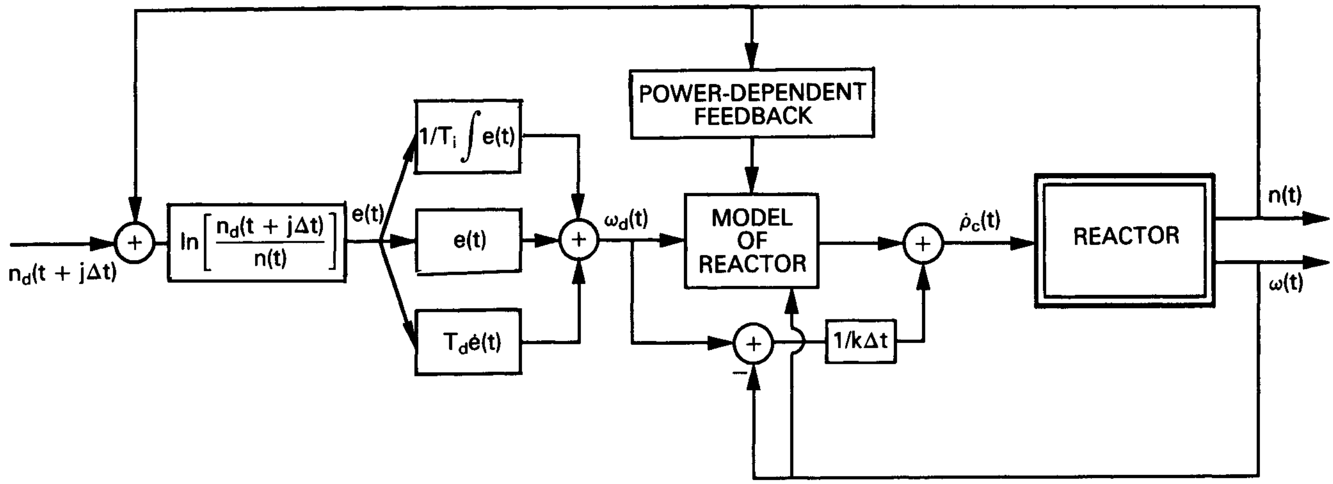

Fig. 9. Period-generated control as applied to trajectory tracking of reactor power.

expression, is the determining factor in the system's response. Its use here results in accurate tracking because the incorporation of a system model in the period-generated method causes the observed inverse period to equal that which is demanded once acceleration effects have died out. This will occur regardless of whether the process being controlled is linear or nonlinear. In contrast, were that same PID expression to be applied directly to a nonlinear system with no use being made of a model, the tracking would not be accurate except for the specific trajectory for which the controller had been tuned.

V.B. Time-Optimal Response

Optimal control is normally achieved by applying techniques such as Bellman's dynamic programming or Pontryagin's maximum principle. These have the disadvantage of being computation intensive. For example, application of the Pontryagin approach yields a set of partial differential equations with split boundary conditions. Such systems of equations must be solved iteratively. The result is that the time required to calculate the control action that corresponds to the optimal trajectory may exceed that available for implementing the associated control signal. Under such circumstances, the optimal control is calculated off-line and applied in an open-loop manner. No use of feedback is possible. Hence, if the system model is inaccurate or if a perturbation occurs, the resulting response will not be as desired.

A major advantage of the period-generated technique is that it results in closed-form control laws that can be implemented in real time and that may approach a time-optimal response. Specifically, for systems that are subject to a rate constraint, the time-optimal trajectory will be the one that moves the system along that constraint. Hence, rather than identify the optimal control by solving the system's describing equations subject to both the constraint and a performance index, it is more direct to define the physical conditions that correspond to system movement along that limiting constraint. This can be achieved using period-generated control by taking the demanded period to be that associated with the limiting constraint. For example, many nuclear research reactors are operated subject to limits on the power, temperature, coolant flow, and rate of rise of power. Suppose that the limit on the latter quantity for the MITR-II were a period of 100 s. In that case, the power and reactivity profiles shown in Fig. 7 are those of the time-optimal trajectory.

The degree to which a period-generated control law approaches a time-optimal response depends on the treatment of the acceleration term. In the ideal case, the trajectory would be instantly switched to and from the limiting path. The presence of the acceleration term makes this scenario physically impossible. However, the impact of the acceleration term can be made quite small provided that the forcing function can be rapidly changed. Under such circumstances, period-generated control laws can closely approximate time-optimal responses for rate-constrained systems.

V.C. Replication of Human Control Approach

The foregoing discussions of nonlinear control and time-optimal behavior make clear that one reason for employing model-based control is superior performance. However, there is another, perhaps even more compelling reason. Model-based control laws offer the possibility of replicating certain functions that humans perform during the course of controlling a process. Specifically, as was discussed earlier, one of the four aspects of the human approach to process control is the prediction of plant response. Humans determine if a change should be made in a control signal by comparing their estimate of the plant's future state to that which is desired. Thus, decisions are made on the basis of future expectations. Model-based control laws can enable a digital controller to replicate part of this process, albeit in a manner very different from that of a human. Specifically,

1. The model can be used to predict the future state of the plant. Given modern computing equipment, many models can be solved at rates much faster than real time. Hence, it becomes possible to test various control options before having to select one for actual implementation on the real plant.

2. Model-based control provides excellent tracking of demanded trajectories. Hence, the anticipated plant response is accurately known. This in turn makes possible the rapid identification of deviations. The cause of the deviation will still be unknown, but there will be no uncertainty as to whether or not something is amiss.

3. System models can be used to provide estimates of all parameters associated with a plant, not merely the output. These analytic estimates can be compared to measurements as part of a signal validation scheme.

4. System parameters that are not subject to direct measurement can be calculated. For example, the margins to various thermal limits could be displayed.

5. Should there be a malfunction, the model can be used to check possible diagnoses. Candidate initiating events could be simulated, and the output of the model compared to observation. In this way, the actual cause of the malfunction might be identified or at least narrowed to a few possibilities.

The incorporation of an accurate plant model in a digital controller means that a single piece of software can be used in conjunction with many types of transients. This relieves the operator of the burden of determining the conditions under which the digital controller will perform reliably.

VI. CONTROL LAW IMPLEMENTATION

Figure 10 depicts a possible design for a research reactor's digital control system. Major features include a separate safety system, a means for signal validation and instrument fault detection, a supervisory algorithm that precludes challenges to the safety system, a set of selectable control laws, a reconfiguration logic to identify the most appropriate law given the operational objectives and the plant's state, a means for the verification of signal implementation, a module for automated reasoning, and a man-machine interface. The controller shown in Fig. 10 represents complete automation, and the application of digital technology to the operation of research reactors should not be viewed as requiring all of its components. Research reactors can be partially automated, and doing so will both make their operation more efficient and provide experience that will benefit the entire nuclear community. However, partial automation brings with it several important caveats. Namely, the control functions that are to be performed by a machine should be clearly delineated, the machines should be designed to perform those functions correctly under all allowed operating conditions, and licensed reactor operators should be trained to recognize machine limitations. If these objectives are not met, then a serious mismatch between operator expectations and machine capabilities may develop with the result that operators may either rely too much on the machine or else ignore it. The former has implications for safety. The latter would be a waste of scarce economic resources.

Relative to the MITR-II, only three of the features shown in Fig. 10 are considered essential. These are the separate safety system, the signal validation and instrument fault detection system, and the supervisory algorithm. Also of importance is the hierarchical structure of the controller in which the actions of the control law chosen by the reconfiguration logic are reviewed by the supervisory algorithm so as to ensure an absence of challenges to the safety system. The rationale for requiring these features and that for conducting research on several others is summarized in Secs. VI.A through VI.E. More detailed information is given in Refs. 8 through 11.

VI.A. Separation of Safety and Control Systems

The nuclear safety system is separate from the closed-loop controller. The word "separate" is defined as meaning that the output of an instrument used in the safety system must not be influenced by interaction with the control system. Thus, if an instrument is common to both systems, its signal must be passed through an isolation device, such as an optical transformer, to preclude any possibility of feedback from the control system. The purpose of keeping the two systems separate is to ensure that the capability of the safety system to perform its intended function will never be compromised.

VI.B. Signal Validation and Instrument Fault Detection

All sensor information is processed by signal validation and fault detection routines. There are several methods for accomplishing this. The simplest is to verify that each reading is within the range expected for a given plant condition. A more sophisticated approach is to identify the largest consistent subset of signals and to reject any that is not a member of that set.

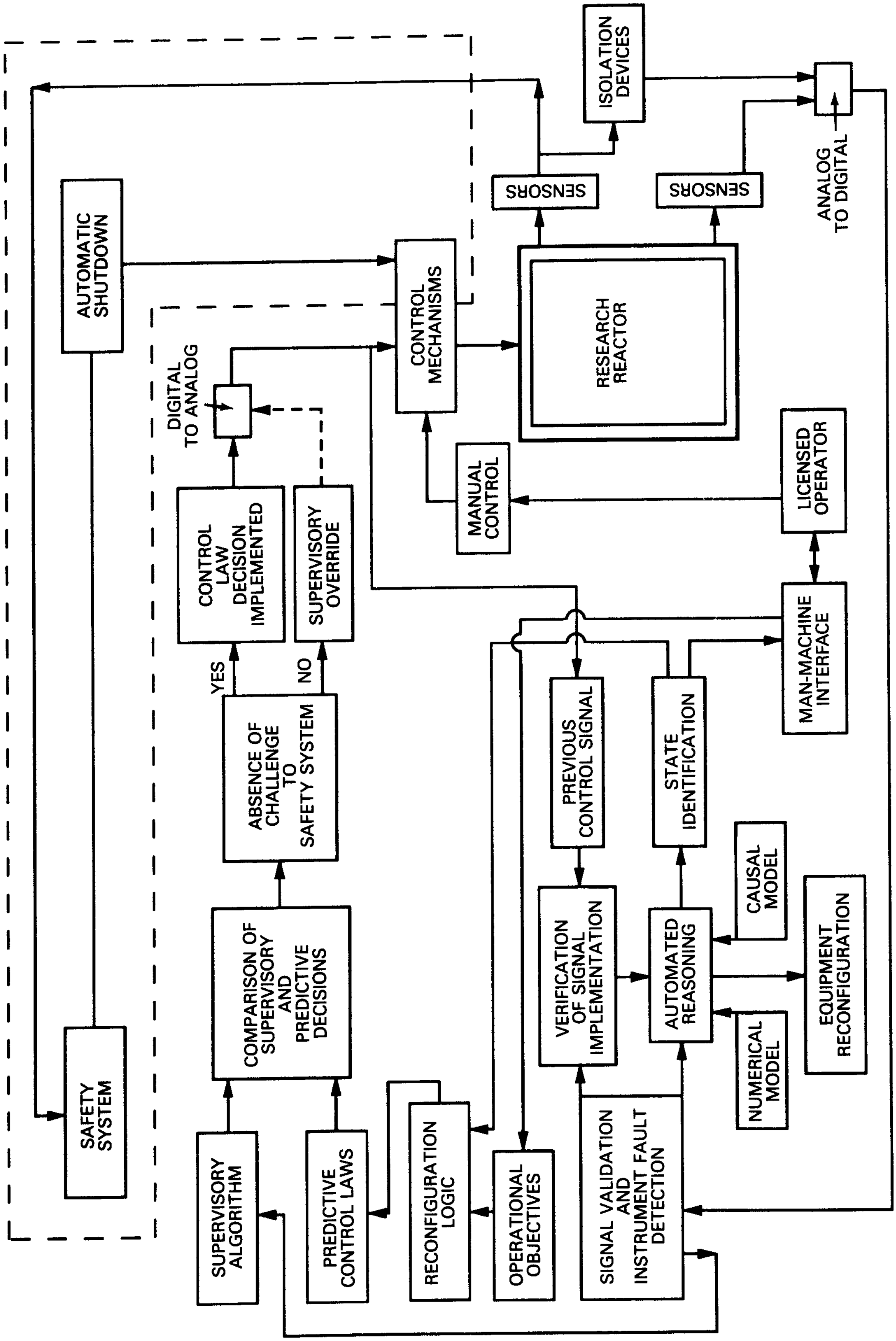

Fig. 10. Structure of digital closed-loop controller.

A further refinement is to incorporate a real-time system model that generates an analytic value for the measured parameter. Sensor readings are then checked for consistency both with each other and with the calculated value. This latter method has been demonstrated on the MITR-II as part of a numerical technique known as the "parity-space approach." In addition to validating sensor readings, this methodology performs instrument fault checks in which the weighting factor for each sensor is adjusted in proportion to the frequency with which its readings are judged to be valid. Thus, reliance on a failing sensor is gradually reduced, thereby ensuring a "bumpless" transition when complete failure actually occurs.

Figure 11 illustrates the importance of using validated signals. Shown is a strip-chart recording of the logarithm of two power signals obtained during a power increase of three orders of magnitude that was accomplished on the ACRR using the Standard MIT-SNL Period-Generated Minimum Time Control Law. The specified period was 1.0 s. Power was increased from 0.57 to 500 kW in 6.73 s. Initially, the sensor on the right was on scale while that on the left was off-scale low with the reactor power at 570 W. As the power increased, the sensor on the right saturated and failed while that on the left became functional. The software was programmed to recognize this. As a result, the power increase was completed properly. Had some means of signal validation not been available, the controller would have withdrawn the ACRR's transient rod bank continuously in a vain effort to raise the power as seen by the saturated sensor.

VI.C. Supervisory Algorithm

The selection of an appropriate control law is often perceived as the sole requirement in the design of a process controller. Yet, control laws are merely a mathematical means of translating a demanded system output into an actuator signal. They make no judgment as to whether or not the demanded output is appropriate, nor do they verify that the actuator is capable of generating the required signal. The transients that were shown in Figs. 1 and 2 are examples of the failure to properly address these two issues. In Fig. 1, the control law raised the power without proper allowance for the future impact of the delayed neutron contribution. In Fig. 2, it drove the control rod into a region where its differential worth was so low as to render the rod ineffective. Difficulties such as these can be averted through the use of supervisory algorithms that restrict the system state to those conditions for which control will remain feasible.[6] For a reactor, these algorithms take the form of constraints that limit the operating state to those combinations of reactivity and available rate of reactivity change for which it will be possible to halt a transient on demand. The mathematical form for this condition is derived from the dynamic period equation, which, assuming the prompt neutron lifetime is small, is as follows:

$$\tau(t) = \frac{\bar{\beta} - \rho(t)}{\dot{\rho}(t) + \lambda_e'(t)\rho(t) + \sum \bar{\beta}_i[\lambda_i - \lambda_e'(t)]} \quad . \quad (22)$$

To halt a transient, the period must be made infinite. This in turn requires that the denominator of Eq. (22) be made zero. Hence, the magnitude of the terms $\lambda_e'\rho$ and $\sum \bar{\beta}_i(\lambda_i - \lambda_e')$ must be constrained to be less than the available rate of change of reactivity, here denoted by the symbol $|\dot{\rho}_c|$. Thus,

$$\{\lambda_e'(t)\rho(t) + \sum \bar{\beta}_i[\lambda_i - \lambda_e'(t)]\} < |\dot{\rho}_c(t)| \quad . \quad (23)$$

Equation (23) is a reactivity constraint. If a relation of this type is observed during a power increase, then inserting the control device will make the quantity $\dot{\rho}$ sufficiently negative so that when added to the terms $\lambda_e'\rho$ and $\sum \bar{\beta}_i(\lambda_i - \lambda_e')$, the denominator of Eq. (22) will go to zero, and the period will go to infinity. When the transients shown in Figs. 2 and 3 were repeated using such a constraint, no overshoots resulted. This is shown in Figs. 12 and 13.

In these cases, the constraint caused reductions in reactivity and control device position, respectively, so that it was possible to level the power smoothly.[d]

VI.D. Automated Diagnostics

Figure 14 shows the reactivity and power profiles from a run in which the ACRR's neutronic power was raised from 3 kW to 3 MW, three orders of magnitude, on a period of 1.0 s. Reactivity was estimated using the parity-space approach with inverse kinetics being the default in the event of indecision. Note that power is shown on a logarithmic scale. The transient was completed in the allotted time of 6.7 s with essentially no

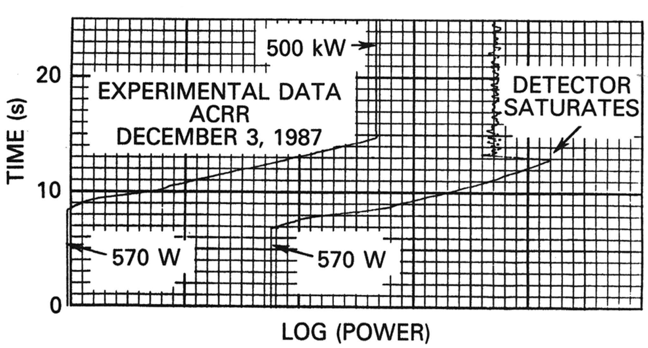

Fig. 11. Importance of signal validation.

[d]The constraint used in Figs. 12 and 13 was not Eq. (23) but one based on the standard dynamic period equation. Also, terms reflecting the redistribution of precursors among the defined groups are never retained in the final form of the constraints.[6-8]

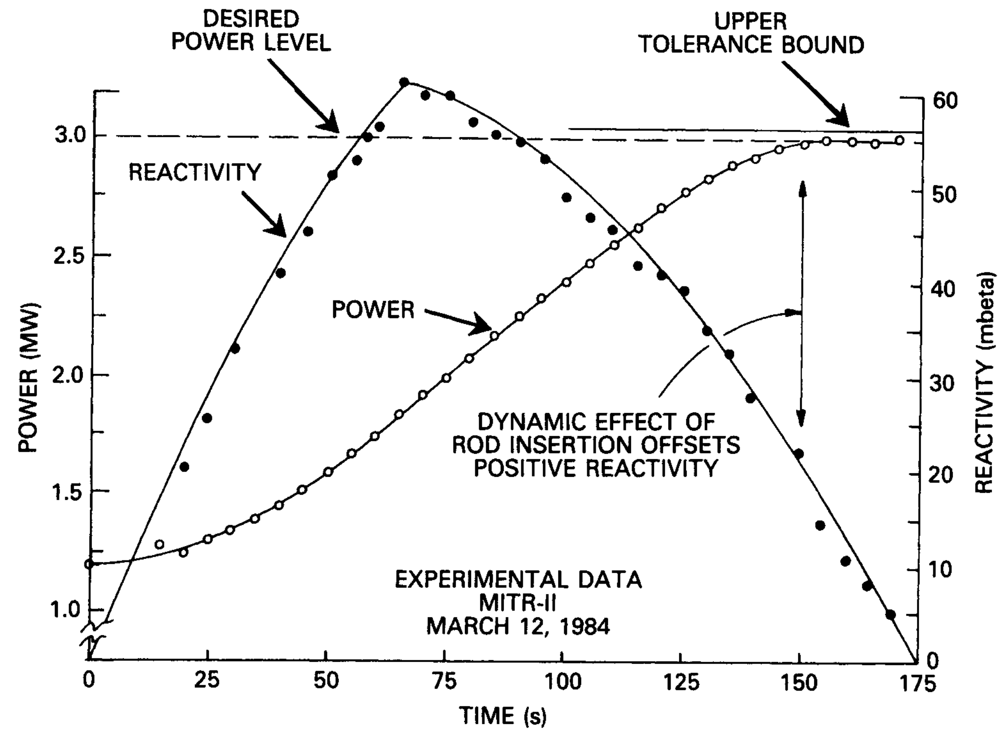

Fig. 12. Reactivity constraint approach limits reactivity thereby precluding a power overshoot.

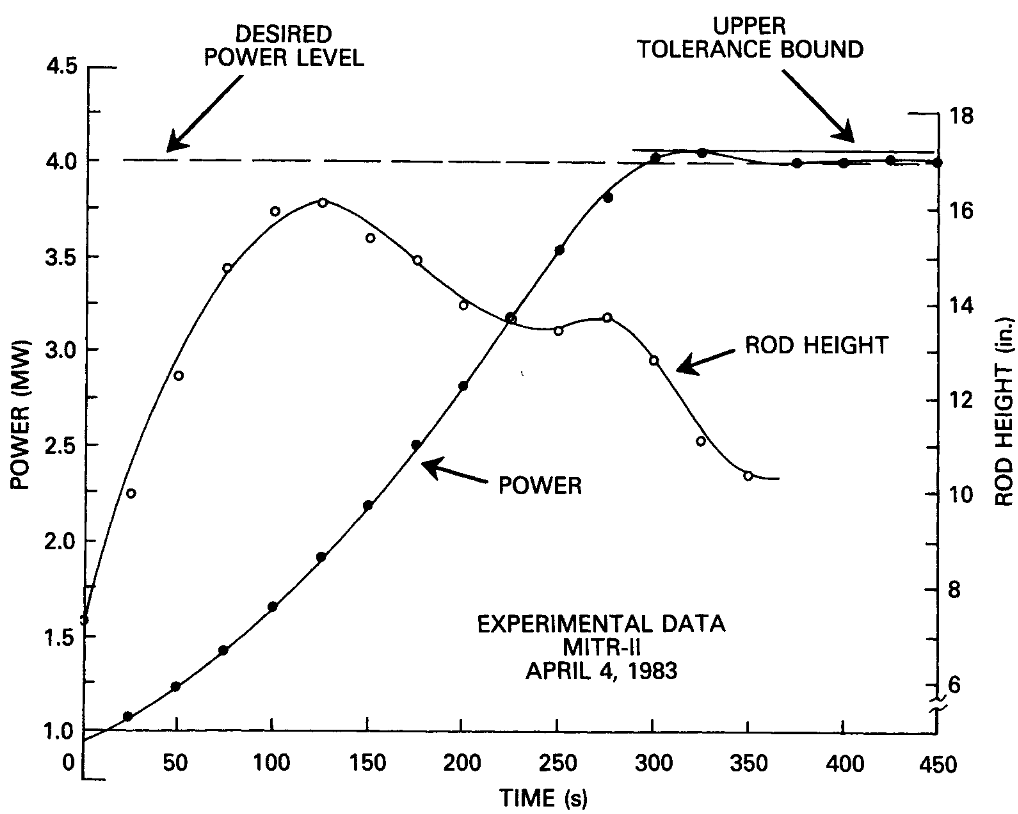

Fig. 13. Reactivity constraint approach restricts rod withdrawal in region of low differential worth thereby precluding a power overshoot.

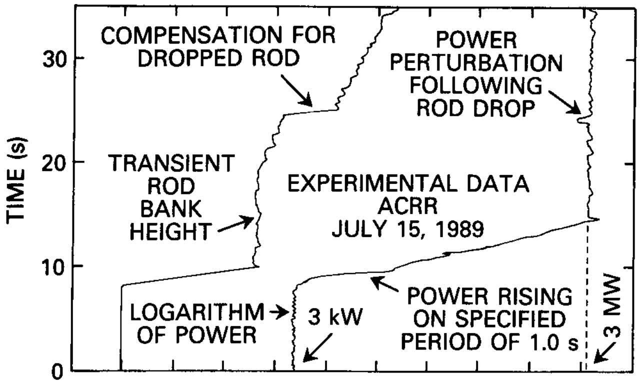

Fig. 14. Strip-chart recording of power and rod bank height: dropped rod experiment.

overshoot. The slope of the power profile is straight, indicating that power was indeed rising on the specified period of 1.0 s. Upon attaining the desired power level, 3 MW, the power was held at that value. Of special significance is that at 24 s, one of the ACRR's three transient rods was deliberately dropped back into the core. This caused a reactivity insertion of −400 millibeta. The controller was not "told" of this perturbation. Yet, excepting only a minor downward blip in the power trace, it held the power constant at 3 MW. Specifically, the remaining two rods were withdrawn to provide the necessary compensation. The foregoing action occurred during a carefully monitored experiment and was most impressive. However, suppose that the controller acted in the same manner for a situation in which the loss of reactivity was only temporary. If that reactivity were to return after the controller had provided compensation, a serious power excursion might occur. Hence, the challenge to the designers of autonomous controllers for safety-constrained systems is not merely to devise a control law that can compensate for perturbations but also to identify the cause of all such perturbations.

Automated diagnostics is currently the focal point of much research, particularly in the area of expert systems.[17] Currently, the MITR-II's digital controller is equipped so that a transfer to manual operation will occur should there be a sudden insertion of negative reactivity. Diagnosis remains the responsibility of the licensed operators.

VI.E. Man-Machine Interface

User acceptance of a digital controller may well depend on whether or not the man-machine interface is designed to support human cognitive needs. In this respect, the display should reinforce both the operator's understanding of the plant and his or her mental approach to the analysis of plant behavior. Displays that show trends and predictions satisfy the first of these two criteria because such information will assist operators in anticipating plant response. As for the second criteria, graphics should be emphasized so that an operator need only look at a display to comprehend it. This approach allows experienced operators to continue using their pattern recognition skills. In contrast, if text were to be displayed, an operator would have to switch to a deductive mode of reasoning to make sense of the information.

Figure 15 illustrates an approach developed for the MITR-II. As shown, a maneuver is in progress in which the reactor power is to be raised to 2000 kW. Emanating from the current operating point (100 s, 1500 kW) are three power projections. These show the operator what the effect will be of continuously withdrawing the control device (line A), maintaining its position constant (line B), or continuously inserting it (line C). Should the lowermost of the three projections touch the target power line, then the control device should be inserted. Otherwise, there will be a power overshoot. The display is quite simple. Yet, it conveys the information that the operator needs, and it does so in a manner that does not intrude on the operator's thought process. In particular, the operator can continue to use his or her pattern recognition skills.

In addition to the features noted in the preceding sections, the MITR-II's digital controller is equipped with a number of special circuits. These cause transfers to manual control and sound an alarm upon detection of a hardware system failure, upon failure of the software to execute in the expected sequence, upon the existence of too short a reactor period, and in the event of indecision within the signal validation system.[18] The Appendix provides brief descriptions of the MITR-II

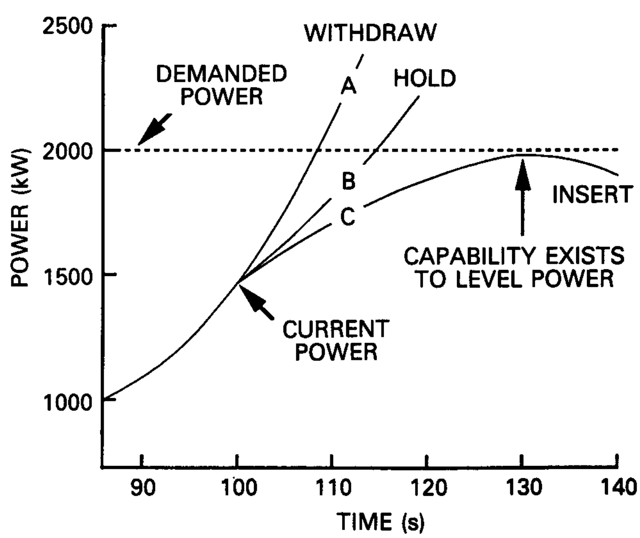

Fig. 15. Display for man-machine interface.

and ACRR facilities and their control systems as well as the experimental protocols observed during the experiments reported above.

VII. CONCLUSION

Digital technology can improve the operation of research reactors. Moreover, its application to those reactors will eventually generate a much needed data base for the commercial nuclear industry. The implementation of digital technology on research reactors should be accomplished in a planned, systematic manner with the objective of replicating each of the functions now performed by licensed operators. In this regard, model-based control laws offer superior performance because they provide excellent trajectory tracking, allow the possibility of a time-optimal response, and can be used to predict the subsequent state of the plant. This latter feature facilitates diagnosis. It should also be recognized that a control law is not in itself sufficient for the digital operation of a research reactor. Validated signals, supervisory algorithms, man-machine interfaces that reinforce human cognition, and ultimately automated diagnostics are also essential. The development of digital controllers for research reactors is a tremendous challenge, but it is also a necessary one if the U.S. nuclear industry is to remain competitive in international markets and if the United States is to achieve its objectives for the exploration of space.

APPENDIX

EXPERIMENTAL FACILITIES AND PROTOCOL

The experiments reported here were conducted on both the 5-MW(thermal) MITR-II and the ACRR that is operated by SNL. Descriptions of both facilities are given below. Those interested in the approaches taken by others for the closed-loop digital control of research reactor power are referred to papers by Ball et al.[19] and Cohn.[20]

Massachusetts Institute of Technology Research Reactor

The MITR-II is a 5-MW(thermal), light-water-cooled and -moderated, heavy-water-reflected, tank-type reactor that uses plate-type, uranium aluminide fuel. The fuel is enriched to 93% ^{235}U. Energy is continuously removed by forced circulation of the primary coolant. The maximum permitted operating temperature is 55°C.

The nuclear instrumentation used for the research described here consisted of three neutron flux sensors and a gamma-ray sensor that correlated neutron power with the radioactivity (^{16}N) of the primary coolant. All four sensors were directly proportional to the power over the range of interest. Measurements were also available of the coolant flow, coolant temperature, and control mechanism position. Four independent measurements of primary coolant flow were obtained from the pressure differences across orifices. Primary coolant temperatures were measured as follows: two sensors for the hot leg, two sensors for the cold leg, and one sensor for the temperature difference between the legs. In effect, three measurements were available for the temperature difference. All sensors were hard wired to a portable LSI-11/23 minicomputer through appropriate isolators, signal conditioners, and analog-to-digital converters. None of the sensors that form the MITR-II's safety system were used for this research. The sampling interval for the LSI-11/23 was 1.0 s.

Coarse control of the power in the MITR-II is achieved by positioning a bank of six shim blades. Once critical, the neutron flux is normally maintained constant by adjusting the position of a fine-control regulating rod. Both the regulating rod and one of the shim blades were made available to the experimental program described here. Each is normally moved at a fixed speed of 4.25 in./min. However, for the research reported here, each was specially equipped with a variable-speed stepping motor so that the rate of change of reactivity could be made to vary as specified by the control laws. The minimum allowed periods on the MITR-II are 50 s steady and 30 s dynamic. There is a negative coefficient of reactivity associated with the fuel, coolant, and reflector temperatures. Its magnitude averages -8×10^{-5} $\Delta k/k/°C$. The MITR-II's effective delayed neutron fraction and prompt neutron lifetime are 0.00786 $\Delta k/k$ and 100 μs, respectively.

Annular Core Research Reactor

The ACRR is a modified TRIGA reactor that uses UO_2-BeO fuel elements enriched to 35% ^{235}U. Its annular-shaped core is formed by 236 of these elements arranged in a hexagonal grid around the 23-cm-diam, dry, central irradiation cavity. The reactor operates in either a steady-state or a pulsed mode. For steady-state operation, the maximum allowed power level is 2 MW(thermal). For pulsed operation, there is no restriction on the power. Rather, there is a limit of 500-MJ total energy per pulse and one of 1800°C on the fuel temperature.

The ACRR is controlled by two fuel-followed safety rods, three poison transient rods, and six fuel-followed control rods. The transient rods, which are operated as a bank and which are driven by variable-speed stepping motors, were used to conduct the experiments. The negative coefficient of reactivity associated with the fuel is, in units of $\Delta k/k/°C$, given by the expression $(-3.85 - 730/T) \times 10^{-5}$, where T is the temperature of the fuel in degrees kelvin. The ACRR's effective delayed neutron fraction and prompt neutron lifetime are 0.0073 $\Delta k/k$ and 24 μs, respectively.

The computer used on the ACRR was an LSI-11/73 that was operated with a sampling interval of 0.05 s. To perform transients over several decades of operation, overlapping neutron flux sensors were used with a signal validation routine programmed to identify on-scale instruments.

Experimental Protocol

The testing of novel control strategies on the MITR-II is permitted if the following protocol is observed. First, the heat removal and the reactor safety systems are prepared for operation at full power, 5 MW. Second, the control strategy that is to be tested is permitted to raise or lower the power over some portion of the normal operating range, usually 1 to 4 MW. Third, the decisions of the novel controller are reviewed by the MIT/Charles Stark Draper Laboratory nonlinear digital controller (NLDC) prior to their being implemented. The NLDC is based on the "reactivity constraint approach" and is programmed to intervene if a decision made by the novel controller could result in the power exceeding some fraction of the maximum allowed power, usually 4.5 MW. This arrangement guarantees that the novel controller will not challenge the safety system while permitting it to act as if it had full control. Hence, when examining the experimental results shown earlier, it should be realized that the fact that power overshot the targeted value in some cases was significant to the experiment, but never to the reactor, which was at all times operated conservatively.

It was necessary to modify this protocol for use on the ACRR. The limiting condition for the ACRR is not a specific power level but rather the total energy produced during the transient. Accordingly, it was originally thought necessary to develop an energy constraint that would ensure that the reactor would be at or below its allowed steady-state operating power prior to the limit on integrated power production being exceeded. Such a constraint was developed and used for the initial experiments performed on the ACRR (Ref. 9). However, as confidence grew in the technology and as experience was gained by the experimenters on the operation of the ACRR, it was realized that an energy constraint was not necessary. The final protocol adopted for ACRR control experiments contained three provisions. First, limits were imposed through software on the allowed power, net energy production, fuel temperature, startup rate, and stepper motor drive frequency. Second, hard-wired circuits were employed to preclude conditions such as overspeed of the stepper motors. Third, the ACRR's safety system was maintained as a separate entity.

ACKNOWLEDGMENTS

Appreciation is expressed to Allan F. Henry (MIT), John E. Meyer (MIT), Francis J. Wyant (SNL), and Frank V. Thome (SNL) for their constructive comments. The contributions of Kwan S. Kwok and Shing Hei Lau as well as those of Wyant and Thome regarding certain experiments are noted as are those of Takashi Washio regarding the stability analysis. Carolyn Hinds, Georgia Woodsworth, and Leonard Andexler assisted with preparation of the manuscript. Special appreciation is expressed to Ara Sanentz, who prepared the figures and did the proofing.

This research was supported by the U.S. Department of Energy under contract DE-FG07-90ER123.90 and by SNL.

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