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Roger A. Kisner
Oak Ridge National Laboratory
Instrumentation and Controls Division
Oak Ridge, Tennessee 37831-6010

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ABSTRACT

Oak Ridge National Laboratory (ORNL) and Argonne National Laboratory (ANL) are undertaking a joint project to develop control philosophies, strategies, and algorithms for computer control of the start-up mode of the Experimental Breeder Reactor II (EBR-II). The major objective of this project is to show that advanced liquid-metal reactor (LMR) plants can be operated from low power to full power using computer control. Development of an automated control system with this objective in view will help resolve specific issues and provide proof through demonstration that automatic control for plant start-up is feasible. This paper describes the approach that will be used to develop such a system and some of the features it is expected to have. Structured, rule-based methods, which will provide start-up capability from a variety of initial plant conditions and degrees of equipment operability, will be used for accomplishing mode changes during plant start-up. Several innovative features will be incorporated such as signal, command, and strategy validation to maximize reliability, flexibility to accommodate a wide range of plant conditions, and overall utility. Continuous control design will utilize figures of merit to evaluate how well the controller meets the mission requirements. The operator interface will have unique "look ahead" features to let the operator see what will happen next.

INTRODUCTION

A joint program is underway between Oak Ridge National Laboratory (ORNL) and Argonne National Laboratory (ANL) to develop a new controller concept that allows intelligent automatic start-up of the Experimental Breeder Reactor II (EBR-II). EBR-II, operated by ANL and located at the Idaho National Engineering Laboratory (INEL) site in Idaho Falls, Idaho, is a pool-type 62.5 MW(th) liquid metal reactor (LMR). The plant generates 20 MW(e) at full power. EBR-II has been in operation since 1964.

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An important requirement of the automatic control system is to allow start-up to proceed from a variety of initial conditions with sufficient robustness to accommodate a limited amount of equipment malfunctions both at the initiation of start-up and as the start-up proceeds. No LMR power plant has such a system at this time.

The program's practical goal is to demonstrate a working automated start-up system on the EBR-II that integrates the operating crew's role during start-up with an efficient control system design. The ultimate goal is to develop a general control system structure on EBR-II that will become a prototype design for future LMRs. A staged approach is being taken to develop the control system with several demonstrations planned. The first demonstration is of a procedure recall system which receives data from the plant data acquisition system (DAS) and allows the operator to complete an electronically generated, screen displayed checklist as he manually starts the plant. The second demonstration is of a limited automatic start-up system which utilizes, as much as possible, existing sensors, actuators, and controller hardware. The third demonstration is of a more advanced automatic start-up system which utilizes more sophisticated fault-tolerant computer-based hardware. This paper outlines the approach being taken and some of the issues that must be addressed.

BACKGROUND

A well-trained operating crew currently maneuvers the EBR-II plant from low-power or standby conditions to full power operations whenever start-up is required. As would be expected, the crew accommodates a wide variety of plant prestart-up conditions and negotiates the start-up through a variety of system and equipment malfunctions as they occur. Although operators are guided by plant operating procedures, their individual skills, training, and previous experience contribute to the overall success of start-up. The development of an automated start-up system for EBR-II must transform written operating procedures into functioning rules of a computer-based control system as well as capture the operator's expertise.

An automated start-up control system is a computer-driven decision-making engine containing rules that govern all relevant aspects of the start-up process. Power plant start-up is a time of transitions in which various subsystems are engaged and disengaged; therefore, the start-up control system must possess capability to coordinate the functioning of continuous processes (e.g., flow modulation and pump speed) and discrete-event processes (e.g., pump off-on, isolate subsystem, and change mode). Start-up is also a high-risk period in which some component failure and malfunction is anticipated. Thus the start-up system must be intelligent to cope with abnormal equipment and process conditions by maneuvering around problems or by providing safe routes to shutdown.

HFIR Experience

The high-flux isotope reactor (HFIR) at ORNL [a 100 MW(th) research reactor] has been started automatically since its initial start-up in 1965.[1] Automatic HFIR start-up covers the range from source-level to the point at which sensible heat is generated. The HFIR start-up system is a discrete electronics system — not computer-based; hence, its intelligence is insufficient to handle unusual start-up conditions or malfunctions. The HFIR start-up system presumes that all systems are operating correctly. In the event of an abnormal condition or equipment malfunction, the start-up system returns to a shutdown state with the control rods fully inserted. The start-up system was designed utilizing a fixed sequence based on *a priori* knowledge of the process. In addition, a preprogrammed sequencer automatically restarts the balance-of-plant (BOP) equipment on inadvertent shutdown due, for example, to loss of electric power.

To start the HFIR reactor, specific preconditions must exist (e.g., neutron source inserted, control rod servos engaged, control rods fully inserted into core, and normal primary coolant flow and temperature conditions established) after which the automatic start-up proceeds by withdrawing rods to establish a period which escalates power to the desired level without further action by the operator. Once a suitable period is established, power continues to escalate until the set point is reached. Only a minimal amount of rod motion is required to hold the period throughout the start-up range.

Balance-of-plant start-up is also automatic; however, the start-up proceeds from one step to the next as a result of timed sequences only after necessary process conditions are met. The conditions are based on a set of rules which embody constraints on the operation of systems and equipment. For example, the main circulating pumps can only be started after the pressurizer pumps have been started and the system pressure has reached a predetermined minimum value.

Start-ups with both reactor and BOP automatic systems have been reliable. A small number of unexpected events during start-up have occurred. Experience with HFIR indicates that a more intelligent system could further reduce the time required to bring the plant to a power producing state. A faster start-up would be particularly important following inadvertent shutdowns where delays may allow xenon concentrations to increase to a level which prevents restart of the reactor. (This is a particularly severe problem with a high-flux reactor.) Present management rules require that causes for reactor trips be identified before restart can proceed. The reasoning process for identifying trip causes, at present the operator's burden, can be embodied in an intelligent automated start-up system. The inherent rapidity and repeatability of digital computing equipment may allow restart of the reactor before neutron poison grows to the point of rendering the core unusable.

Brief EBR-II Plant Analysis

In general, control structure follows the natural plant structure, that is, controllers are assigned according to the division of the plant subsystems. Such would be the case for an automated start-up control system. Figure 1 shows EBR-II divided by subsystems and grouped according to prime, support, and utility relationships. Also shown are the subsystem-affiliated controllers. To effect start-up, both the prime control systems and the controllers for support systems must be coordinated. This diagram is useful for illustrating the various lower-level controllers. From this diagram the next step is to create tables of input and output relationships.

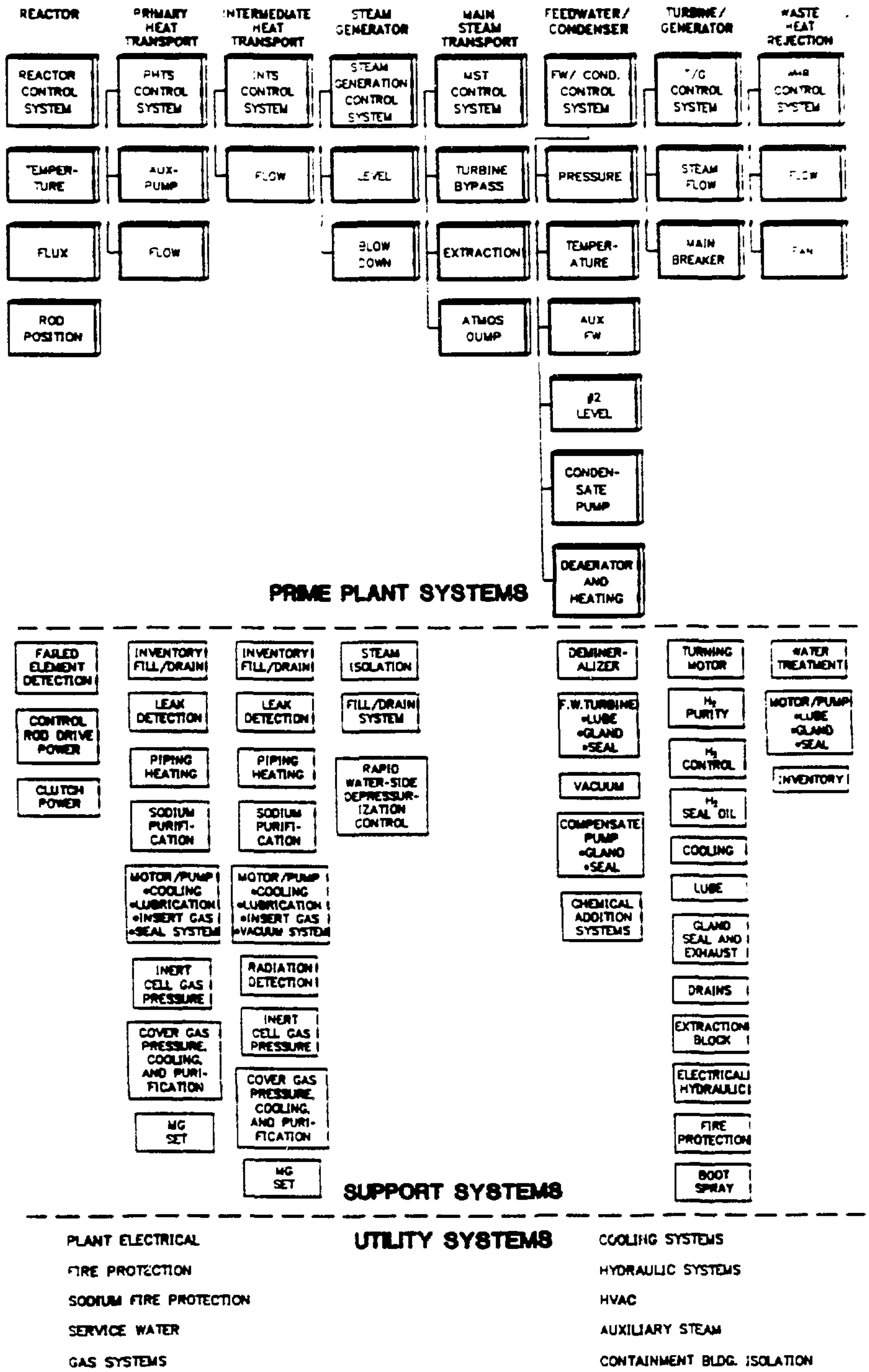

Fig. 1. EBR-II plant subsystems with local control modules.

Basic Requirements of Automatic Start-Up Control System

Control system design involves five development aspects that constitute overlapping phases through which development advances.[2] A unique, distinct expertise is required for each development aspect. These aspects apply to start-up control as well as other operational modes. The design aspects are (1) formation of goals and objectives, (2) development of strategy, (3) identification and adaptation of a control technique, (4) implementation of strategy and technique in real-time hardware and software, and (5) field tuning and refinement of the final controller within its intended environment. These aspects may be viewed as phases in which each subsequent phase is built on the specifications originated in the previous one, although some parallel activities may be possible. Errors occur and problems result from misinterpretation of the specifications passed from one phase to another. The five aspects are discussed briefly below.

(1) Formation of Goals and Objectives. The goal generation aspect of a control design project produces and maintains a statement of the entire system's goal and purpose, which includes plant system, control system, and operational system (humans). Initially, general performance requirements are established, especially requirements concerning reliability and availability, and the degree of automation and range of human participation in system operation. This aspect of development is dominated by project leaders, plant specialists, and system engineers.

(2) Development of Strategy. The physics of the process to be controlled are studied and existing operating experience is cataloged to identify the most appropriate operating procedures, set points, and control logic. Strategy development is independent of the means used to accomplish it. The means are taken up in the next aspect. For example, a typical strategy for (LMR) reactor control may be to maintain reactor inlet temperature at a constant set point thus allowing core-exit temperature to track reactor power and primary flow. Plant and component specialists participate in the strategy development. Strong emphasis is placed on historical experience of similar systems.

(3) Identification and Adaptation of Control Technique. A control technique is a mathematical, procedural, or symbolic mechanism for mapping measurements into actions according to a control law. The control technique makes operational the control strategies developed in aspect (2) above. The diversity of control techniques available to designers is very great. Examples currently being applied in the Advanced Controls Program at ORNL include the well-proven proportional-integral-derivative (PID), linear-quadratic-Gaussian (LQG), adaptive, rule-based, and nonlinear tracking types. A substantial development effort is required to combine the control strategy and technique into a system-specific design. Many iterations are required to arrive at a suitable design. This aspect of control system development is the domain of control engineers, and modeling and simulation specialists.

(4) Implementation of Strategy and Technique in Real-Time Hardware and Software. Most modern control systems are implemented in a digital computing environment. Because of the distinction between computing hardware and software, parallel developments are taken for each. This distinction also requires the expertise of both computer specialists and software engineers to accomplish system design. An unambiguous and complete specification for the control system's functionality [from (3) above] is required to ensure

that subsequently developed software meets the intended objective. Lack of clarity or incompleteness in this specification is a well-known source of error.

(5) Field Tuning and Refinement of the Final Controller in Its Intended Environment. Provisions must be made for on-line tuning and verification of proper tuning of the automated start-up control system. Traditionally either operations personnel or highly skilled specialists become involved in field tuning depending on the complexity of the process. Field tuning of single-input single-output (SISO) PID controllers may be accomplished by closed- or open-loop methods such as the Ziegler-Nichols method;[3] multiple-input multiple output (MIMO) tuning is more involved. Fortunately, computer technology offers an opportunity to provide a more meaningful interface to tune MIMO controllers than has been realized by analog technology.

The EBR-II start-up system project is concurrently working on the first three of the development aspects described above. Requirements for the automated start-up control system are currently being written. These will be added to and improved in the course of this project. Some of the salient guidelines are discussed briefly below.

Hardware. Bailey digital and analog controllers are currently in use at the EBR-II plant. These will be used for the initial demonstration of automated start-up. For the advanced demonstration, fault-tolerant control architectures will be employed. This will necessitate a changeout of some of the currently operating controller modules since they are not of redundant architecture.

Interface with the plant. For the initial demonstration, the control system will use existing sensors and actuators, although this may limit the potential of the new system. Other sensors and actuators may be added in the future based on the results of cost-benefit analyses. Sensor outputs are available through existing instrumentation and from the plant-wide DAS, although the DAS's update scan is relatively slow for some control functions.

Interaction with the operating crew. Reporting of meaningful information to the operator is a necessity if maintaining operator confidence in the controller and maintaining operator awareness of the system state is required. The start-up controller must be capable of explaining its actions to the operating crew so that they identify (1) what the controller is doing now and why and (2) what the controller is about to do next and why. The importance of the latter explanation should be stressed. The following actual account of an automated aircraft landing system illustrates the point:

> Some years ago, an aircraft landing system was developed that automated landing from the point the aircraft passed the outer marker through inner marker to touchdown. The automatic controller signaled the pilot at each checkpoint. Indication was given when it found the outer marker and inner marker, respectively. However, at the point of flare, the most critical phase of landing, the controller gave indication only at the moment of initiation. In operation, the pilot monitored progress through the checkpoints; however, during the last 50 feet of descent, he became concerned that the controller might fail to flare. Inevitably, the pilot intervened to manually flare the craft. This occurred in almost all uses of the system. The problem was that the controller did not give indication of what it was intending to do next and when.[4]

A criticism often heard in utility circles concerns the predictability of controller behavior during abnormal situations, especially during transient conditions in which the controller may behave in a seemingly unexpected manner. Operators, sometimes as a matter practice, revert to manual control at the onset of a transient. Part of the problem relates to lack of explanation by the controller as to what it intends to do next, as explained above. Another part of the problem is the operator's lack of understanding or misunderstanding as to how the control strategy or technique works. Inquiries have uncovered numerous occasions when the operator seized manual control, in which the controller would have chosen the correct course of action. A requirement placed on the start-up control system is that it be cast in a form that is understandable to control room operators and that it should project its course of action some seconds or minutes ahead to indicate to the operator what it will do.

Anticipated Problems Areas with Retrofit

A new system design and installation has many problems and issues to confront. A retrofit installation will encounter most of those problems plus some additional ones. Below are listed some of the issues and challenges facing development of the automated start-up control system. Although not elaborated here, these must be addressed during the course of the project.

Instrumentation and actuators. Some sensors may no longer be available or reliable. Some sensors may not be accurate enough to perform some of the tasks needed. The control design will have to account for these factors. Also not all actuators needed by the automated system are remotely operable. This limitation determines where the manual segment of start-up ends and the automatic segment begins. Pulling new cables may be difficult when new signals must be routed. During the first two demonstration phases, the problem of installing new equipment and cables will be minimized since existing will be utilized to the fullest extent.

Identification of *True* Procedures. Not everything that operators do is in the procedures. The missing facts must be accounted for by other investigative means. In addition, obtaining up-to-date procedures is sometimes difficult, even in well-managed organizations. Recent technical meetings between light-water-reactor (LWR) nuclear power plant designers and operators, with which the author was involved, have revealed that misunderstandings still exist concerning actual plant behavior. Neither designers nor operators independently have a complete understanding of all operational nuances. The generation of *true* procedures is a product of the data from several sources.

Personnel Involvement. Plant personnel must be involved at the onset of the project.[5] This will be done by including plant operations and maintenance personnel in the development process by soliciting their suggestions for improvements and review of the system at several stages. This involvement leads into a training program for the new system.

Scheduling. Because EBR-II is an operating plant, installation and testing will directly interfere with normal power-producing operations. Planning must take place to schedule modifications and upgrades during normal outages and minimize the installation time required. This may not be as much of a problem at EBR-II as at other commercial plants owing to the experimental nature of EBR-II.

SYSTEMATIC APPROACH

Staged Approach

Development and demonstration of automated start-up will occur in stages for flexibility and opportunities to include appropriate research and development. Demonstrations are planned at several points. Although not yet formalized, the stages are described below.

Requirements Development. Functional requirements for start-up are needed to steer the software development toward the final goal. The requirements under development will roughly correspond to the five control system design aspects described earlier: (1) start-up system goals and objectives; (2) start-up strategies; (3) control techniques and functional architectures; (4) software and operating system; (5) controller hardware; (6) plant interface; (7) regulations, standards, and codes; and (8) field adjustment and maintenance.

Demonstration Stages. Several progressive stages of simulator and plant demonstrations are planned:

(1) The first demonstration project develops an automated procedure recall and check-sheet system based on database and expert system technology. Several stages are planned in which the demonstrations will become progressively more complex. Currently the procedure prompting system is under development on an IBM/386 class machine using KES expert system. The procedure prompting system next will be moved to a SUN workstation with rules written in KES and C-language supported by SUN Unify database management system. The SUN implementation will be first demonstrated using a simulator environment. Later the system will be demonstrated using real-time EBR-II data. Finally, installation at the plant will be made.

(2) The second demonstration project develops a simplified autostart system that makes maximum use of existing EBR-II control equipment. This project will also evolve over several stages. Simulator development and testing will be performed first followed by in-plant demonstrations:
   - Stage 1: Development of basic control of continuous and discrete event processes
   - Stage 2: Addition of testing and validation tasks to Stage 1 design
   - Stage 3: Expansion of Stage 2 to include means for coping with contingencies and degradation
   - Stage 4: Addition of maintenance and calibration features to Stage 3 design

(3) The third demonstration project develops an advanced automatic start-up control system using enhanced control equipment including fault-tolerant technology and additional plant sensors and actuators. Much of this work will build on the results of (2) above. It is likely that similar stages of development will be followed. New equipment will be purchased to fulfill the requirements of this demonstration.

Demonstrations will prove the competence of the strategies, techniques, and implementation technologies used. Further, the demonstrations will lead other reactor control programs to important technological advancements. Roughly, the first demonstration project will take place late in fiscal year (FY) 1989; the second in FY 1990; the third in FY 1991.

Candidate Control System Functions

The concept of a control system limited to a loose collection of SISO continuous-mode servo controllers limits the capabilities of the plant to respond to off-normal conditions and disruptive events. In a manual environment, an operator acts to engage and disengage loop controllers and command new set points to coordinate the interactions of the various plant systems connected to those loops; however, for automated operation, the scope of the basic control system must be expanded to include supervisory functions previously accomplished by human operators.

An examination of EBR-II and other power plant operating procedures reveals that the procedures direct operators to perform several distinct categories of important tasks such as (1) controlling operating modes of plant equipment (e.g., equipment off-on status and valve alignment), (2) adjusting continuous controller setpoints and gains, (3) configuring controllers according to plant mode and condition, (4) testing the integrity and operability of sensors, instruments, and other components, (5) verifying the status of the plant systems, (6) calibrating specific instruments during the start-up cycle, and (7) reporting to management, maintenance, and other groups the progress and problems encountered. These seven task types must have their counterparts in the automated control system. The system proposed in the block diagram of Fig. 2 incorporates functions to accomplish these tasks.

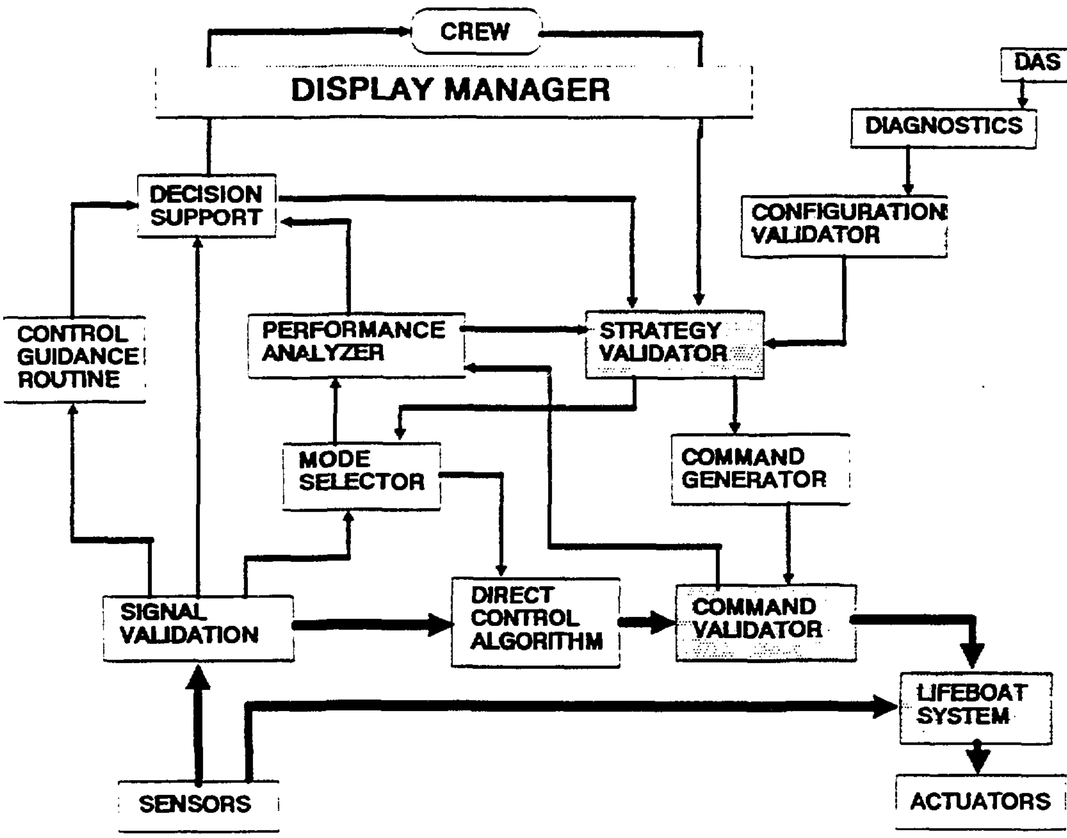

Fig. 2. Block diagram of start-up control system

Signal Validation. This function block contains multiple methods for processing raw sensor data and generating validated data prepared for specific uses. The concept of signal validation is fairly well understood even though further research and development may be needed. It is envisioned that multiple validation techniques will be concurrently observing the data. An intelligent supervisor then votes or weighs the outcomes of the various techniques to arrive at a validity parameter. Data sample and validity parameter are broadcast as a couple to wherever needed. A more exhaustive study of candidate signal validation techniques is underway at The University of Tennessee.[6]

Command Validation. The objective of the command validation block is to determine the accuracy of the command generated by the control system, and to validate the resulting output of the actuator system. A command validator as a distinct function is a relatively new concept to process control. It parallels to some extent sensor signal validation. Actuators come in many forms such as a (a) pump-valve systems, (b) control rod drives, and (c) heaters. Thus the overall command validation involves verification of control signal input (to actuator) and actuator system output (plant response). For illustration, the classic example of a command validator is the conflict resolver circuit of a traffic-light controller. Should the timers and phase sequencers produce simultaneous *green* lights at an intersection, the conflict resolver overrides the situation to produce flashing red and yellow lights.

A definition of the requirement for valid control strategy is that the controller's output to the actuator and the actuator system's output (within the plant process) must remain within certain bounds of a desired strategy or trajectory. The procedure for command validation consists of (a) identifying faulty control signals, (b) isolating plant component malfunction, and (c) quantifying the control signal's variation from the nominal value.

One of the approaches for command validation is to generate command signals on-line using a plant component model and drive this with the same inputs that go into the plant controller. Compare the controller and actuator system outputs with their corresponding predicted values.[7] This approach is similar to dual consistency checking.

Strategy Validation. This function block determines whether the current strategy in use by the control system (or operator) is valid for the condition of the plant and the desired objective. This form of validation may answer questions such as (a) are the set points correct? (b) is the system performance and stability as expected? (c) is the overall trajectory within the normal operation envelope? (d) is the system configured correctly given the current status of instrument, equipment, or control system failures? and (e) are the continuous controllers gains within the proper tuning range?

Configuration Validation. This function block identifies the current plant mode and subsystem operability status. The data generated consists of current mode of each subsystem, current status of subsystem equipment (e.g., in-operation, available/unavailable, under-maintenance, and faulted), and look-ahead status (i.e., planned outage).

Direct Control Algorithm. This function block houses the continuous control algorithms for all systems employed during start-up. The control algorithms must be robust to handle the wide range of conditions and parameter variations encountered during start-up. Candidate control techniques currently under development at ORNL include (1) nonlinear reconstructive,[8] (2) adaptive,[9] (3) linear-quadratic-Gaussian (LQG) control with compensation from exogenous inputs,[10] (4) LQG with loop-transfer-recovery (LQG/LTR),[11] (5) Proportional-Integral-Derivative (PID), (6) closed-loop nonlinear control, and (7) fuzzy-logic control.

Lifeboat System. The *lifeboat* concept is that of a simple controller employing a simple algorithm designed to bring the specific subsystem under its scope of control to a pre-established safe and stable state. The lifeboat system is implemented on separate hardware from the remainder of the start-up control system. Thus, hardware (or software) failures in the "principal" controller are captured by the lifeboat and not allowed to propagate through the process. Because the lifeboat is functionally upstream from the actuators, it is reasonable that the lifeboat module also function as a local hand-auto (H/A) station as illustrated in Fig. 3. If the lifeboat is limited to SISO or multiple-input single-output (MISO) architecture, then lifeboat modules can be matched to plant actuators. Lifeboat controllers may contain both continuous and discrete-event control algorithms as needed.

Mode Selector. A discrete event is a discontinuous change in the state of a component or system. Discrete-event control stands in contrast with continuous control in which states exist on a continuum. For example, turning a pump on or off represents a discrete event; however, controlling the pump's speed to meet a flow or pressure set point is a continuous action. The mode selector, which controls the discrete changes required for start-up operation, can change the mode of the direct control algorithm block or the plant directly by actuating pumps motors and aligning block and isolation valves to distinct configurations. Further information is available from a study on feedwater system control.[12]

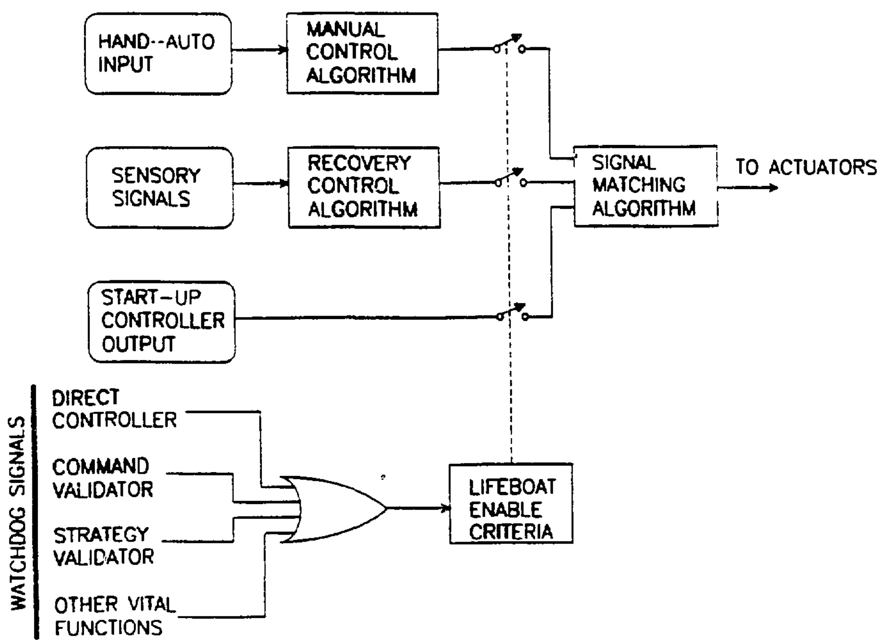

Fig. 3. Simplified diagram of lifeboat controller.

Performance Analyzer. This function block identifies failures and deteriorating performance in the major components and subsystems of the plant. Performance of various systems is tracked and compared with tolerance limits. Various tests may be performed to detect long-term problems such as bearing wear, tube leak, and heat-exchanger fouling[12]

Decision Support. This block contains the information system to support the operator's decision-making processes. Included in the block are the procedure prompting system and an intelligent planning system. Three major modes of operation are supported by this system: (1) *Manual* control gives the operator real-time control of all aspects of plant start-up. The control system is in an information processing mode supplying refined data and suggestions to the operator. The control system receives commands from the operator which are relayed directly to the plant components. (2) *Semi-automatic* control gives real-time control to the automatic control system except at break points. Operator permissives are required to continue to the next segment. (3) *Full-automatic* control gives real-time control to the automatic control system from starting point to final power level. The operator has inhibit power to halt start-up progress during a segment. The control system may be switched between these modes without perturbation to the process. The decision support system supplies appropriate information to the operator corresponding to which of these modes are active.

Information Needed to Develop an Automated Start-up System

Much information is needed to design an automated start-up control system. Some of the more important information requirements relate to (1) low-power models of EBR-II components, (2) detailed start-up procedures, (3) catalog of available signals, (4) catalog of remotely operable actuators, (5) performance requirements for continuous controller operation, and (6) operator information requirements for developing the decision support system. These elements of the design are discussed below.

Modern control system design begins by developing a mathematical understanding of the behavior of the plant components and systems. The mathematical models of the plant are used to formulate the continuous controller gains and structure. The models may also be incorporated as an active part of the controller architecture. Further, the models will be used as simulators for testing and evaluating plant performance using various control schemes. A linear model has been previously developed for EBR-II[13] using $MATRIX_X{}^{©}$ control system design environment. Portions of the linear model have been relinearized about a low-power operating point. Results using the linear model compare well with measured plant data taken during start-up mode. Figures 4 and 5 show reactor power and core-exit temperature during a start-up. Solid line represents measured data; dotted line is model results. The model predicts plant response relatively accurately; however, the control rods on the model were not moved precisely the same as the actual reactor. This accounts for the discrepancy between measured and modelled outputs.

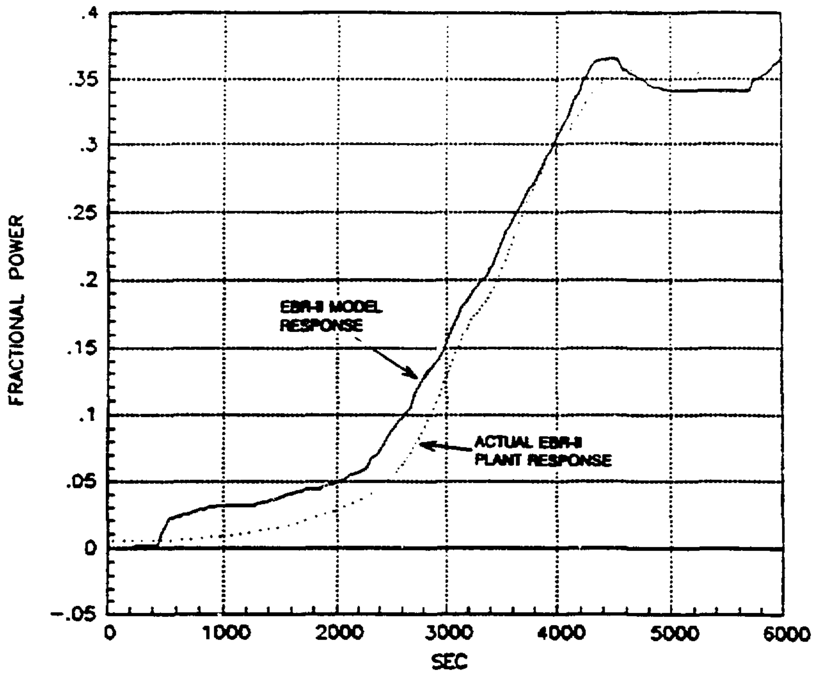

Fig. 4. Core power response during start-up.

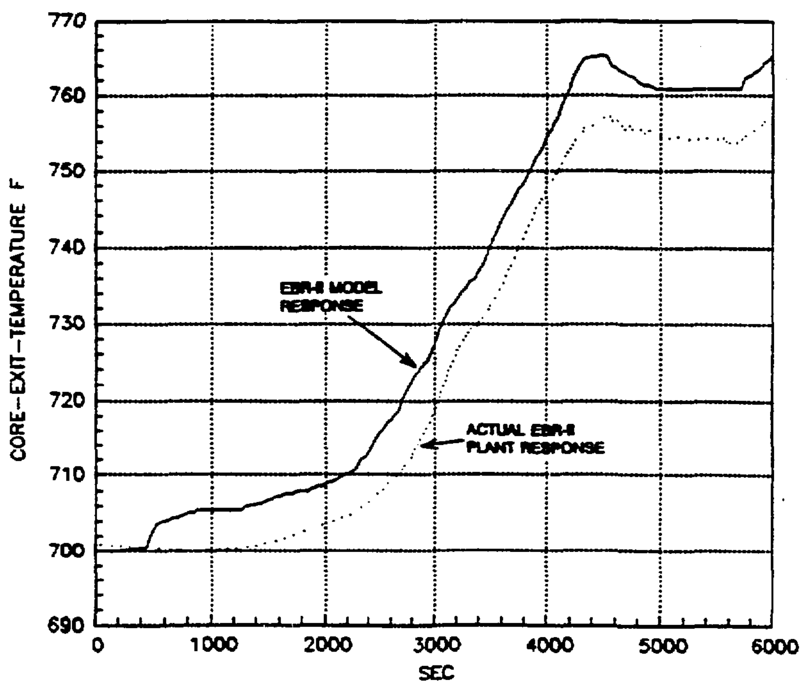

Fig. 5. Core-exit temperature during start-up.

The controller's rules for plant start-up are derived primarily from plant start-up procedures. EBR-II procedures are conveniently arranged for methodical analysis. Most procedures have companion checksheets that prompt correct operator actions and provide a record of the process. The procedures are arranged into four categories as follows.

Prestart-up Procedures. These procedures, which are directed individually at major subsystems, are for bringing about the necessary initial conditions required for start-up. The seven major subsystems and corresponding procedures are listed below:

- Electrical System
- Radiation Monitoring System
- Auxiliary System
- Reactor Control Checksheets
- Fission Product Monitors
- Sodium and CGCS System
- Primary System

Preparatory Procedures. These procedures do not activate any systems but instead verify plant-wide status and operability. There are 14 preparatory procedures.

Direct Procedures. Direct procedures require operators to activate subsystems and equipment as well as verify status. The 25 direct procedures bring the plant to a minimum steady-state power level in the range of 50-400 KW.

Approach to Power. These procedures carry the plant to full-power operation in 10 MW steps. There are seven approach-to-power procedures. The turbine-generator is placed on-line during approach to power at 30 MW.

From these procedures, computer-executable rules can be written. Operator expertise can be added to this framework of rules to form a more complete set of rules representing the *true* procedures.

A detailed cataloging and examination of the available sensor signals and remotely operable actuators must be performed. Some 900 sensor signals are available on the DAS. The task of collecting sensor and actuator data is just now beginning.

Selection of the rule execution engine has been made for the procedure prompting system, namely KES. For early demonstrations of the automatic start-up control system, the same software will be used. However, execution speed restrictions will force a recasting of the software in C-language.

An effective (continuous) controller for low-power-range operation must be developed. Besides information on plant physics and behavior, measures of utility must be established to guide the proper selection of control techniques. Measures of utility, which are an expansion of the traditional performance measures, include additional factors that express how well the controller meets the mission requirements.[2] Such factors include robustness, resource consumption, and human related items. These are outlined in the following table.

Table 1. Measures of Utility

Real-Time Performance (traditional measures)	
	Time-Domain
	Frequency-Domain
Tolerance of Degraded Conditions	
	Noise
	Process Parameter Variation
	Sensor and Actuator Failure
Effects on Downstream Components	
Compatibility with Human Operators	
	Field Tuning
	Meaningful Information
	Understandability
Resource Requirements	
	Real-Time Computational
	Sensor Count, Accuracy, Placement
Future Considerations	
	Flexibility

State-Transition and Data Transformation Modeling Techniques

A structured state-transition and data-transformation technique is proposed for the mode selector and portions of the decision support system.[14] The basic method is an application of the structured analysis and design techniques of Ward and Mellor.[15] The approach is first to build a logical model of the control system (i.e., what the control systems must do to control the process). Then from the logical model, a physical model is built of the computer processors, interconnection networks, and code environment (i.e., real-time applications software, operating system, computer hardware, data highway structure). The first task, building a logical model, consists of constructing a model of (1) the interface of the control system to its environment, and (2) the internal behavior of the control system. Logical models are implementation free, that is, the development effort should be independent of the programming language or computer type selected.

The context diagram and the external event list are the tools used to represent the control system's environment. To create a model of the control system's internal behavioral, network graphics tools model the flow and transformation of data through a system, the time-oriented behavior of the discrete states that a system may exhibit, and the organization of stored data associated with data transformations. The tools are data-flow diagram (DFD), state-transition diagram (STD), and entity-relationship diagram (ERD). The tools and techniques are described in the references cited.

When completed, the mode selector block of Fig. 2 contains the STDs for all start-up operations. Figure 6 shows the overall state transition diagram for the plant. The controller's objective is to select the proper sequence of states to get from "waiting in cold shutdown" to "minimum power under supervisory control." The starting point depends on the initial conditions including which instruments and equipment are available. For EBR-II's second demonstration project, the starting point may have to be further along than "waiting in cold shutdown" because of an incomplete set of remotely operable actuators. (Note that "cold" for an LMR is not ambient.) An example set of start-up states that might be selected is shown in Fig. 7. The actions commanded by the transitions from state to state drive the plant components and the modes of the controllers contained in the direct control algorithm block of Fig. 2.

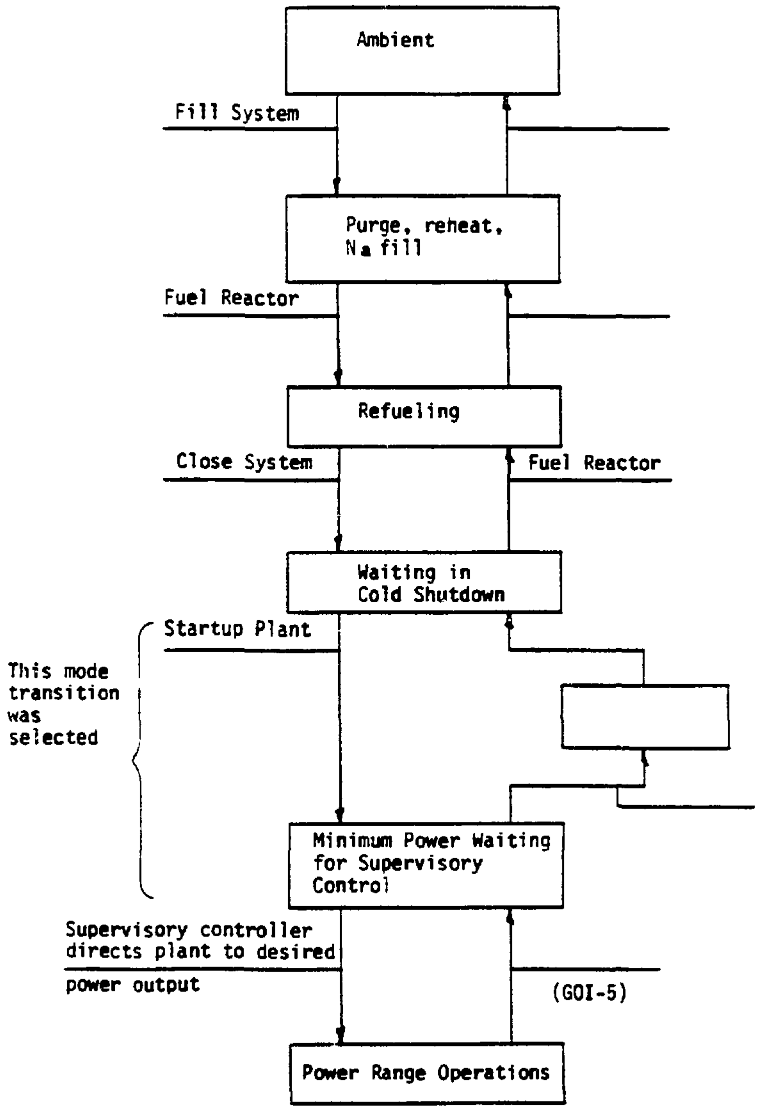

Fig. 6. Overall state-transition model of EBR-II. Note: many transitions have been omitted since this figure represents a framework for illustration only.

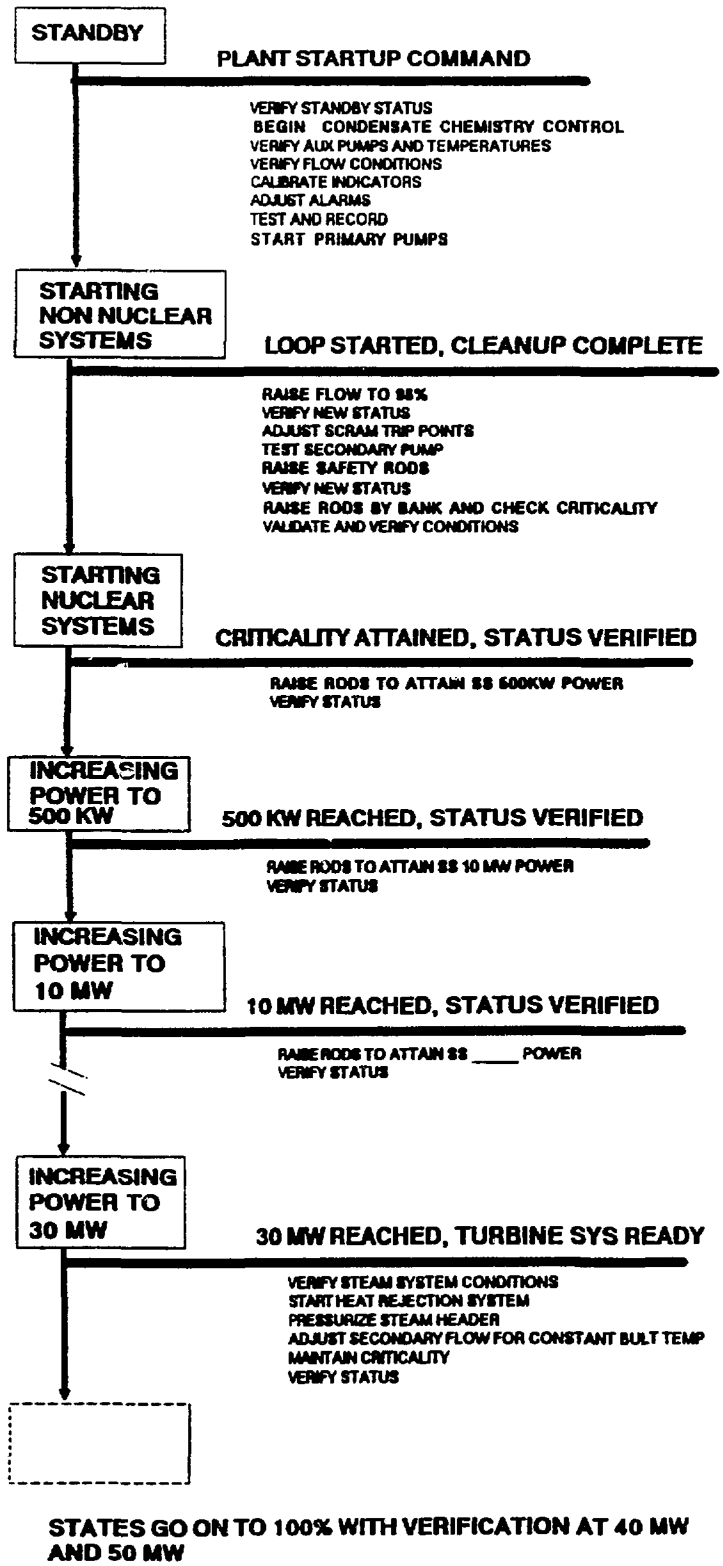

Fig. 7. Example state transitions for a start-up sequence.

The STDs are directly implementable by *if-then* rule structures. This will reduce the burden and the risk of error of passing the logical model to the software system developers. As an added benefit, the DFD and STD diagramming techniques may be suitable as a method of communicating meaning information to the operator.

CONCLUSIONS

This paper describes an approach currently being used to develop a computer-based automatic start-up control system for EBR-II. The approach is methodical and builds the system in stages. Modern control techniques are being developed for the continuous controllers. A state-structured, rule-based approach is being developed for mode control. The control system is being designed for flexibility to accommodate plant start-up from a variety of initial conditions and degrees of equipment operability. Many innovative features will be incorporated to solve the problems encountered in starting a complex large-scale system.

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