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Automating Large-Scale Power Plant Systems: A Perspective and Philosophy

R. A. Kisner
G. V. S. Raju

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Automating Large-Scale Power Plant Systems: A Perspective and Philosophy

R. A. Kisner
G. V. S. Raju*

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*Ohio University, Athens, Ohio

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

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ABSTRACT

This report is intended to convey a philosophy for the design of large-scale control systems that will guide control engineers and managers in the development of integrated, intelligent, flexible control systems. A liquid metal reactor, the large-scale prototype breeder, is the focus of the examples and analyses in the report. A structure for the discontinuous and continuous control aspects is presented in sufficient detail to form the foundation for future expanded development. The system diagramming techniques used are especially useful because they are both an aid to control design and a specification for software design. This report develops a continuous-system supervisory controller that adds the capability for optimal coordination and control to existing supervisory control design. This development makes possible global minimization of variations in key system parameters during transients.

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

ACRONYM LIST

AI	artificial intelligence
CAD/CAM	computer-aided design/computer-aided manufacturing
CRBRP	Clinch River Breeder Reactor Project
DFD	data flow diagram
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ERD	entity relationship diagram
FW	feedwater
GE	General Electric
HTGR	high-temperature gas-cooled reactor
HVAC	heating, ventilation, and air conditioning
IHT	intermediate heat transport
IHTS	intermediate heat transport system
LMR	liquid metal reactor
LSPB	large-scale prototype breeder
LWR	light water reactor
MST	mainstream transport
OTSG	once-through steam generator
PACC	protected air-cooled condenser
PCRD	primary control rod drive
PID	proportional-integral-derivative
PHT	primary heat transport
PHTS	primary heat transport system
PPS	procedure prompting system
SCRD	secondary control rod drive
SDD	system design description
SME	subject matter expert
STD	state transition diagram
T-G	turbine-generator
WHR	waste heat rejection

1. INTRODUCTION

1.1 PROJECT BACKGROUND

This project began out of a need that the U.S. Department of Energy (DOE) felt for improving control of liquid metal reactors (LMR). Although much work had been done on LMR control, a new perspective was needed to stimulate us to rethink our objectives and methods. Such introspective activity may be especially needed and useful during transition periods such as has been occurring in control engineering with digital system implementations replacing analog controllers.

With few exceptions, the capabilities of mini- and microcomputer technology exceeds that of previous control technologies. Real-time, computer-based control, offering a higher level of intelligence, can perform high-level decision making and complex-goal optimal control, as well as implement multivariate control schemes. The end result of such development would be more responsive, cost-effective operations.

In comparison with discrete analog and digital (relay) design, these new capabilities demand a different perspective on automation and control system's role in plant operation. The usual approach to the design of microprocessor-based control systems (which has been taken in various industries) simply emulates the functions of classical analog control modules without realizing the added benefits of the new technology. This is our justification for proposing some expanded concepts of control.

1.2 PURPOSE OF RESEARCH

The basic purpose of this project is to provide systems-oriented design guidance for the large-scale prototype breeder (LSPB) to improve its licenseability, availability to generate electricity, and maneuverability of plant systems under normal and abnormal conditions. The design guidance should be sufficiently general to apply to future plants, such as LMRs, advanced light water reactors (LWR), or high-temperature, gas-cooled reactors (HTGR).

The functions that the plant control and protection systems perform can dramatically affect the reliability of expensive plant equipment and the operating cost of the plant, although the cost of the control and protection systems represents only a small portion of the overall plant cost. As evidenced by many plant designs, lack of integration of the control and protection functions with the overall system mission requirements and constraints usually overly complicates the design, unnecessarily compromises safety, and disregards economic factors.

Many control and safety issues require a more nearly optimum resolution, especially those related to the human factor. Resolution of these issues subsequent to plant design forces retrofitting (e.g., patched procedures, additional operational limits and restrictions, and additional equipment). The design of the plant control and protection system can be further optimized for objectives of LSPB and other prototypical LMRs. Part of this optimization would involve vesting more intelligence in the control system to give it better capability to maneuver the plant through degraded conditions and to allow a decision-making capability that is adapted to weighing alternatives within the confinement of the multiple layers of operational constraints and objectives.

Another form of optimization may involve building a high degree of flexibility within the software and hardware of the control system. This is needed because of the continually changing nature of control and computer technology and the expanding knowledge of both the controlled system and systems that control. Over the nominal 40-year life of an LMR, major replacements of computer hardware can reasonably be expected as well as changes, additions, and perhaps deletions to system software; thus, a certain independence of implementation particulars is also desirable.

Investigative research in the function and design of control systems leads ultimately to the topic of role and function allocation, specifically, functions allocated to the human and automated subsystems. Previous research (Pulliam et al. 1983) has indicated that allocation of control functions is an intractable problem, which increases in severity with the increasing complexity of systems. Allocating functions to man and machine parts of the system should be attempted during the early stages of a new system design. One of the first items in the statement of requirements of the next section includes the role of man in the system described, capabilities of the technology, and functional requirements and constraints.

1.3 SCOPE OF THIS REPORT

This report is intended to convey a philosophy for the design of large-scale control systems that will guide control engineers and managers in the development of integrated, intelligent, and flexible control systems; that is, the report should help engineers involved in conceiving, analysing, and designing control systems for large systems and for planners who are involved in the conceptual phases of plant design. This report does not present a "cookbook" for the design of control systems. Some of the material presented is preliminary and requires further application and testing. Some of it has been drawn from the work and experience of others and integrated to form a systematic structure.

The scope of the analysis and design of the LSPB that was performed in the course of this work was to illustrate the concepts and methods being presented. Thus, the models and control system organization presented are incomplete but accurate as far as they go. Some of the concepts in this report are well developed while others are less developed. This imbalance is somewhat unavoidable because of the limited scope of this work. Much of the earlier work of this program examined the broad aspects of large-scale system control in an attempt to identify specific areas on which to concentrate work. From this broader examination, a perspective and philosophy emerged. However, to test their usefulness and demonstrate their application, a specific but more limited analysis was needed. The limited analysis, which takes the form of an example, appears more developed because of the detail needed to describe an automated plant startup.

1.4 RECOGNITION OF SIMILAR WORK

Much of the mathematical work in optimal control theory, analysis of stochastic processes, and classical proportional-integral-derivative (PID) control is valuable for designing controllers of continuous plant variables at the lower levels within the structure of a control system. However, these concepts and techniques are not very helpful in determining the function and design of the upper-level supervisory structure where the discontinuous activity of decision making is a dominant transaction.

A theoretical basis for characterizing and analyzing multilevel hierarchical systems was begun by Mesarovic et al. (1970) where the concepts of multilevel and multilayer hierarchies were introduced. This initial work was continued by Findeisen et al. (1980) and Jamshidi (1983). The base that this work provides is somewhat abstract so that it does not translate directly into techniques that are readily applied by systems and control engineers.

An assortment of tools and techniques for analyzing and designing the function, data connections, and structural characteristics of control systems has been developed and refined by several analysts (Yourdon and Constantine 1979; DeMarco 1979; Page-Jones 1980; and Gane and Sarson 1979). Contrasted with the mathematical and abstract nature of the techniques of Mesarovic or Findeisen, the goal of these tools and techniques is data management and state analysis from a software engineering perspective. This work is application oriented and can be applied without necessarily drawing on advanced analytical mathematics.

One of the products of this report is a collection of tools and techniques that draws from both the abstract and practical work of control theory and computer science. These tools should prove useful to control engineers engaged in the design of large-scale control systems.

1.5 BACKGROUND OF CONTROL SYSTEMS

In general, plant control and protection systems for LMRs have evolved from LWR and fossil power plant experience. The approach taken to transfer this technology into the LMR domain and further develop it has been characterized as highly conservative with a basic underlying rule to extrapolate minimally from the known to the unknown. Whether or not this approach was justified, it has tended to suppress creativity and new developments that might lead to a more nearly optimum solution to the overall control problem.

Historically, industrial control practice restricted the development of control systems to the final phases of a project. Thus, after physical components have been designed, procured, or perhaps even installed, only then would the control engineers be asked to "make it work together." This bottom-up or equipment approach, also characteristic of the nuclear industry, lacks the system-wide integration required to ensure that the successful functioning of the parts meets the mission of the whole. This approach to control system design emerges if the designers do not consider control and instrumentation to be concept-determining factors (i.e., that control-related factors have no significant influence on the overall plant or equipment design). Because of this approach, many system designs have had to be altered to make them controllable.

For large-scale systems, integrated and coordinated control functions are required to maximize plant availability, to allow maneuverability through various stages of degradation, and to meet externally imposed regulatory limitations. Control engineering, viewed in this perspective, has a broader scope than the "classical" view of process control, historically held by equipment designers. Control engineering should have a prominent role in the total engineering of a plant that spans the initial requirements phase to startup and beyond as necessary.

The function of overall system integration is a natural activity for the control engineers of a large-scale plant system because the scope of control should encompass the entire plant. The need for and means to implement this overall integration has not been widely recognized. Indeed, many control theoreticians and practitioners have confined themselves to such limited areas that the larger perspective of overall integration has been ignored. With the limitations of earlier technologies, a well-integrated and coordinated plant-wide control system may have been difficult to realize economically. Now, however, the technology of implementation may have outpaced our design methodology.

1.6 ORGANIZATION OF REPORT

Following the introduction, a tutorial section (Sect. 2) defines terms and concepts related to the design and analysis techniques applied in Sects. 3 and 4. Section 3, based on the perspective and philosophy of Sect. 2, uses structured software analysis techniques to derive an organizational structure for an automated plant-wide control system. Section 4 derives a structure for hierarchical, distributed supervisory control of the continuous plant systems. The system developed in Sect. 4 is one of the components of the overall control structure developed in Sect. 3.

Because this report merges several engineering disciplines, primarily those of control and software engineering, occasionally an overlap of terms occurs. This is somewhat unavoidable since the alternative would be to invent new terminology either totally or for the overlapping areas. Such added terminology would perhaps also add more complexity and confusion to engineering disciplines already profuse in terms and definitions. An example of this overlap is in the use of the terms "state" and "transition." These terms are used in discussing regions of control (Sect. 2), control of discontinuous systems (Sect. 3), and control of continuous systems (Sect. 4). The terms are used differently in each context. An effort has been made to avoid confusion by defining the terms as they are introduced in each section and in the Glossary.

Conclusions and recommendations for further work are presented in Sect. 5.

Detailed analyses have been placed in the Appendixes. Appendix A contains a brief summary of the structured software analysis tools. Appendix B contains diagrams that detail the inner portions of the control system described in Sect. 3. Appendix C contains the details of mathematical models for the reactor, intermediate heat exchanger, and steam generator used in Sect. 4. Finally, Appendix D lists a procedure for assuring closed-loop optimal control of the local controllers of Sect. 4.

2. INTELLIGENT AND FLEXIBLE CONTROL IN AUTOMATED SYSTEMS

This section of the report discusses issues related to extending the boundaries of controlling large-scale processes. Definitions of some of the terms and concepts that are used and developed below are given both in the text and in the Glossary.

2.1 CHARACTERISTICS OF LARGE-SCALE NUCLEAR PLANT SYSTEMS

2.1.1 Subsystem Classifications

A nuclear power plant is representative of large-scale systems. A large-scale system,* as it is used in this report, may be described as a complex system composed of a number of constituents or smaller subsystems serving particular functions and governed by interrelated goals and constraints. The subsystems may be catagorized either as those that are placed in the plant to govern or those that are governed. Physical and informational interactions occur among these subsystems. Informational interactions among the governing subsystems occur in several ways: hierarchically (vertically), where a subsystem at a given level controls or coordinates the units on the level below it; laterally (horizontally), where data or control signals are passed between subsystems at the same level, both within a control hierarchy or between different hierarchies; and externally to the human overseers of the system.

The subsystems that constitute a nuclear power plant can be classified according to their functional relationship to the overall plant and according to the type of control required to make them operational. Thus the plant is composed of *prime systems, support systems,* and *utility systems.* And within these classifications, systems can be further divided into those that exhibit continuous and discontinuous behavior types. These classifications will be useful later in developing a control structure.

Prime systems are those that contribute directly to the behavior of the plant's ultimate output. The prime systems are usually cascaded and constitute the flow path for the process. Situated in the stream of the process, their function is to change the incoming feed material so that an interim product is made available to the next subsystem. In the case of a nuclear reactor system, the unidirectional flow through the prime systems is one of energy. Between the prime systems are the flows of various materials that effect the transfer of energy from heat generation in the reactor core to electrical transmission to the power grid. Although the flow of energy is unidirectional, the flow of materials is looped. Because of the cascaded nature of the system, individual prime systems are influenced by upstream and downstream conditions of their neighbors. The prime systems of an LMR are (1) reactor, (2) primary heat transport (PHT), (3) intermediate heat transport (IHT), (4) steam generator, (5) main steam line, (6) feedwater-condensate, (7) turbine-generator, and (8) waste heat rejection.

Support systems are those that supply necessary functions and services to the prime systems of the plant. These services may be in support of (1) equipment such as motors, pumps, and valves; (2) facilities such as containments, tanks, and piping; and (3) process materials and products such as sodium, water, argon, and air. Support systems supply electric power, cooling, lubrication, and expendable materials. Unlike the prime systems, support systems are not interconnected in cascade form. Often they are independent of each other with little if any direct influence on each other. This is not to say that their failure is not felt in the performance of the plant. A support system may be totally necessary to the functioning of a prime system and hence the plant (e.g., condenser vacuum control).

Utility systems are, in a sense, support systems. They are the common services that supply bulk materials, energy, or data to the prime and support

*The terms "plant" and "large-scale system" are used interchangably in this report.

plant systems. These systems are even more removed from the prime flows of interim products than the support systems described above. Some of the plant utilities are plant electrical, fire protection, sodium fire protection, service water (of which there are several classes), gas supply (e.g., argon, helium, nitrogen, compressed air, and instrument air), building environment [heating, ventilation and air conditioning (HVAC)], hydraulic supply, auxiliary steam supply, radioactive waste handling, and fuel handling. In many cases, support systems direct the products of the utility systems in support of the prime systems.

Further classification of the plant's prime, support, and utility systems will prove useful when applying control to coordinate plant-wide changes in mode. It is useful to identify the subsystem type by the way the system is called into operation and the states that it assumes. Two classes of system control are then proposed: *continuous* and *discontinuous*. To many, the distinction between discontinuous-event control and continuous-event control is unclear because in past designs role allocation assumed that human operators perform most of discontinuous activities (e.g., start-stop and valve lineup) and local (continuous) controllers regulate to maintain a setpoint. To automate a large-scale system, both classes of control must be integrated to carry out the functions required to achieve the goals and objectives of the entire plant.

Subsystems that exhibit continuous parameter variation, and thus may be controlled proportionally, fall under the first category of *continuous control*. In general, the continuously controlled subsystems lie within the prime plant systems. This form of control is the type most often associated with control engineering. The fields of classical and optimal control theory are directed primarily at the control of continuously variable systems.

The second category, *discontinuous control*, refers to subsystems that exhibit discrete operational states and are called on to function by an enabling command with no element of proportionality contained in the command. Although within a subsystem enabled by a state-oriented command, local control loops may function in proportion to measured values; these loops, however, are hidden from the subsystem's superordinate. A discontinuously controlled subsystem may be off-on or start-stop in operation or may have a limited number of additional modes to which it may be commanded. Batch control, logical control, mode control, and sequence control are forms of discontinuous control.

2.1.2 Procedures

The strong dependence on procedures by the human component also characterizes large-scale nuclear power systems. Much of the role that the operator assumes can be derived from an examination of plant procedures (Kisner and Frey 1982). With an understanding of the role of the operating crew, a basis for plant-wide supervisory control can be established. From the procedures, many of the specific sequences needed for starting the plant or coping with abnormal conditions can be extracted.

Singular dependence on procedures alone to supply the necessary information on which to build the algorithms for automation can result in error. Because plant operators act to filter and improve plant procedures, operators should be consulted to interpret the procedures. This information and equipment design and analysis information constitutes the basic input to the design of an automated control system.

2.1.3 Safety Systems

Nuclear power plants are also characterized by the inclusion of a specialized protection system that protects the reactor core and other components associated with containment of radioactivity by the rapid insertion of control rods to stop the nuclear reaction and other actions. The safety system may be regarded as a control system with a highly specialized function. In general, the control systems and the safety (protection) systems are separated to ensure that the failure of a control-rated component does not disable or nullify the function of the safety system. Thus, the safety system is provided with an independent and redundant view of the plant parameters. In earlier designs, which exhibited hardwired single-sensor-to-single-display (dedicated) technology, this independent view was easy to assure; however, with multiplexed data and other technological trends away from dedicated measurement, total separation of control and safety is becoming difficult to achieve.

The safety system concept is unique to the nuclear industry. By contrast, in the aircraft and space industry, critical operational functions are identified, and redundancy is employed to ensure the continuation of these functions in the event of a problem. In these industries, complete shutdown during a mission is not a viable alternative. Other industries provide protection of investment through protection of equipment. While this is also a part of the strategy of operation in a nuclear power plant, ultimate protection of the public can require sacrificing certain plant components.

The reactor safety system is generally designed to a rule of simplicity. Although this increases hardware reliability, it forces plant operators to interact with the safety system at various times during the operation of the plant, mostly during startup and shutdown. These interactions, inhibit, verify, or permit a safety system function. Thus the operator becomes the supervisory controller of the safety system, and he becomes a common link between the nominally separated systems.

The rule of simplicity is often suspended on experimental reactor types, when an uncertainty exists about the behavior of the overall system. Under these circumstances, downstream process measurements are often used to anticipate a condition that might compromise the integrity of the core. The presence of anticipatory trips usually restricts the range of maneuverability allowed to the control system unless these trips are bypassed. In general, they increase the probability of unnecessary reactor trips.

2.2 AUTOMATION OF LARGE-SCALE PROCESSES

2.2.1 Dimensions of Automation

Automation has different meanings for different groups (factory automation, aircraft automation, office automation, process automation, etc.). Automation, in a general sense, has come to mean the delegation of tasks to machine or computer systems, thus freeing human operators from vigilance over routine or tedious tasks. A distinction is made between process control and process automation. Process control, referring to the continuous regulation of a process, is a subset of automation, in which discontinuous activities, including problem solving, also occur. For simplicity in this report, an automatic control system refers to a system which contains both continuous regulation and discontinuous control activities.

A classification scheme for automation has been devised as a part of developing a design guidance for large-scale nuclear power systems. For process systems, automation separates into four components, each of which carries with it a discipline of its own. These types of process automation are *controlling*, *configuring*, *monitoring*, and *diagnosing*.

This four-component breakdown is an expansion of earlier work by Kisner and Frey (1982), where the idea of analysing plant automation was proposed to gain an insight into the operator's relationship to the machine portions of the plant. The types of automation were described as dimensions in automation space so that the degree of automation in a plant could be represented graphically as a multidimensional geometric form. In most systems, the form is skewed because of the dominance of automation in the dimension of process control. The other dimensions are less automated, meaning that the functions of changing the configuration of the plant, diagnosing problems and potential problems, and, to a certain extent, monitoring the process parameters are left as manual* activities. The four dimensions are defined in the following paragraphs.

Controlling refers to the regulation activities directed at maintaining specific characteristics of a product stream or achieving a specific overall system performance. Stability, in the classical sense, is an objective of this dimension. Classical and modern control disciplines focus on controlling as it is defined here.

Configuring refers to the restructuring of the flow of process material or data, reordering the operation of a system, or altering the function of a system to meet a different plant goal or mission than was in effect previously. A goal shift may occur because the overall mode of the plant is changing normally, as in startup, because of equipment failure or other abnormal conditions, or because of equipment maintenance and repair. Unlike process control, configuration control is accomplished predominately by discrete (discontinuous) actions. Stability is an issue here, although it is characterized differently than in the continuous system case. Complete startup-shutdown capability for all systems, preparation for maintenance and repair with restoration to operation when complete, and further realignment capability to meet abnormal circumstances would comprise highly automated plant configurability.

*Manual activity refers to both totally manual and mechanized tasks, in which the operator controls the application of whatever power or energy is required, but a machine generates the power or energy (e.g., remote actuation of a valve).

Monitoring refers to the measurement and transfer (or communication) of process parameters and variables. Although one usually thinks of process measurement as being an automated function, in fact, chemical analyses in power plants are mainly a manual activity carried out by technicans. In the most recent plant designs, computer systems provide data storage and busing to various control systems and to plant operators. Measurement of all needed plant parameters, the distribution of these data to all systems and components that need them, and the validation* of these data and estimation of unmeasurable parameters would comprise highly automated plant monitoring.

Diagnosing refers to the ability to detect or anticipate an anomaly, identify its cause, predict the consequences or propagation, and determine the proper response with respect to the mission of the plant. Computerization of this aspect of automation is by far the most challenging to the engineering community. Some aspects of diagnosis are routinely automated as in alarm generation. However, as it is currently implemented in most plants, alarm generation is accomplished by simple limit comparison. Work is in progress at many organizations to increase the intelligence of alarm diagnosis so that fewer extraneous data are presented to the operator. As far as automating the other aspects of diagnosis, the consensus of opinion indicates that artificial intelligence techniques, such as automated reasoning and expert systems, may offer a means to resolve problems that do not easily yield to the application of a simple rule or template.

2.2.2 Allocation of Functions

Increased automation is expected to produce a dramatic change in the role of the nuclear power plant operator. This change is expected to be for the better: automation may provide the best capability for mastering the complexity of plant control; and it may permit the design of control systems which are at the same time safer, more efficient, and better suited to the characteristics of man.

The proper allocation of functions among human and machine components is required before automation can achieve its full potential. Although it seems reasonable to approach the design of a large-scale system by attempting to state initially some mixture of human and machine participation, the actual motivation comes from the level of technology at the time of system design. After the capabilities of technology (to a large extent, computer technology) have been determined, then the appropriate allocations can be made. This is in agreement with the procedure developed by Pulliam et al. (1983). In selecting the proper allocation of control functions, it may be necessary to return some of the control back to the human component to ensure complete and unfragmented tasks so that the operator's human factors structure and cognitive support are adequate, and job satisfaction is more nearly optimal.

2.3 CONTROL UNDER VARYING CONDITIONS

Regardless of how much care and expense has gone into the engineering of large-scale systems, they occasionally fail to function as designed because of component failures and external environmental disturbances. The range of environmental disturbances for large-scale systems is greater than for that of a system consisting of a smaller number of components, interactions, and states. The ability of a system to withstand a wide range of disturbances, specifically the tolerance to failed components, is referred to as *fault tolerance*. A further distinction is often made to systems whose parameters may range far from their usual values without serious degradation of performance. This property is refered to as *robustness*. The properties of fault tolerance and robustness can become indistinguishable at times; however, fault tolerance is associated with internal equipment failure whose probability for failure should have been known during design. Robustness is associated with the ability of a system to recover from large variations in system parameters, including process variables exceeding design limits and other unplanned excursions.

A goal of control design is to build in both of the properties of fault tolerance and robustness. One approach could be to duplicate equipment critical to the functioning of the plant. This physical redundancy, if it could be afforded, could be implemented to the extent necessary to meet whatever reliability goals apply. A second means of fault tolerance can be provided by the plant control system. This comes about by drawing on the four dimen-

*The association of data validation with monitoring is debatable, since it is, in a sense, a form of diagnosis; however, certain techniques of validation are common to parameter observation.

sions of automation described previously, thus giving the control system reconfigurable capability to accommodate specific anticipated failures. The extent of this capability is determined from a knowledge of plant availability requirements and from cost versus benefit considerations and safety considerations.

One means of accomplishing intelligent control, which can achieve the system-wide fault tolerance and robustness desired, is to provide good control for the plant operating in normal or nearly normal conditions and also to provide control that accommodates various stages of degradation of equipment or equipment interconnection. This can be done by embedding a goal structure within the control system. Thus, as operating conditions change, the control system should be capable of detecting such changes, overlaying the new goals that the plant should be striving towards, and adopting new strategies for meeting those goals.

Initial work has begun on a method for implementing condition-dependent control strategies. The method is based on a hierarchically structured control system. For discussion purposes, a hierarchical structure is composed of levels or layers of control modules. A module or node of the hierarchy can link with both superordinate and subordinate modules. These links are communication pathways or pipelines. The data flow from superordinate to subordinate is refered to as *efferent* flow; the flow from subordinate to superordinate is *afferent* flow. A more involved description of hierarchical structure and control will be presented later in the report.

The method for condition-controlled strategies involves dividing the state space for the controlled system into contiguous regions of control. The three regions are the *homeostatic*, *degraded*, and *uncontrollable*. Associated with each region are appropriate operating goals and strategies for controlling to meet those goals. Into this space of regions, a state vector is projected. The elements that the vector comprises are a mixture of continuous variables and discontinuous parameters. A discontinuous parameter can assume only discrete values, and in many cases may be purely off-on in character, perhaps indicating that a pump or stop valve is on or open. The result is a point in space that moves with the changing state of the plant. Figure 2.1 illustrates the control regions for a simple system of two state variables.

ORNL-DWG 84-9549

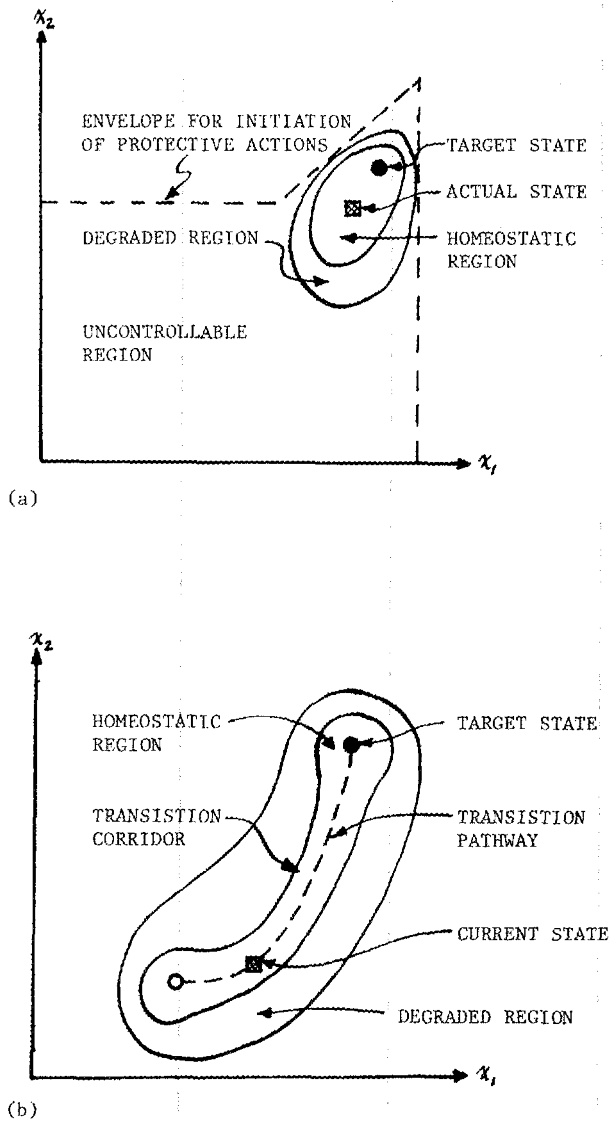


Fig. 2.1. Control regions in state space: *(a)* steady-state conditions, *(b)* transient conditions.

These multidimensional regions are not fixed in space but rather are related to the target state (for steady-state operation) or to both the target state and the pathway of transition (for a system moving from initial to target state). Thus, not only is the vector moving as it follows the dynamics of the plant, but also the regions are being readjusted as margins to specific limits change and as the availability and operabilitiy of plant equipment change. The boundaries separating the contiguous regions are flexible; their relative positions depend on known conditions of the plant. Real-time calculations are required to continuously determine the shape and coverage of the regions. These calculations must have their basis in an a priori quantitative knowledge of the behavior of plant components, their failure modes, and the extent and range of maneuverability that the control system has over them. Creation of the regions also must be based on identification of the immediately available capabilities of the control and protection systems.

The creation of one complete and overall state space for the entire plant would require concurrent analysis of thousands of data entries from the monitoring and data-handling system. Such an analysis would require a large amount of computing power. A better approach is to decompose the system: resolve the state space into a set of spaces, each of which is associated with a single plant subsystem. To effect coordination of the plant at higher levels within the control hierarchy, spaces would also be created which represent grouped systems. The complexity of the overall computation is then reduced by the power of separation and simplification. Some autonomy of control is given to the lower-level controllers as they select the best strategy of control based on the commands received from the superordinate and the region of control that their state vector occupies. In effect, the state vectors of the lower-level systems become the elements of the upper-level vectors. Decisions made at the lower levels would be communicated upward to allow supervisory coordination of the entire plant.

The movement of a system's phase-space point into the next bordering region is an indication that significant changes have occurred or are beginning to occur in the plant. This denotes the need for a complete change in the general strategy that was being applied in the control of the affected system, and hence a change in the specific rules and procedures that were being used. This change of strategy may require not only proportional changes in setpoints and limits but also abrupt rerouting of process flows and other reconfigurations of systems and components.

The three regions are discussed in greater detail in the paragraphs that follow. Many of the concepts and terms are adapted from studies of electric power system stability (Zaborsky) because of the similarities that exist between control of large-scale power distribution and large-scale power generation plants.

2.3.1 Homeostatic Region

The goal of control within the homeostatic region is to effect production of the desired outputs of the controlled plant system. In the absence of major equipment failure, behavior in this region tends to converge on the target state, which is the desired operating state. The target state, nominally a point, is a smaller statistically defined region within the homeostatic region.

Strategies for optimal control and adaptive control are employed when the system is situated in the homeostatic control region. As appropriate for the mode of control, various criteria may be chosen to meet minimum error, time, energy, or mechanical stress in controlling the system.

Power plants often change states because of maintenance schedules, load demand changes, and refueling schedules. To accomplish the transition from one known state to another desired state, a preferred pathway to the target is established and a corridor that surrounds the pathway for the transition is created. The determination of the target pathway and the rates of change along the pathway should be based on optimization, because alternative pathways may offer a range of energy consumptions, power requirements, mechanical or thermal component stress, time to completion, or safety margins. Two possible approaches to forming a pathway or trajectory are to (1) identify all of the *bad* places in state space and maneuver around them or (2) identify a multidimensional channel and guide the plant through it. Real-time identification of the *best* transitions should be part of the control system's capability. Similar to the homeostatic region that is formed around the target state in steady-state operation, a corridor is formed that envelops the transition pathway.

Operation anywhere within the homeostatic region is considered *normal,* although the actual system state may not be precisely within the statistical boundary of the target region. The latter condition could be described as off-target normal, and the control system is assumed to be driving the system to the target point.

Structural defects, which are minor faults in equipment or their interconnection, are tolerated within the homeostatic region so long as the capability of the control system to maintain the target state has not been voided. Likewise, *security defects,* which are losses of redundancy, are tolerated in this region. Activities which are involved with defect restoration could occur simultaneously with normal operation.

The determination of the boundaries between the three regions, not necessarily being a rigorous and precise quantitative calculation, may require some a priori engineering judgment in assessing the control system's capability under various possible operating conditions. Indeed, the prediction of plant response to control input becomes a matter of expert opinion.

Should structural or security anomalies exceed tolerable limits, the homeostatic region must be redefined. For directly observable and consequential failures, the region can be shrunk to the target state or removed entirely, thus leaving the system in a declared degraded state. Both major equipment damage and malfunction as well as external disturbances of sufficient magnitude can drive the system out of the homeostatic region.

2.3.2 Degraded Region

The goal of the control system with its phase-space point in the degraded region is to allow for efficient restoration of the faulted systems so that return to the desired target state may proceed in minimum time. More specifically, the control objectives of the degraded region are to (1) maintain continuous and uninterrupted (although perhaps reduced) delivery of principal products of the system if possible; (2) prevent or minimize equipment damage; and (3) avert intervention by the plant safety and protection systems by maneuvering the system away from the envelope inscribed by the safety systems. For all control system responses, downtime can be reduced by generating proportionate control reactions to evolving situations rather than overreaction because of a lack of alternative reactions on the part of the control system. Three types of crises are possible within the degraded region. Each requires a different strategy for control.

1. *Stability Crisis.* This crisis describes a case in which the controlled system has become unstable (stability must be defined for the specific system). The strategy is to maneuver the system to an intermediate safe and stable state that is near the original target state and which will continue to deliver the principal product for which the system was designed. Thus the major systems to which the degraded system is providing a product can remain on-line, although at a reduced level. A collection of safe states must be identifiable based on constraining conditions such as known equipment or equipment interconnection failures. Preferred pathways from the current state to the alternative safe states must be known. The precalculation and storage of the pathway, as in a sequence of actions, may not have to be made if the rules for determining the correct next state and the procedure for getting there can be embedded in the control system. This is the case with the Procedure Prompting System (PPS) under development at Hanford Engineering Development Laboratory (Colley 1983; Colley 1982; Colley et al., 1982; Smith 1984).

A component-level example: A valve controller malfunction has introduced flow oscillations in a coolant stream, thus inducing temperature fluctuations elsewhere in the process subsystem. By reducing the heat generated (by lowering the power level) or bypassing the malfunctioning control valve through a smaller channel of flow, the subsystem would have a reduced output but maintain a stable state.

2. *Viability Crisis.* This crisis describes a case in which no stable state can be found in which the principal product can be delivered to downstream systems. Thus, the strategy is to suspend, at least temporarily, the delivery of product until repair can be effected.

Component-level example: The control valve of the previous example represents the only path through which essential coolant can flow. The induced temperature fluctuations cause substantial error in the subsystem's product output, regardless of the power level selected. The only alternative is to shut down the process to repair the control valve.

3. *Integrity Crisis.* This crisis describes the case of a system with imminent equipment damage, therefore, the strategy is to invoke immediate protection of equipment and associated subsystems. Delivery of product would most likely be suspended pending restoration.

Component-level example: The coolant flow control valve of the above examples has frozen shut, preventing any coolant flow to the subsystem's equipment. No other means of cooling is available. Without cooling, expensive equipment would be damaged within seconds. Thus immediate shutdown is required to prevent damage.

The homeostatic regions and transition corridors are normally enveloped by the degraded region. This region may be entered either by a change in system state (i.e., system state traversing the boundary separating the regions) or by redefinition of the homeostatic region (i.e., a receding of the boundary, thus leaving the system state in the degraded region). In the former case, a component failure itself may be incipient or as yet unobserved, although its effect on the process would be to drive the state vector out of the homeostatic region. In the latter case, the failure may be observed before the system state has had an opportunity to change.

2.3.3 Uncontrollable Region

A goal of the control system upon entering the uncontrollable region is to alert the plant operators that a problem in controllability exists. Prior to entering this region, the control system should have been attempting to shut down or subdue the process. Entry into this region is an indication that the procedures or rules used while in the degraded region were ineffective. Further, the control system may have exhausted its ability or resources to control or restrain the situation. A subsystem whose phase-space point is in the uncontrollable region may exhibit one of several behaviors: (1) the subsystem is on a trajectory to an undesirable, possibly destructive state and is unresponsive to commands from the control system; (2) the subsystem is static and in an undesirable state, also unresponsive to commands from the control system; or (3) the subsystem is chaotic, in which very small control commands produce large swings in the system response, and the cause and effect relationship may appear illogical (i.e., true mathematical chaotic behavior) (Feigenbaum 1984). Several situations may have caused the state of the system to have moved to the uncontrollable region from the degraded region. The designer's understanding of the behavior of the system was incomplete or in error, or failures occurred beyond the scope of the system's design and outside of its fault-tolerant capability.

Surrounding the uncontrollable region are the initiators for the plant safety and protection systems. Failure of the control system to regain control of the process should eventually invoke a safety-system response. However, the failures or damage that impeded control action, hence led the system to the uncontrollable region, also could possibly prevent effective safety action.

2.4 A PHILOSOPHY FOR GUIDING CONTROL SYSTEM DESIGN

A general philosophy for guiding the design of an intelligent automated system can be described based on the perspective developed in the previous sections. This philosophy is the beginning of a statement of overall design goals for the control of large-scale nuclear power systems. Sections 3 and 4 of this report represent an attempt to transform this somewhat abstract set of goals into a structure that can support a sophisticated system.

2.4.1 Role Allocation

One of the more important tradeoffs that can affect the short-term and long-term performance of a large-scale nuclear power system is the allocation of control functions and tasks among the computer and human elements. After an allocation* is made, the necessary support for both elements must be designed. In general, it is our goal to maximize the proportion of the mission accomplished by the machine, because it is the purpose of machines to unburden man and to increase his productivity. Ultimately, man must retain the responsibility for the behavior of the plant and, for this reason, must retain control at some level.

A management role is assumed for the operators of the nuclear power plant. In this role, the crew is not normally involved with the day-to-day operation of the plant, except in the request for power-level change (which could come from the regional dispatch center), reactor refueling, and plant maintenance and repair. Special tests and maintenance procedures need to be performed when starting from a refueling outage. These are perhaps operations that also should involve direct human participation. This allows for complete system checkout, and the operators and others are given a chance to refamiliarize themselves with the plant, its equipment, and its unique behavior. The capability of technology has approached the point where a high level of operational automation is economically feasible, in contrast with the automation of maintenance and equipment repair both of which will of necessity draw on the fields of robotics and image recognition. Should robotics technology advance sufficiently, one can envision a power plant of the future with a network of specially designed corridors that would allow robotic repair systems to access all the components of the plant. The technology for the latter type of automation is not presently ready to address the complexity of a

*An allocation need not be permanently fixed but can be designed to be somewhat flexible. Dynamic allocation allows situation-dependent allocation of functions between man and machine (Chu and Rouse 1979). Also allocations may shift over the life of the plant as old equipment is replaced and upgraded.

nuclear power plant but is close at hand. Some experts argue that robotic systems could be implemented in the next generation plant (10 or 20 years). Sections 3 and 4 approach the design of the control system from the perspective of supporting the operator as a manager of the plant. The usefulness of the approach, however, is not diminished if it is used in a less than full automation setting.

2.4.2 General Goals

The general goals of automating the LSPB can be viewed as time-oriented layers. They are listed below beginning with the longest time-horizon goal and ending with the shortest:

1. extend reactor core life as long as possible to decrease downtime and enhance fuel conversion,
2. minimize wear on plant components to increase their service life,
3. protect equipment, facilities, and instrumentation from immediate damage,
4. provide turbine-generator output power demanded,
5. keep plant parameters within design specification and away from safety trips,
6. minimize the control actions required to accomplish the control objectives, and
7. maintain the stability of the process.

These goals become the operational objectives of the various control modules in the hierarchy of the plant control system. To meet these goals, an intelligent control system that goes beyond the traditional feedback controlled regulation is required. One can view the merging of intelligence with a control system as moving the operator's knowledge and skill into the realm of the system. This should lead to improved diagnostic and decision-making capability and, in addition, facilitate operator understanding of some of the internal processes of the control system.

2.4.3 Intelligent Safety Systems

The operator, in current designs, is obliged to disable portions of the safety system to prevent it from tripping the reactor unnecessarily as he maneuvers the plant from state to state. As the control system is extended further in the dimensions of automation and executes more of the operator's functions and tasks, a predicament arises: the control system must interface with the safety system to disable it at various stages in the progression of the plant from one state to another. This contradicts the rule of separation of control and safety. The alternative is to design intelligent safety systems that do not require pathological* coupling with either the control system or the plant operating crew. Unfortunately, work in this area has not progressed as far as analogous work in intelligent control systems.

2.4.4 Software Tools

The engineering of a computer-based control system contains an extra step in the design process over the traditional modular-based (analog) system. A software team, usually separate from the control design team, is contracted to implement the control system in a computer environment. Software engineering, this extra step, requires a functional specification for the control system in order to produce a good product. The passing of the system design between these groups of engineers is often the source of error and inefficiency. One means of improving their communication is to use a common set of tools and definitions to create the documentation for transfer. Structured analysis techniques are becomming accepted by many control engineering organizations (Lakely 1982; Morrow and Robinson 1983; Ward and Campbell 1983; and Weaver 1983). A structured analysis tool set is proposed for use by control engineers. A brief description of the terminology and graphic symbols is given in the next section and Appendix A. In the next section, these tools are used to describe automation of startup for the LSPB.

2.4.5 Phases of Design

Design of an automated system that can accomplish all of the objectives and functions that have been discussed thus far represents a complex and time-consuming program. Like all large tasks, however, it can be partitioned into more manageable subtasks by progressively developing the system design. The progression can be thought of as a series of logical phases in the unfolding of the design; each phase adds another layer of intelligence to the control system. They somewhat follow the dimensions of automation. The phases are described as logical, not necessarily chronological

*Pathological coupling, a computer science term, refers to intermodular connections that reach within a module to an entity inside it, thus bypassing the normal afferent and efferent data flow in the hierarchy. (Yourdon and Constantine 1979).

stages. Although in reality, design would progress through the phases as a series.

In Phase 1, the basic regulatory control and automatic actions required of the control system are developed. This phase of design does not have to account for equipment failure. In a sense, the plant components are assumed perfect, not requiring maintenance or repair. The design thus concentrates on maintaining stability of the processes and on automatic execution of actions to maneuver the plant through its various states to the target state with its associated power level. Also, tolerance to noise and minor process disturbances are considered. A structure emerges in this phase that will be expanded and added to in the subsequent phases.

In Phase 2, the basic control structure of Phase 1 is amended and expanded by including the tasks of subsystem and equipment testing and validation. Analysis of operating procedures reveals that a sizeable portion of the startup and shutdown activities of the operators are related to verification of equipment availability, condition, and mode.

In Phase 3, the system emerging from Phase 2 is amended and expanded by including decision-making capability and required actions for coping with contingencies. Some contingency actions, closely associated with the basic control of certain pieces of equipment, may have been included in Phase 1 or 2 design. Phase 3, however, is mostly devoted to improving plant response in the degraded state so as to return the plant to a productive state and prevent the plant from lapsing, in the worst case, into the uncontrollable region. Design emerging from Phase 3 employs features that can recognize a problem and select or devise a procedure or plan for the system to follow to restore normal operation to the plant.

In Phase 4, maintenance and calibration functions are added to the structure of the Phase 3 control system. Limited robotic devices may allow automation of many maintenance and calibration procedures; however, because of the particular need of human dexterity to get to and manipulate equipment, a well-developed Phase 4 system may not come into being until far in the future.

3. STATE TRANSITION AND DATA TRANSFORMATION TECHNIQUES FOR CONTROL OF DISCONTINUOUS SYSTEMS

3.1 INTRODUCTION

This section of the report illustrates a technique for structured analysis that can be applied to all phases of control system design as described previously. However, the example given here is limited to Phase 1 design (basic automatic control action). No maintenance, testing, or contingency capability is discussed in this section.

The large-scale prototype breeder (LSPB) reactor is analysed, and an automatic control structure is developed. The assumption is made that automatic control would, as the name implies, involve human operators only to the extent of specifing the mode and power level desired. Interface for manual operation is possible with this design, although it is not pursued in this report.

To create the control structure, the LSPB system is divided into subsystems and grouped according to prime, support, or utility relationship to the plant. Then the operating procedures are analysed along with procedural data from subject matter experts (SME). To simplify the task greatly, only the startup transition from plant at cold shutdown to plant at minimum power is analysed. (This startup example is used throughout Sect. 3.) This results in incomplete state dynamic models and data transformation models for the plant because some support systems are assumed to be already operational as initial conditions of the cold shutdown state and other systems are not called into service during this transition. However, some of the shutdown transitions and returns to the ground or idle state are shown for closure even though they are not activated during startup. Though incomplete, the example probes the details of the plant and its operation.

Except for an information-only data line to the planning portion of the control system, no links to the safety system are considered. The safety system is assumed to be completely independent of the control system and to internally possess the intelligence to recognize plant conditions and know the proper actions to take.

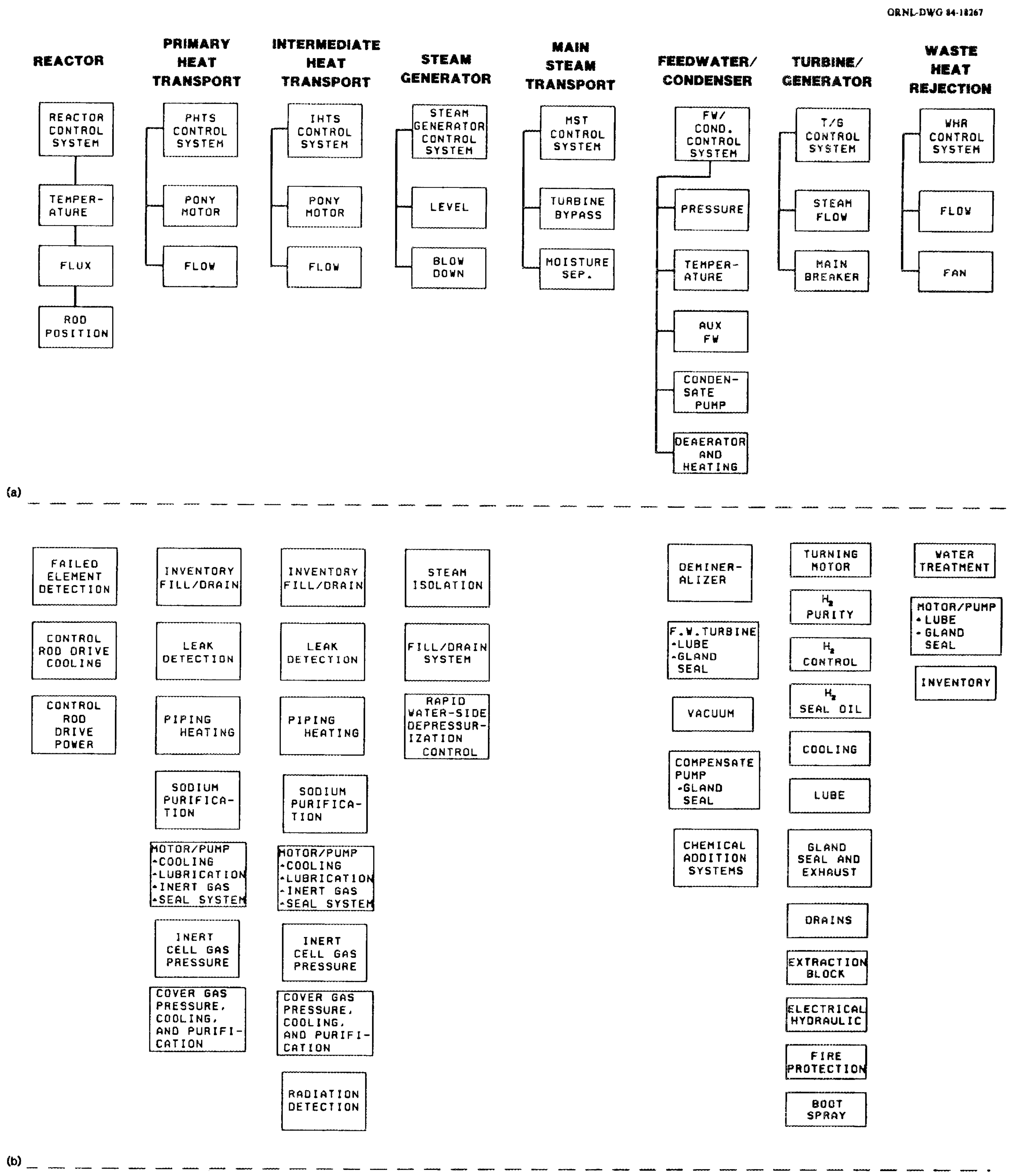
The availability of process data is taken for granted. A real-time data-base management system is assumed to supply all the needed information about plant components and process variables to any module regardless of its position in the hierarchy or location in the plant. The on-line data base is represented as a data store in the model.

3.2 SUMMARY DESCRIPTION OF PLANT SYSTEMS

A list of the plant control modules needed to serve the plant is shown in Fig. 3.1. The list is grouped by the prime plant systems but shows support systems and utilities. These modules are extracted from system design descriptions (SDD) of both LSPB and Clinch River Breeder Reactor Project (CRBRP) and from other system documents. This list is further expanded in Table 3.1 with the prime and support systems shown along with their possible modes of operation and data flows. The data flows are grouped by input and output relation to the subsystem. The input and output flows are further divided: efferent flows are commands or data to subordinates; afferent flows are status or data to superordinates; and transferent flows are inhibits or permits laterally communicated at the same level in the hierarchy. Utility systems are not further elaborated.

3.3 DESCRIPTION OF DATA FLOW AND STATE TRANSITION METHODS

The basic method used to develop the automatic control system for the LSPB is an extention of the structured analysis and design techniques of Yourdon (1984). The approach is first to build a logical model of the control system, then from it build a physical model of the computer processors, interconnection networks, and code environment. The



PLANT ELECTRICAL	COOLING SYSTEMS
FIRE PROTECTION	HYDRAULIC SYSTEMS
SODIUM FIRE PROTECTION	HVAC
SERVICE WATER	AUXILIARY STEAM
(c) GAS SYSTEMS	

Fig. 3.1. Local control modules for LSPB: *(a)* prime plant systems, *(b)* plant support systems, and *(c)* plant utility systems.

Table 3.1. Prime, support, and utility subsystems for LSPB which require local control

System	Mode*	Input			Output		
		Afferent	Efferent	Transferent	Afferent	Efferent	Transferent
Reactor (Prime)	Startup; flux; temp.						
Flux control		Flux	Flux (sp)			Run (in/out)	
Temp. control		Temp.	Temp. (sp)			Flux (up/down)	
Rod control		Rod position	Rod position (sp); run (in/out)	Rod position limit; inhibits from power supply failure and other system failures	Rod status (dropped rod, stuck rod)	Motor voltage and direction	
Primary heat transport (Prime)	Pony; minimum flow; flow control						
Flow control		Flow	Flow (sp)	Pump/motor monitor (shutdown); oil lift inhibit	Status of pump/motor	Speed of motor	Enable pony on failure; disable pony on start
Pony motor control				Disable/ enable pony motor			
Intermediate heat transport (Prime)	Pony; minimum flow; flow control						
Flow control		Flow	Flow (sp)	Pump/motor monitor (shutdown); oil lift inhibit	Status of pump/motor	Speed of motor	Enable pony on failure; disable pony on start

Table 3.1 (continued)

System	Mode*	Input			Output		
		Afferent	Efferent	Transferent	Afferent	Efferent	Transferent
Pony motor control				Disable/ enable pony monitor			
Steam generator (Prime)							
Level/FW flow control	Normal start-up range	FW flow; steam pressure; steam flow; level	Steam header pressure; level; mode (start up/normal)	Close (from RWSDS)	Mode of FW valve system (startup/ normal)	Control FW valve; control FW startup valve	
Blow down control		Flow	On/off; flow (sp)	Close (from RWSDS)		Open stop valve; control throttle valve	
Main steam transport (Prime)							
Turbine by-pass (main steam dump	Normal; hot standby	Steam temp; steam pressure	Mode switch; pressure (sp); temperature (sp) (for TB and Atmos)	Inhibited by circ. water flow; condenser vacuum		Bypass valves (12 valves); atmospheric valve	
Moisture /separator reheaters	Warmup; operational	Temperature; pressure of HP turbine exhaust	Mode; X (sp) =.9975			Control amount of main steam to bring LP steam to saturation; valves	
Feedwater condensor (Prime)	Shutdown; startup; operate						
Pressure control	Startup; run	Pump speed; Δp FW valve; FW header pressure	Δp (sp); FW press (sp)	Pump trip from low lube oil press. or deaeration level low		Pump torque by valve position	

Table 3.1 (continued)

System	Mode*	Input: Afferent	Input: Efferent	Input: Transferent	Output: Afferent	Output: Efferent	Output: Transferent
Temperature control	Power range; shutdown	Temperature of FW (deaerator)	FW temp. (sp)			Steam value	
Feedwater heating and deaerator	Startup; operate	Level of water in heat exch.	Level (sp); high level (sp)			Modulating heater drain valves; extractor steam drain valves	
		Level of water in deaerator; cond. flow; feedflow	Level (sp)			FW deaerator makeup and recirc. valves to storage tank	
Auxiliary feedwater		Pump speed; level in SG	Turbine (on/off); speed (sp); motor (on/off)			Aux. valve position; steam valve to turbine; motor breakers	
Condensate pump		Condensate header pressure low; failure of another condensate pump	Off/on	Inhibits from lube oil; upstream valve lineup; seal motor flow		Motor breakers	
Turbine/generator (prime)	Speed control; load control; warm up						
Stream turbine control		Speed; shell temp.; elec. power from gen.	Load, speed; shell temp.	Inhibit from auto. stop oil pressure		Warmup valve (located in stop valve), 4 turbine control valves	
Main breaker control		Synchronization (off/on)				Main gear breaker (open/close)	

Table 3.1 (continued)

System	Mode*	Input: Afferent	Input: Efferent	Input: Transferent	Output: Afferent	Output: Efferent	Output: Transferent
Heat rejection (prime)							
Cooling tower flow control			On/off	Inhibit from gland seal water; inhibit from pit level		Motor breaker	Inhibits generated in turbine bypass system
Cooling water mode control	River sink; river/tower; tower sink		Circulating loop configuration			Sluice gate; water valves	
Cooling tower fan control	Run; off; de-ice	Outside air temp.; water temp.	On/off; De-ice			Motor breaker; reversing relay	
Reactor (Support)							
Failed element		Neutrons			Degree of fission prod. release	Controls	Enable precision analysis system
CRDM cooling			Enable/disable cooling system		Status of system	Close breakers	
CRDM power			Enable/disable		Status	Close breakers	
RG cover gas pressure, vent control, purification and cooling		Pressure; purity	Pressure (sp), purity (sp)		Status of valves and pump cooling	Run sample; valve position; pumps (on/off)	
Inert Cell gas pressure			On/off			Gas valves	
Fill/drain (inventory control)		Vessel level; fill flow; drain flow; sodium pump level	Vessel level (sp)			Sodium makeup pumps; valves	Inhibit purification system
Leak detection		Hydrogen; O_2	On/off		Degree of leakage		

Table 3.1 (continued)

System	Mode*	Input			Output		
		Afferent	Efferent	Transferent	Afferent	Efferent	Transferent
Piping heating		Temperature	Temperature (sp), zone control			Heaters	
Purification		Flow	Flow (sp)	Inhibit from fill/drain		Valves	
Primary Heat Transport (Support)							
Motor Lubrication		Pressure	On/off			Oil pump motor (on/off)	Inhibits pump and values; turns on backup oil pump
Compartment inert gas			On/off			Gas valves	
Oil lift		Lift pressure	On/off			Oil lift pump	Inhibits pump controller
Static inverter			On/off			Breakers	
Intermediate Heat Transport (Support)							
RG cover gas pressure, vent control, purification, and cooling		Pressure; purity; IHTS-PHTS Δ pressure	Pressure; purity; IHTS-PHTS Δ pressure		Status of valves and pumps	Run sample; valve position; pumps (on/off)	
Inert cell gas pressure			On/off			Gas valves	
Fill/drain inventory control		Expansion tank level; fill flow; drain flow; sodium pump level	Expansion tank level (sp)			Sodium make up pumps; valves	Inhibit purification systems
Leak detection		H_2; O_2			Degree of leakage		
Piping heating		Temperature	Temp (sp) zone control			Heaters	

Table 3.1 (continued)

System	Mode*	Input			Output		
		Afferent	Efferent	Transferent	Afferent	Efferent	Transferent
Intermediate Heat Transport (Support)							
Purification		Flow	Flow (sp)	Inhibit from fill/drain		Valves	
Motor Lubrication		Pressure	On/off			Oil pump motor	Inhibits pumps and valves; turns on backup oil pump
Compartment inert gas			On/off			Gas valves	
Oil lift		Lift pressure	On/off			Oil lift pump	Inhibits pump controller
Static inverter			On/off			Breakers	
Steam Generator (Support)							
Steam isolation		On/off	Close because of RWSDS			Valve (closing/opening)	
Rapid water-side depressurization system (RWSDS)		Sodium water reaction products	Enable (disablers manual)			Dump valve	Close FW; close steam isolation
Main Steam Transport (Support)							
Feedwater/Condenser (Support)							
Demineralizer control	Run; regenerate	pH; conductivity chemical	On/off	Inhibited by condensate pump		Valve group	

Table 3.1 (continued)

System	Mode*	Input			Output		
		Afferent	Efferent	Transferent	Afferent	Efferent	Transferent
FW Turbine/ lubrication			On/off			Turn on oil pump motor	Inhibits startup of FW turbine
Gland seal			On/off			Valve on conden- sate header	Inhibits startup of FW turbine
Vacuum control system		Condensor vacuum	On/off			Energize motor to vacuum pump (if vacuum low)	
Condensate pump gland seal			On/off			Valve	
Chemical addition system (hydrazine)			On/off			Start pumps on hydrazine system	
Turbine/ Generator (support)							
Turning motor rotation control		Turbine speed; turbine rotor temp.	On/off			Motor controller	
Hydrogen purity		H_2 gas measurement	Check		H_2 purity		
Hydrogen control		H_2 pressure	Makeup control (on/off)			Valve	
Hydrogen seal oil		Discharge pressure; tank level	On/off			2 seal oil pumps; seal oil vacuum pump	
Cooling (stator winding)		Temperature; pressure	On/off temp. (sp)			2 water flow pumps; flow valve	

Table 3-1 (continued)

System	Mode*	Input			Output		
		Afferent	Efferent	Transferent	Afferent	Efferent	Transferent
Lubrication		Discharge pressure; bearing pressure; oil temperature	On/off, lube oil temp. (sp)			Main oil pump; ac motor-driver pump; dc pump	Trips steam control valves
Gland seal and exhaust		Gland supply pressure; exhaust vacuum	Main stream on/off aux steam valve (on/off); exhaust blower (on/off) desuperheater spray (on/off)	Availability of steam		Main steam valve; aux stream valve; 2 exhaust blower breakers	
High-pressure and low-pressure drain			Control of 10 valves (on/off)			Drain valves to condense	
Extration steam block valves		Auto stop oil pressure	On/off (with turbine trip)			Block valves	Trips steam control valves
Electrical/ hydraulic		Pressure	On/off; pressure (sp)			Pump; valves	
Fire protection		Presence of fire	On/off			CO_2 valves	
Turbine boot spray		Exhaust trunk temperature	Open/close valve; temperature (sp)			Block valve; spray valve	
Heat Rejection (Support)							
Water treatment control		Sample water chlorine and acid	On/off			Modulates chemical addition valves	
Motor/pump lubrication and gland seal			On/off			Water valve to pump seal	

Table 3.1 (continued)

System	Mode*	Input			Output		
		Afferent	Efferent	Transferent	Afferent	Efferent	Transferent
Inventory (closed mode only)		Level in cooling tower basin	On/off; level (sp)	Inhibited by cooling mode		Open/close makeup valve to basin	
Plant electrical							
Fire protection							
Na fire protection							
Service water							
Normal chilled							
Emergency chilled							
Water source control							
Treated water							
Gas system							
Argon							
Helium				**(Utility systems not analysed.)**			
Nitrogen							
Compressed air							
Instrument air							
Cooling systems							
Water							
Gas							
Hydraulic system							
HVAC (individual buildings)							
Radioactive waste							
Fuel handling							
Auxiliary steam system							

*Only one mode of those listed for any subsystem may be enabled at the same time.

latter model is created as a part of the software engineering step and will not be covered in this report. The logical model, which is generally implementation free, consists of two submodels: one modeling the interface of the control system to its environment and one modeling the internal behavior of the control system. The context diagram and the external event list are the tools used to create the environment model. Network graphics tools, which are used to create the behavioral model, model the flow and transformation of data through a system, the time- and condition-oriented behavior of discrete states that a system may exhibit, and the organization of stored data associated with the data transformations. The first two tools, data flow diagram (DFD) and state transition diagram (STD), are used in modeling the plant control system. Modeling of the stored data, by entity relationship diagramming (ERD), is not done for this system at this time. A brief description of the modeling tools is included in Appendix A.

One of the advantages of this method of modeling is the linking of the data, state, and store diagrams that it provides. This integration allows a DFD to control an STD and vice versa. The actions resulting from a state transition may generate an enable or disable command to a data transformation, thus turning on or off a data flow and the operations being performed on it. Likewise, the outflow of a data transformation can set the condition for a transition in a state transition diagram. This is shown in Fig. 3.2. The DFD and STD may be combined to form a package diagram. This minimizes external interfaces to the package and forms the means for grouping and organizing the control system structure.

After the plant resolves its basic prime and support subsystems, the organization for control follows from the logical modeling methods previously described. Plant startup, as would any plant-wide state change, follows a procedure that cuts across subsystem boundaries. This results in packages that contain a mixture of associated subsystems. The distinction between prime and support systems tends to disappear as they are packaged together allowing the procedures to enable whole systems by simple commands.

The packages of control software that are formed contain both DFDs and STDs. Actually, the LSPB system is primarily driven by state transitions because of the large number of subsystems that must be enabled and disabled in changing modes of a nuclear power plant. This results in disconnected sets of data transformations of which only a small number will be active at a given time.

3.4 SYSTEM ORGANIZATION FOR AUTOMATION OF LARGE-SCALE PROTOTYPE BREEDER REACTOR

The system boundary is defined for the LSPB automated control system by the context diagram shown in Fig. 3.3. This makes a simple starting point for system design. Physical equipment is shown as terminations (drawn as squares) to the data flow to and from the control system software (drawn as a bubble). Human subsystems, shown as a termination, are usually separated from other plant systems because of the problematic nature of the required interface. Thus the delineation is made between sensors and actuators, and the control software.

The system package in Fig. 3.3 can be magnified to show the internal data flows and transformations (transitions of state are as yet hidden in the bubbles). This method of magnifying the contents of a package will be used throughout this section. The contents of the system package is shown in Fig. 3.4. In the figure, seven numbered packages are shown that together constitute the top-level diagram for the basic automatic control phase of the system design. A hierarchical numbering scheme is carried by each child diagram to indicate its parent, similar to section headings in a report.

Although Fig. 3.4 shows the automated control system as a network, it may also be redrawn as the hierarchy shown in Fig. 3.5. Drawn in this way, the subordinate and superordinate relationships are more apparent. At the lowest level, data changes quickly, thus allowing only a short time for the decisions and objectives of the lower levels. The data required to support higher blocks change more slowly, and allows a longer time to make decisions. This section discusses systems 1, 2, 6, 4, and 5 as shown in Figs. 3.4 and 3.5. System 3, which is the continuous system supervisory controller and optimal coordinator, is the subject of Sect. 4. System 7 and the plant sensors and actuators are included for completeness but not discussed further.

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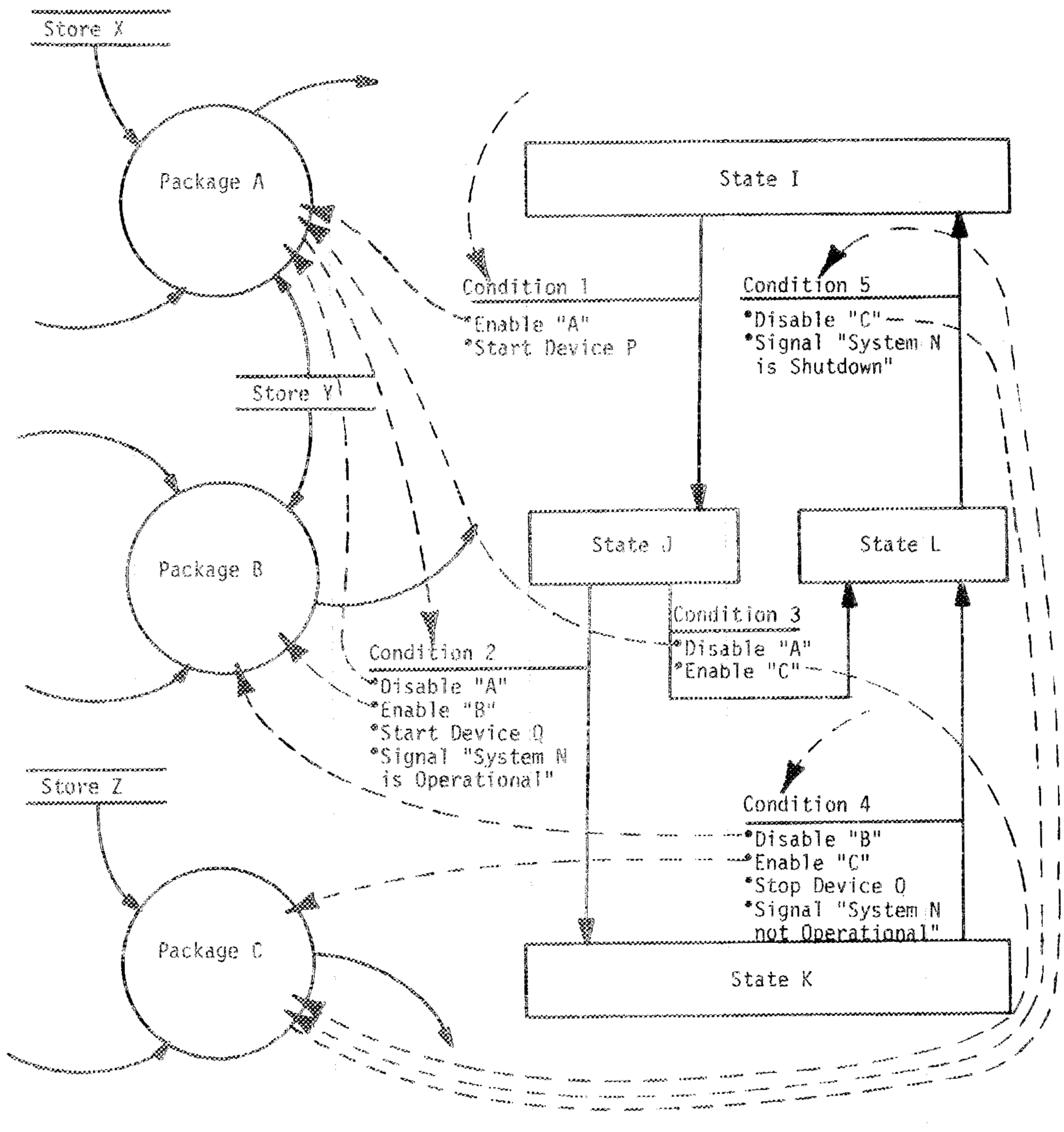

Fig. 3.2. Example showing DFD and STD interaction. The dashed lines, normally not shown, connect the action statements of the STD with the packages in the DFD and conditions requirements of the STD with internal calculations made in the packages.

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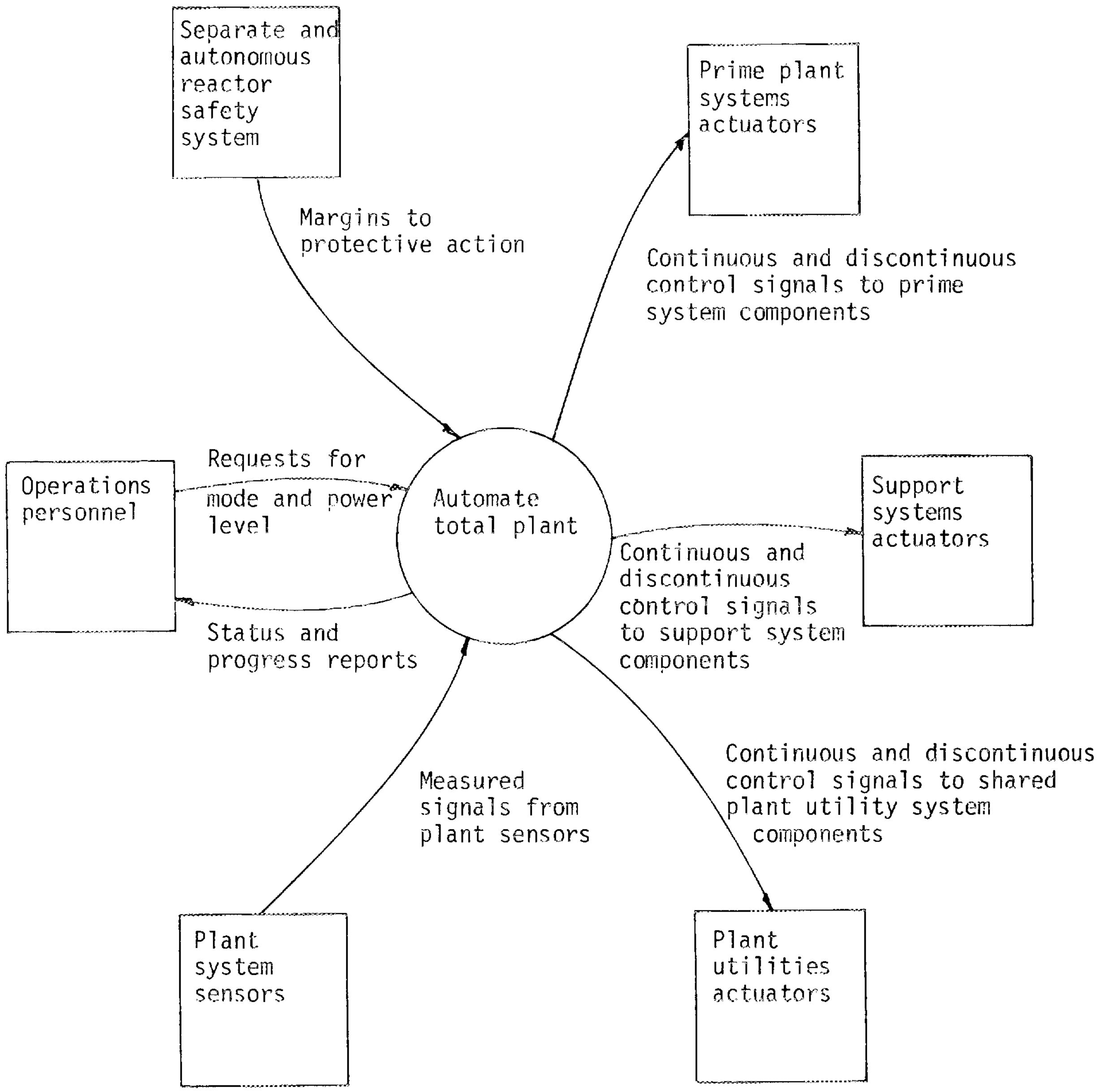

Fig. 3.3. Context diagram showing automated control systems and plant equipment boundary.

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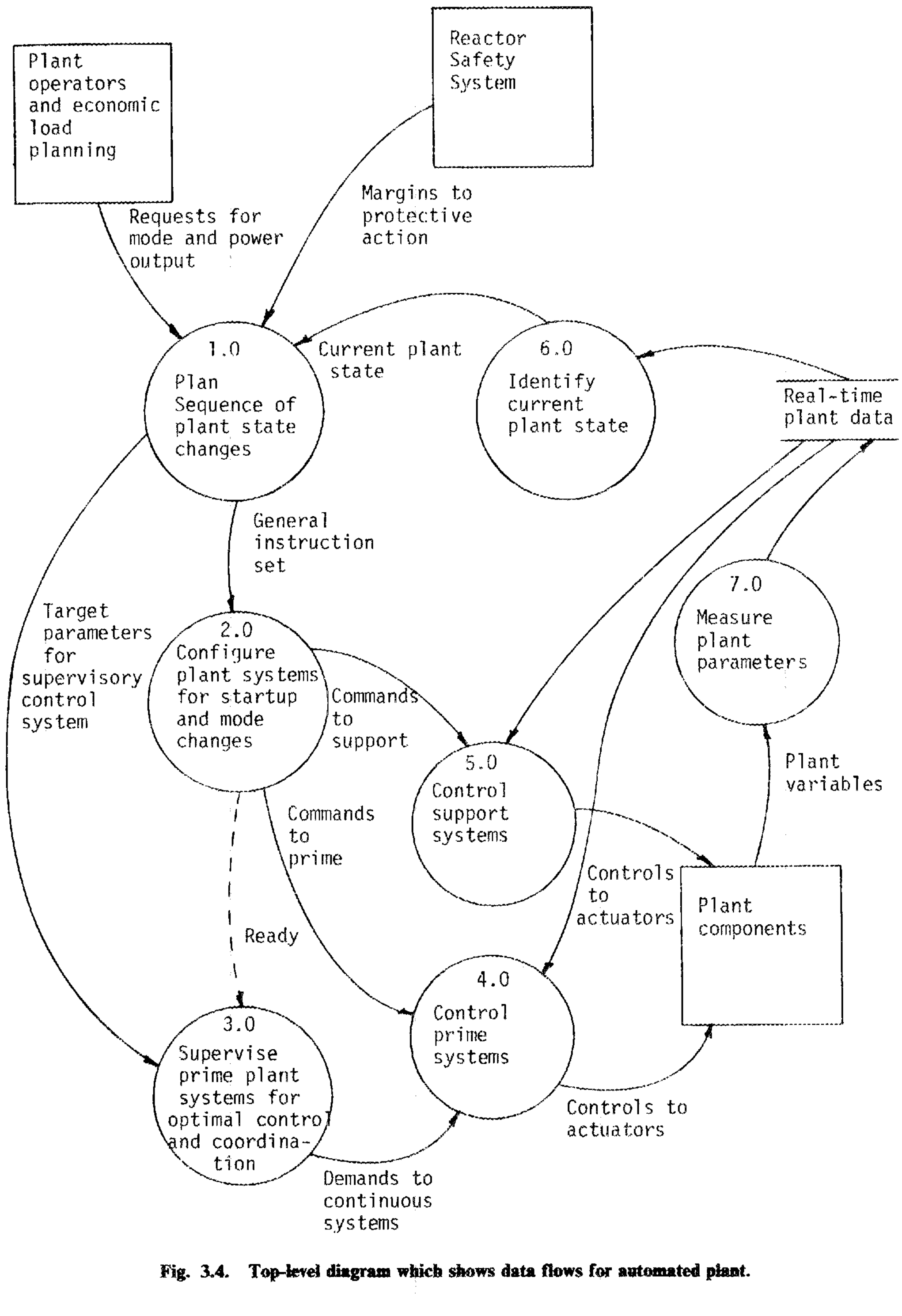

Fig. 3.4. Top-level diagram which shows data flows for automated plant.

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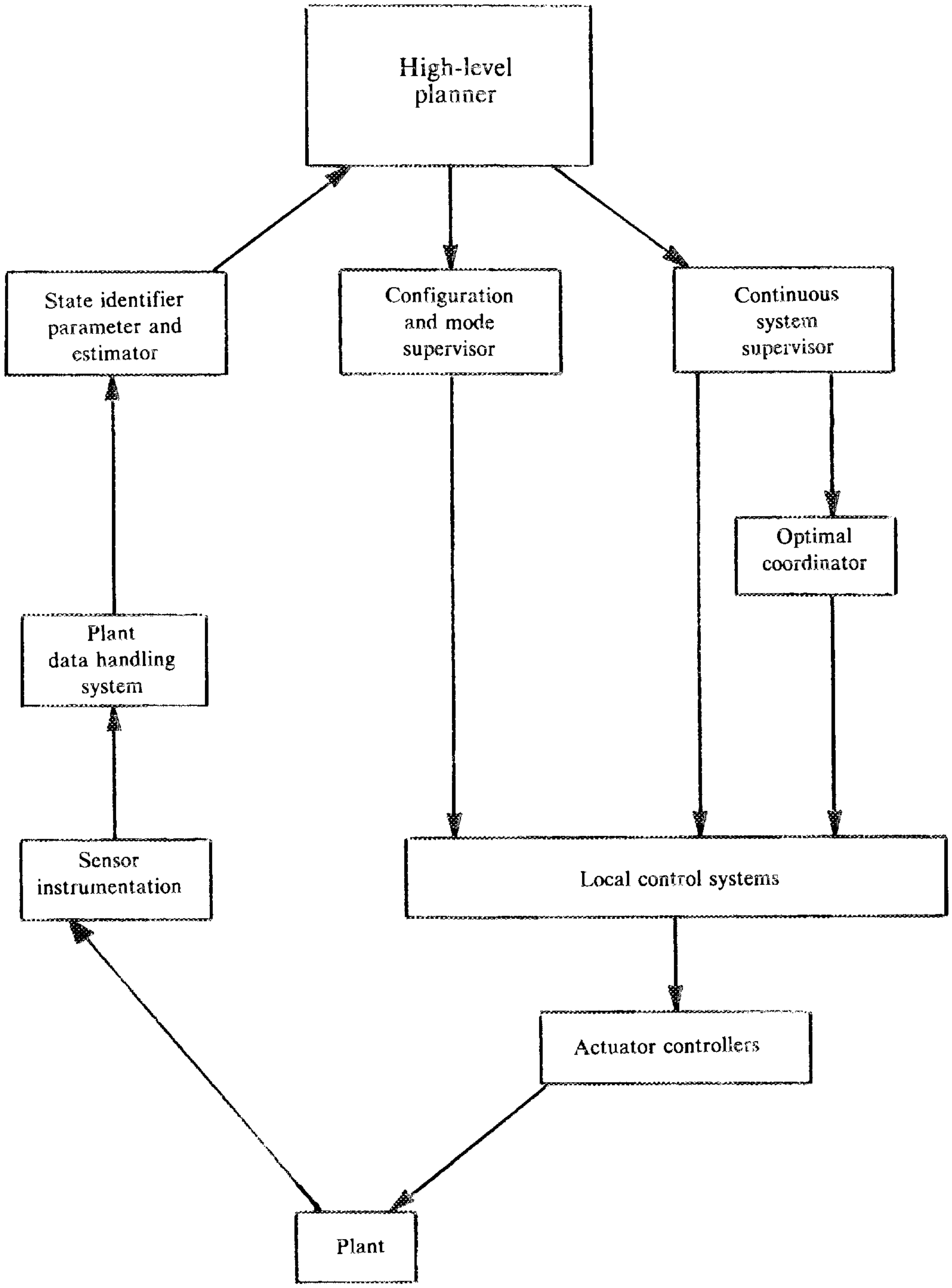

Fig. 3.5. Hierarchial representation of the automated control system for Phase 1, basic control design.

3.4.1 Package 1.0

The model for the planner (1.0) and situation assessment (6.0) packages is taken from an analysis of operator decision-making tasks (Rouse et al. 1984). The analysis concludes that decision making can be modeled by three related tasks: (1) situation assessment, (2) planning and commitment, and (3) execution and monitoring. The relationship among these three decision tasks is shown in Fig. 3.6.

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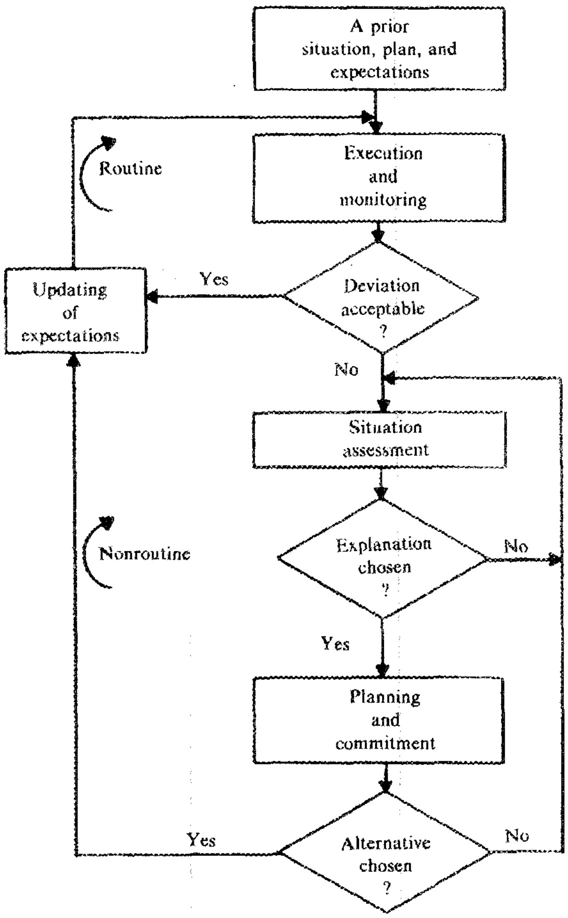

Fig. 3.6. Relationships among decision-making tasks.

Execution and monitoring proceeds directly from the a priori situation, plan, and expectations. However, because execution of a plan seldom results in exactly what was expected, updating is required even if deviations are never sufficient to prompt the situation assessment task. These general tasks can be further subdivided as shown in Fig. 3.7. Elaboration on these tasks can be found in Rouse et al. (1984).

Execution and monitoring are accomplished by the packages or subsystems of the automated control system under the command of subsystem 1 and subsystem 6, which are carrying out the planning and commitment, and situation assessment tasks, respectively. Subsystem 1, the planner that decides all changes in the overall state of the plant, is shown magnified in Fig. 3.8. Data are supplied by the operator, in the form of requests to package 1.1, generate alternative paths, and this package finds a set of possible states through which the plant must pass. The generation function of package 1.1 may consist of either a multivariate search of possible states from a data-base library or a rule-based state generation process based on some form of automated reasoning or expert system. The range of possible states and their sequences are then evaluated in package 1.2. Based on this evaluation, the final paths for the plant are selected, and system target parameters are selected from a data base of plant operational limitations and specifications in package 1.3.

Within the library of plant modes and states in the planning subsystem, an overall state transition description is present to guide the decision-making and sequence-selecting process. Figure 3.9 shows a state transition diagram, although incomplete, for the plant. Many of the transitions have been left out, especially those for shutdown. Associated with each state are a variety of possible equipment and subsystem operational statuses. Table 3.2 lists some of these statuses as initial conditions for the cold shutdown state. Many variations of the cold shutdown state, or for that matter any state, exist because of different possible initial conditions. To take the plant from its current state to the destination state, each set of these conditions will require a different sequence of states or actions of subordinate subsystems.

3.4.2 Package 2.0

The initial conditions, initial state, and destination state are passed to the configuration subsystem, package 2.0. (Details are shown in Fig. 3.10.) With this information, a string of connecting states and their transitions are selected either from a library of precalculated state transition diagrams or

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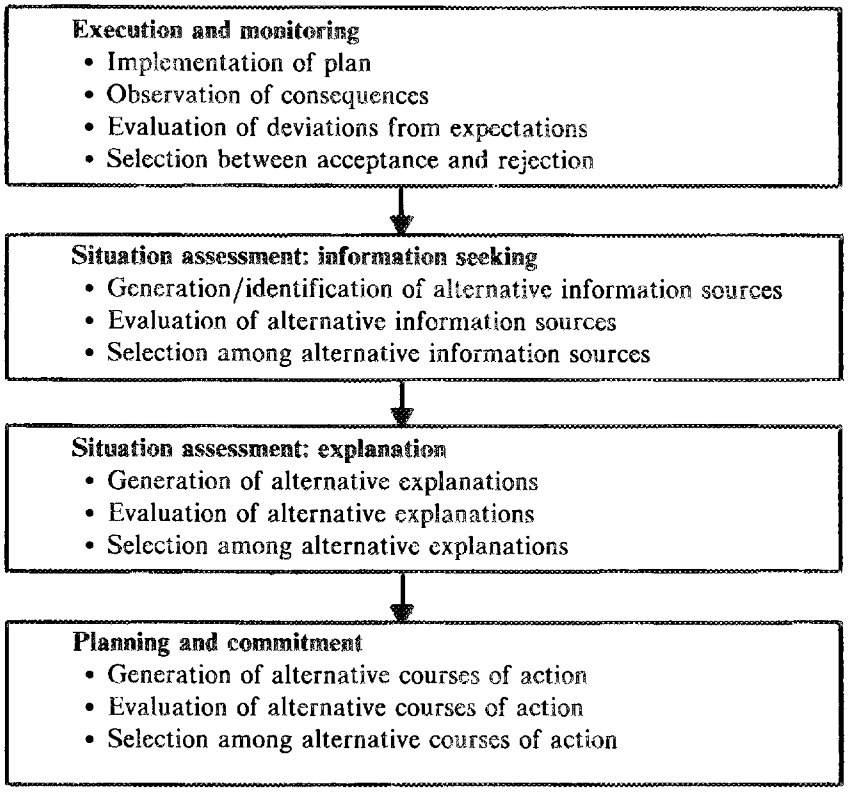

Fig. 3.7. Subtasks of general decision-making tasks.

by a rule-based processor in package 2.1. Package 2.2 then executes the actions specified by the state transition diagram to step the plant through the necessary sequence of states. The execute package monitors for conditions that allow the next transition to proceed and sends a signal to the continuous system supervisor enabling it to function at the appropriate time.

Based on the initial conditions given in Table 3.2 and the initial and final plant states of "waiting in cold shutdown" and "minimum power under supervisory control," the state transition sequence in Fig. 3.11 was selected. The sequence strings together four inner states: (1) nonnuclear systems starting, (2) reactor starting and additional nonnuclear systems starting, (3) reactor and plant heating up, and (4) power increasing from zero to minimum. To initiate a transition to the next state, five conditions must be satisfied and monitored: (1) plant startup signal from planner activated; (2) loops started, condensate cleanup completed, and turbine on turning gear; (3) reactor critical, vacuum established, and turbine auxiliaries operating; (4) hot shutdown temperatures reached, steamline prewarmed, turbine-generator prewarmed, and steam generator chemistry within specification limits; and (5) minimum power reached, feedwater supply on supervisory control. These conditions are available either from the data-handling system or from the lower-level controllers involved with producing the state. When the conditions are met, the actions shown beneath them in the chart are invoked. The next state occurs immediately because the actions are associated with the transitions. This is characteristic of a Mealy model in which the states are predominately a passive aspect of the control system. The state, in this model, represents a waiting period in which the control system continues performing those functions connected with that state until external conditions occur that allow a transition to a new state and thus a new set of functions.

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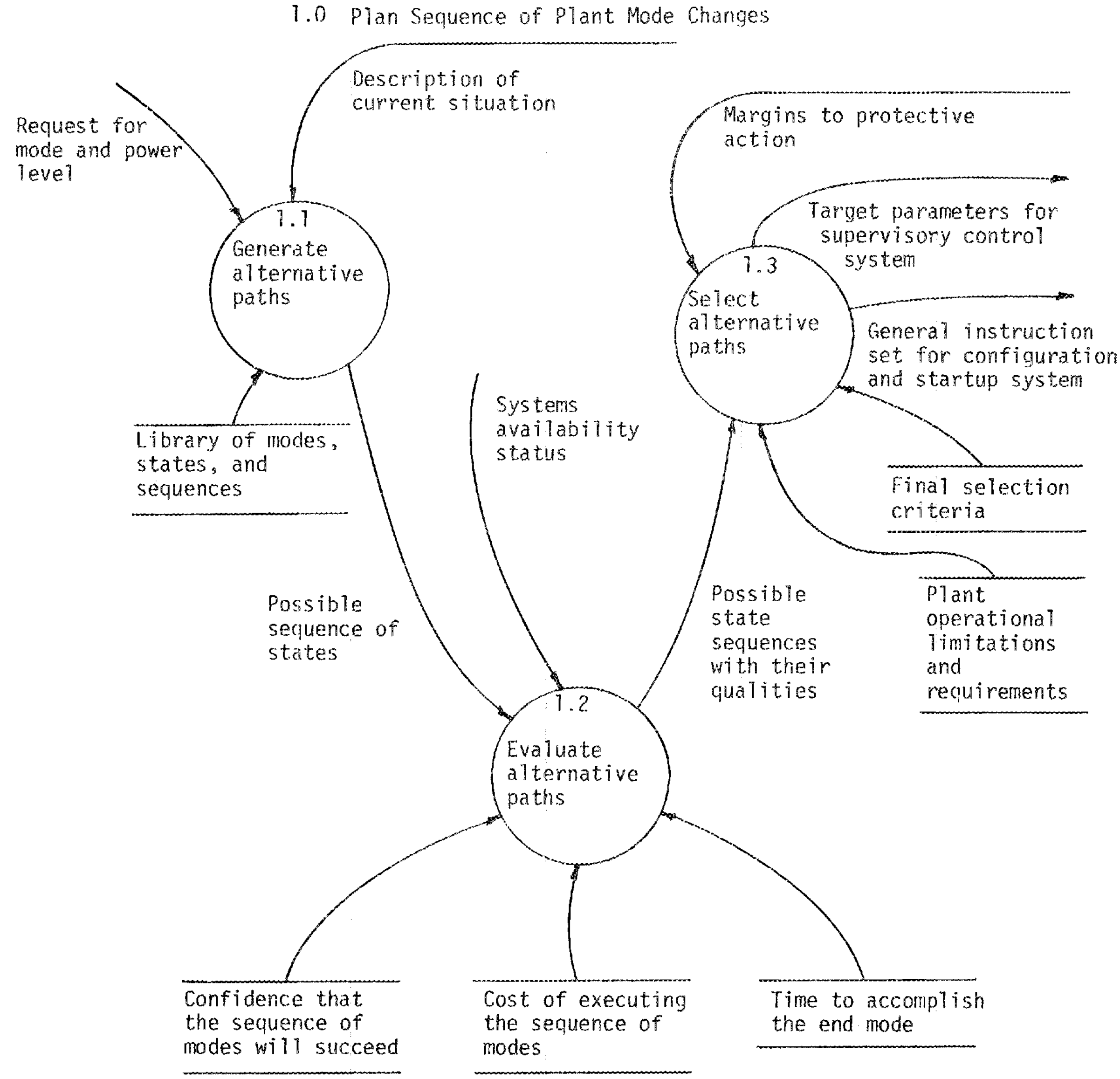

Fig. 3.8. Inner details of Package 1.0 for top-level diagram.

3.4.3 Package 6.0

Consider now package 6.0 of Fig. 3.4. This package provides an assessment of the current plant state. The assessment consists of a description of the current situation and an indication of plant equipment availability. Figure 3.12 shows the inner detail of 6.0. Transformation 6.3 operates separately from the other transformations and compares plant data with preestablished criteria for judging the operability of equipment and subsystems. The resulting list of equipment and statuses feeds into transformation 1.2 of the planner. Transformations 6.1 and 6.2 are magnified in Fig. 3.13. The transformations are an interpretation of the decision-making subtasks of Rouse et al. (1984) shown in Fig. 3.7. The data validation bubble, shown outside of the boundary of 6.0 (residing in the data-handling package 7.0), supplies only the names of valid data elements to store for use by 6.1.1.

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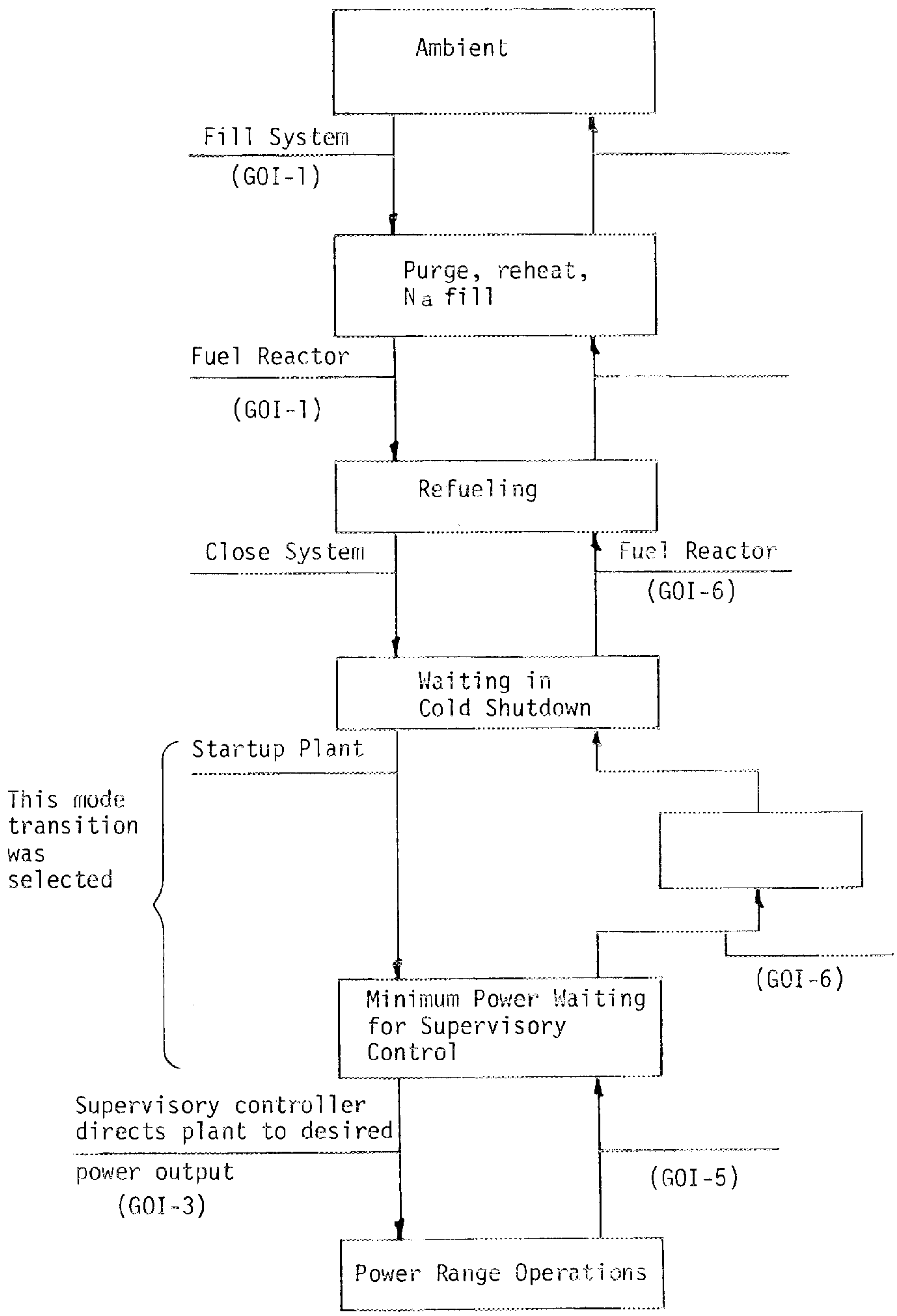

NOTE: GOI-# refers to the general operating instructions that apply to the indicated transition.

Fig. 3.9. Overall state transitions for plant. The transition from cold shutdown to minimum power was selected.

Table 3.2. Partial description of initial conditions: WAITING IN COLD SHUTDOWN

Refueling is complete
Primary and secondary control rod drive motors are inerted and their cooling systems are operational
Electric heating and cooling established with the steam generators and auxiliary vessel recirculating to the protected air-cooled condenser (PACC)
Leak detection and failed fuel element system is operational
PHTS and IHTS are full and on pony motor flow
PHTS and IHTS have reached temperature setpoint of 400°F
Reactor, PHTS, and IHTS have reached cover-gas, pressure-control setpoint
One cold trip is in operation for the PHTS and one for the IHTS
Vent freeze seals have been established for sodium piping
One sodium purification-impurity monitoring system is in operation for the PHTS and one for the IHTS
All plant utilities are operational
All necessary system tests have been performed and passed

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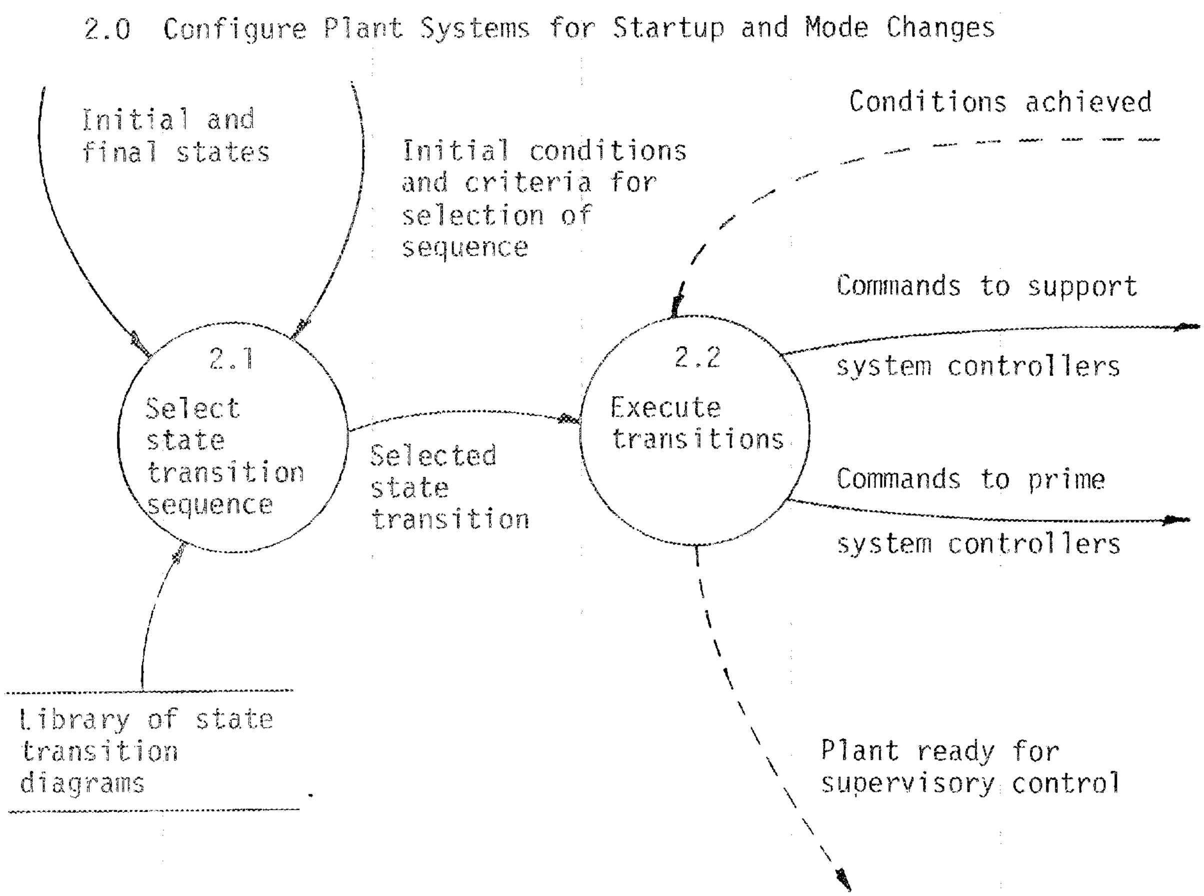

Fig. 3.10. Inner details of Package 2.0 from top-level diagram.

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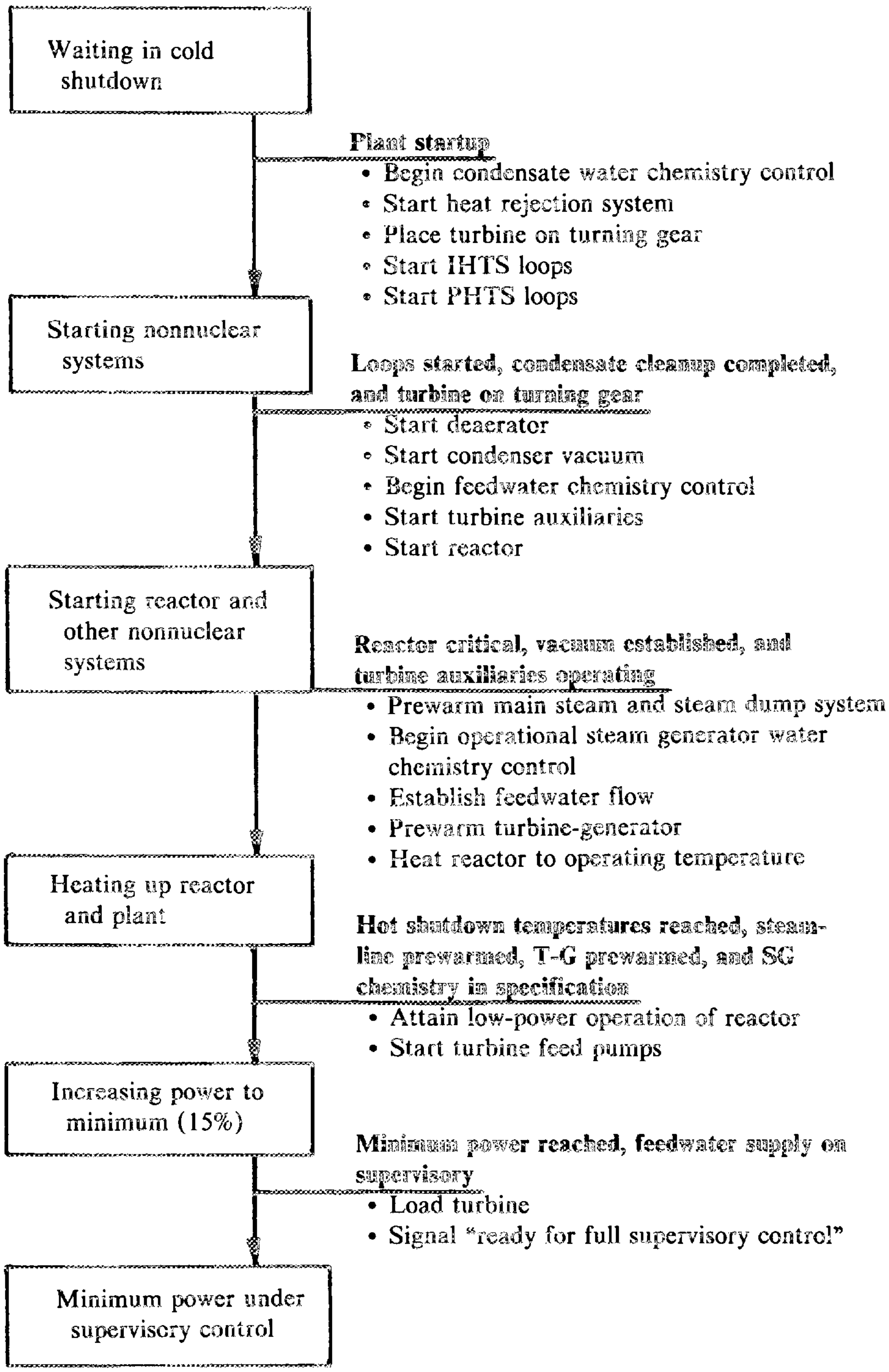

Fig. 3.11. State transitions with initial state "waiting in cold shutdown" and final state "minimum power under supervisory control." Inner states, conditions for transition, and actions to be taken are determined by initial plant conditions and other criteria generated by the state planner, Package 1.0.

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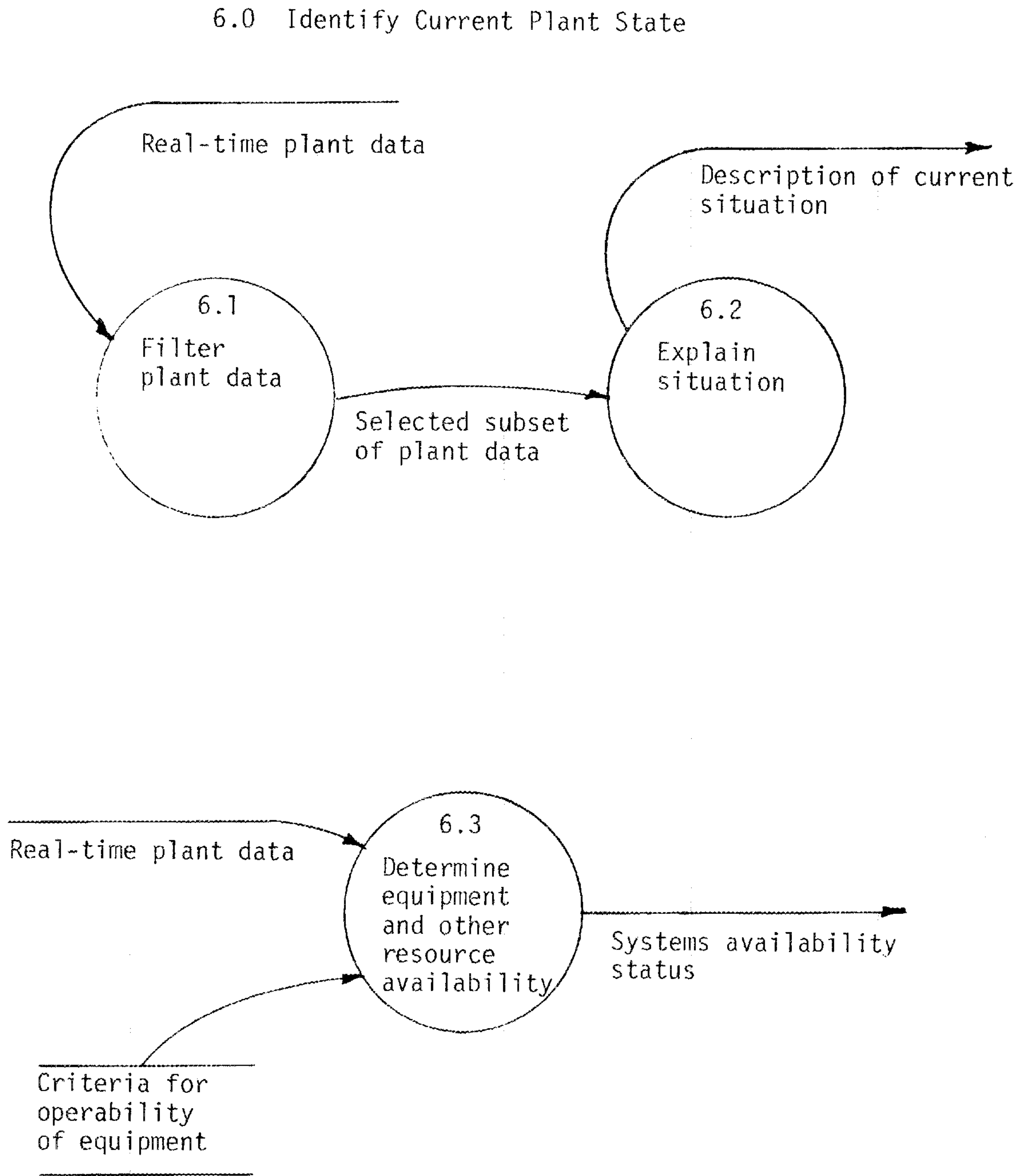

Fig. 3.12. Inner details of Package 6.0 from top-level diagram.

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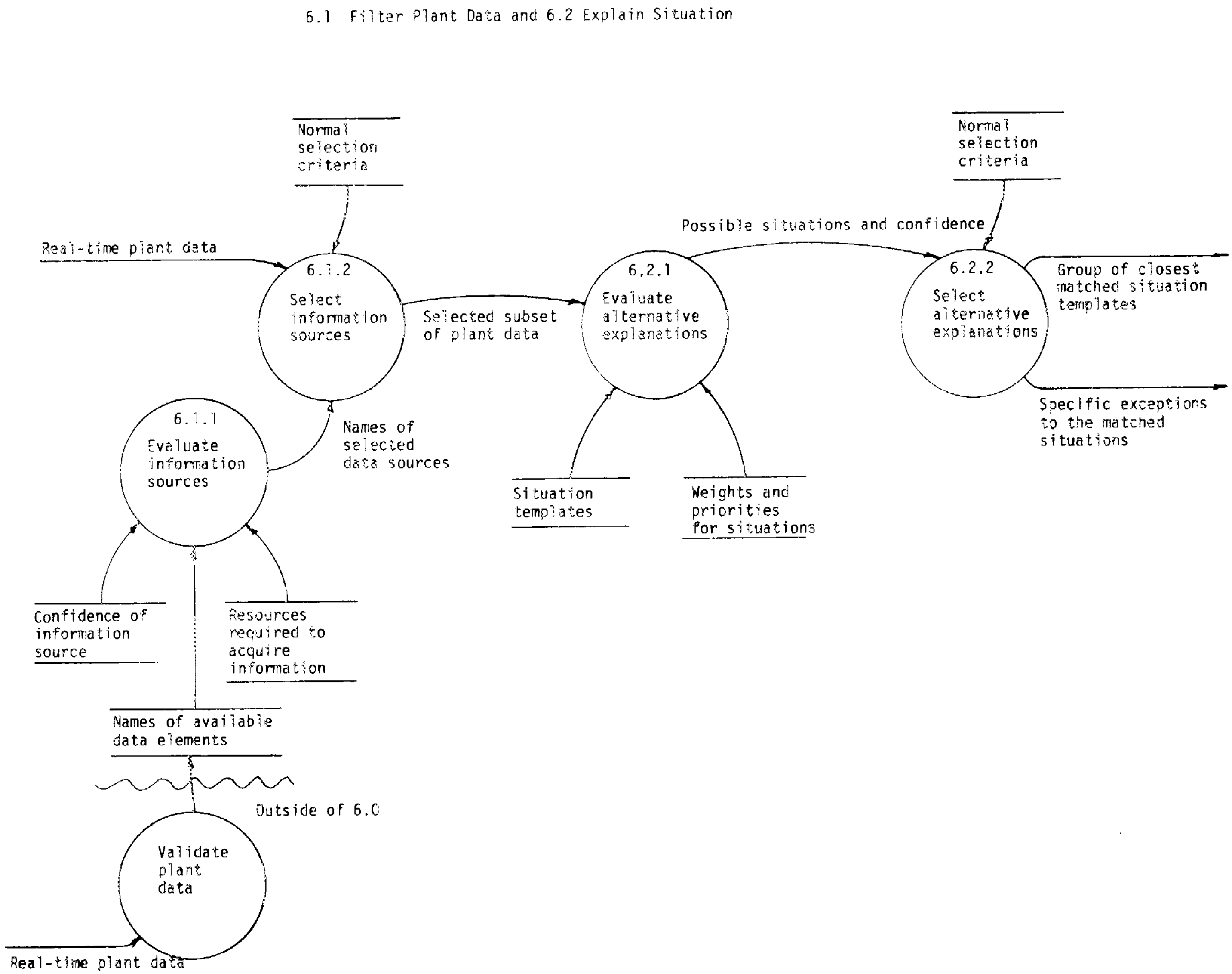

Fig. 3.13. Inner details of bubbles 6.1 and 6.2.

3.4.4 Package 4.0

The package, control prime plant systems, consists of eight lower-level packages, each corresponding to one of the prime plant systems. These packages are shown in Fig. 3.14 with their input and output data flows. The solid lines represent flows of data that will be acted on or transformed by the system within the package. A data flow path may consist of continuous or intermittent data types and most likely does not represent a single element of data but is composed of multiple streams or packets that are grouped under a common name. The dashed lines represent control flows and prompts that activate internal features of a package. The control flows provide only one bit of information, either being on or off. The prompts are momentary control flows that initiate an action (e.g., set a condition for a state transformation or enable a data transformation). The control flows may also be grouped under a common name. Control flows are generally associated with producing a structural change within a package, whereas data flows are operated on by a package to produce new data flows. In Fig. 3.14, any off-on signal or group of off-on signals entering or leaving a package is represented by a dashed line.

3.4.5 Package 5.0

The control support systems package consists of six lower-level packages (see Fig. 3.15). The particular set of subsystems, whose control is represented by these packages, is selected to best carry out the sequence of actions required by the equipment design and the interconnection of systems. We consider the procedures and the advice of subject matter experts to be the best source of instructions for startup and operation of a normally functioning system. Thus, the packaging of the elemental actions derived from these sources proceeds in a bottom-up mode. The same solid and dashed line data and control flow representations apply to package 5.0.

3.4.6 Magnification of Package 4.0 and 5.0

Data and control flow, as well as stored data, needed for the functioning of each subpackage of the prime and support packages of 4.0 and 5.0, are shown in the next sequence of figures. (Packages 4.0 and 5.0 are lumped together in these figures.) The first of the sequence, Fig. 3.16, shows the demand signals coming from the supervisory package, 3.0. These flows are composed of setpoints from the upper level feed forward supervisor and coordination vectors (containing interaction vectors and Lagrange multipliers) from the second-level optimal coordinator. An afferent flow of state vectors and adjoint vectors returns to the coordinator, although not shown on the figure. Further details of the supervisory system are given in Sect. 4.

The second figure of the sequence, Fig. 3.17, shows the discontinuous commands (control or prompt signals as described previously) that come from the configuration package, 2.0. These flows emanate from the actions listed on the state transition diagram in Fig. 3.11. For the most part, these flows are primative; that is, they cannot be further decomposed. As in the continuous supervisory case above, afferent flows are not shown. These afferent flows carry information to the configuration package that establishes the conditions allowing the next state transition to occur.

The third of the sequence, Fig. 3.18, shows plant data flowing from the data-handling system represented by package 7.0 together with the store of real-time plant data. Most of these flows are continuous variables and parameters. To clarify the contents of these flows, a data composition specification is given in Table 3.3. Some of the simpler data flows do not appear in the table. The operators used in the specification follow the conventions of DeMarco (1979), which were adapted from the Bacus-Nauer form. The symbols are defined as follows:

Symbol	Meaning
=	is composed of
+	and, along with
{}	iteration of
[]	choose only one of
()	optional
**	comment

The fourth of the sequence, Fig. 3.19, shows data flowing to actuators and bottom-level controllers, which are directly connected to the controlled devices. Both continuous variable and off-on signals are shown. Table 3.3 also contains the data composition for this figure.

The fifth in the sequence, Fig. 3.20, shows single-bit control signals passed between the pack-

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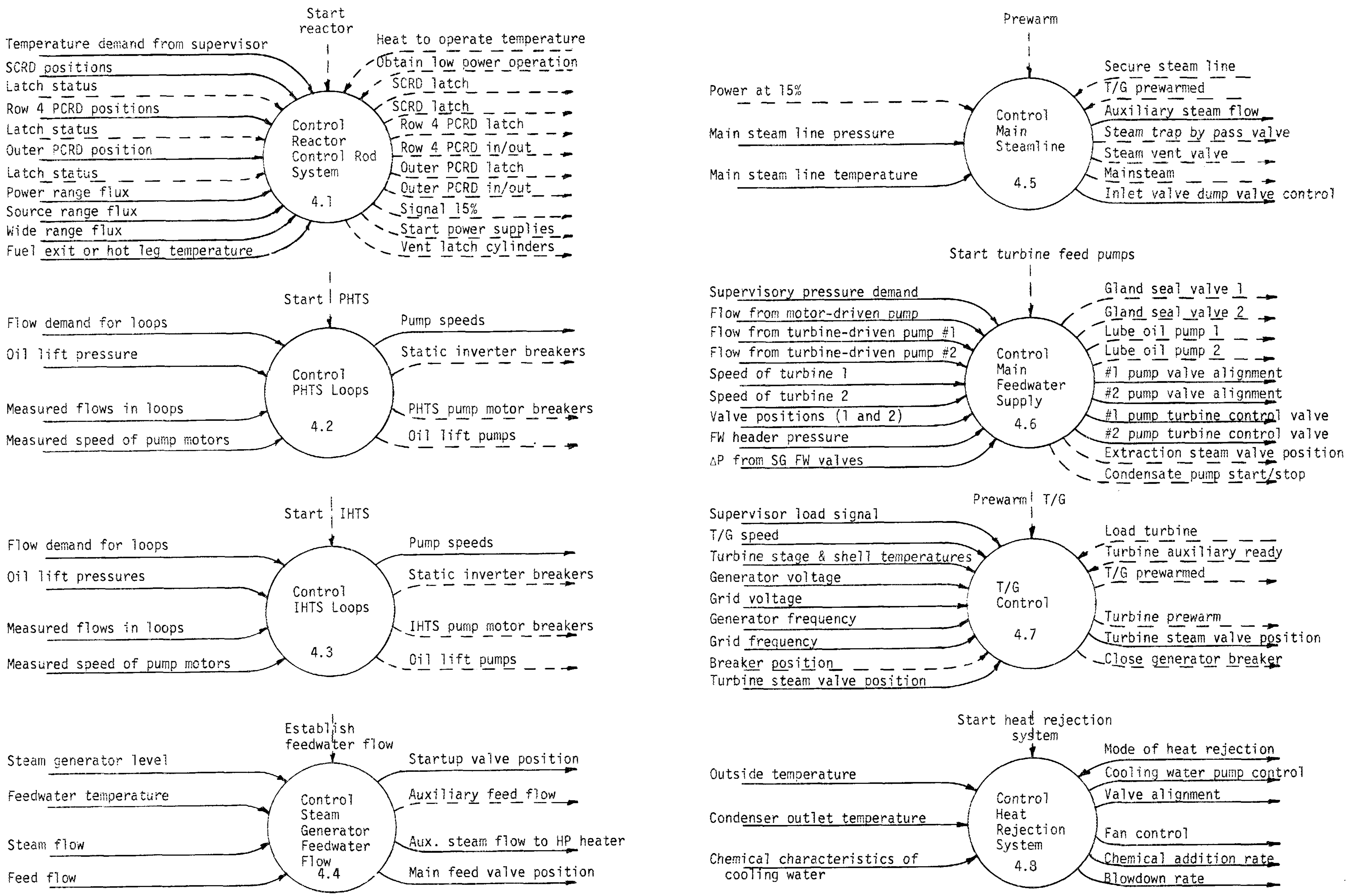

Fig. 3.14. Prime control packages which are the inner details of top-level Package 4.0.

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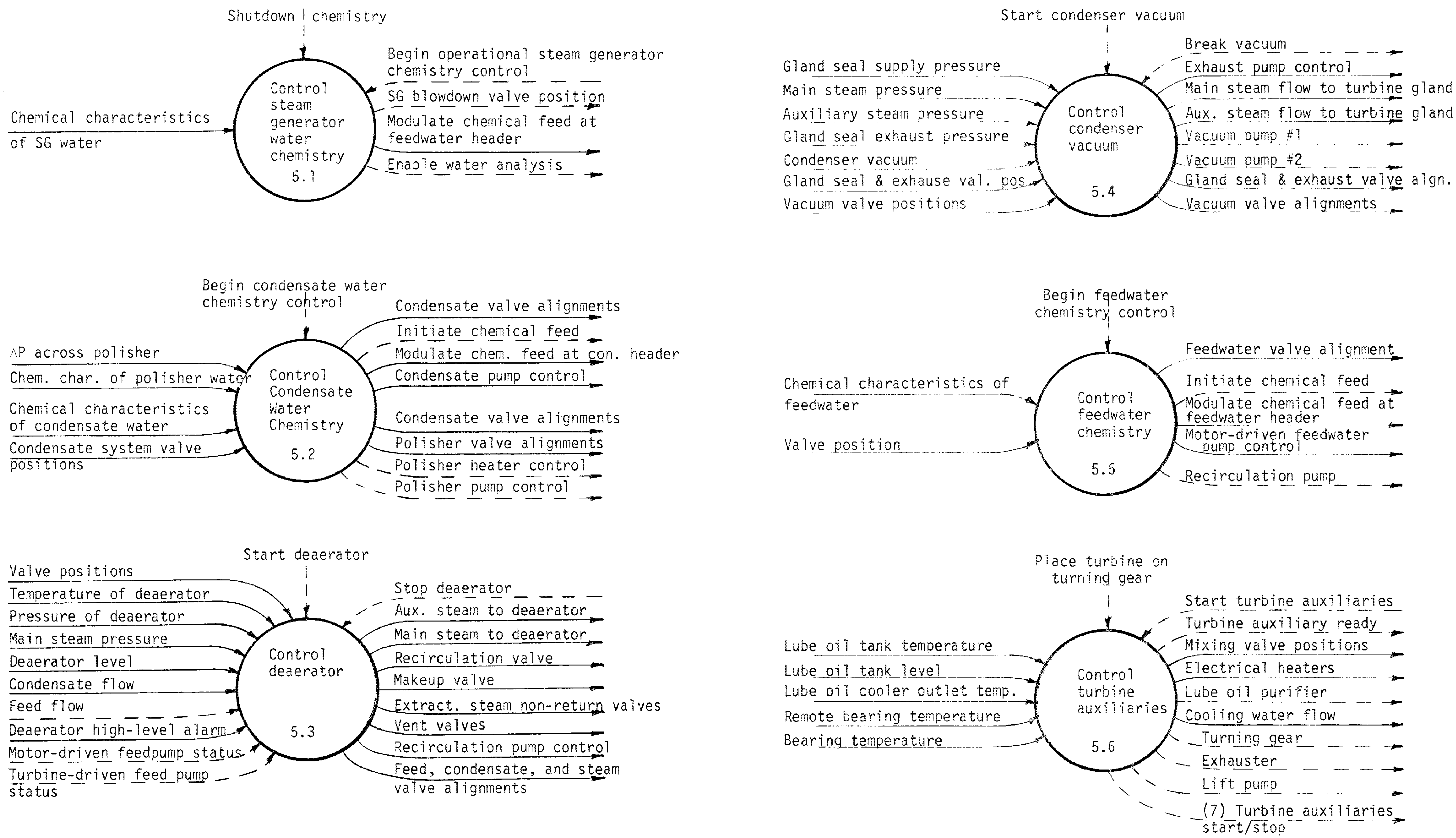

Fig. 3.15. Support control packages which are the details of top-level Package 5.0.

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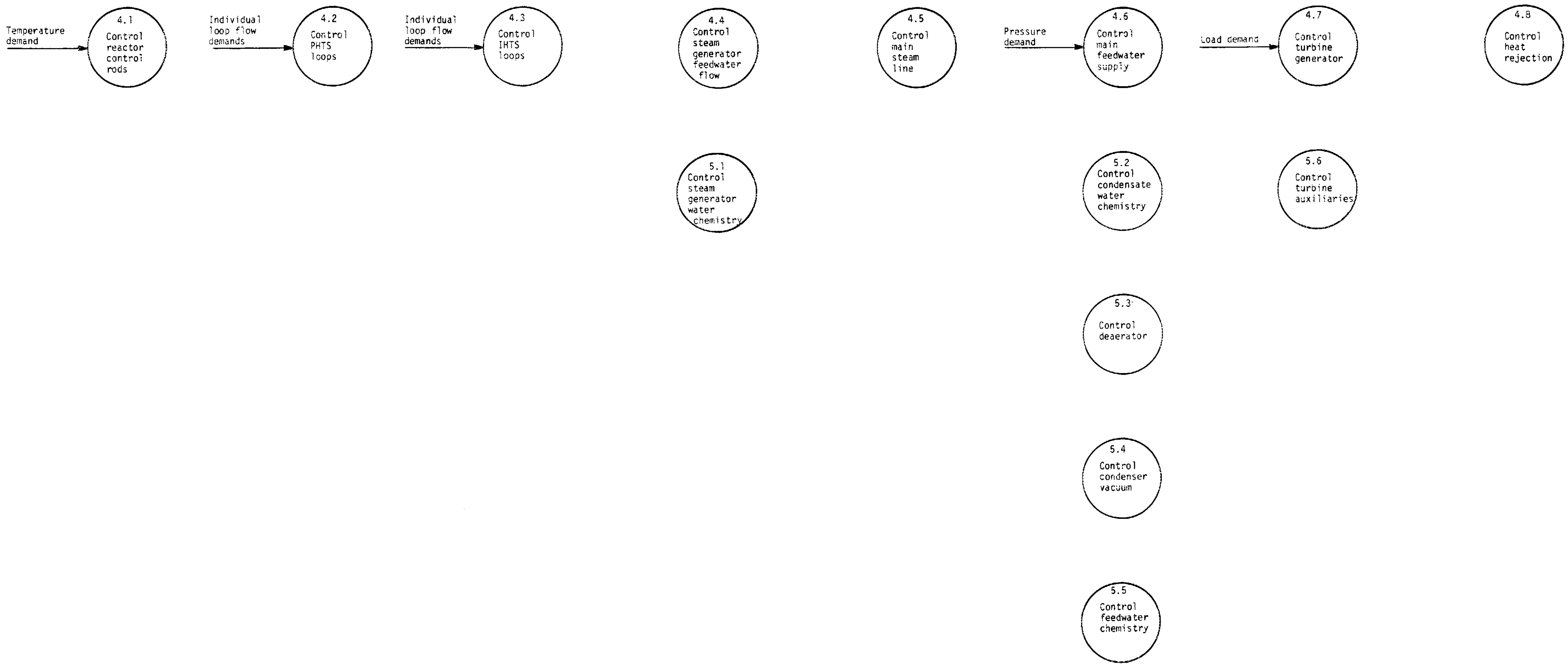

Fig. 3.16. Continuous demand flows from supervisory Package 3.0 to support and prime packages.

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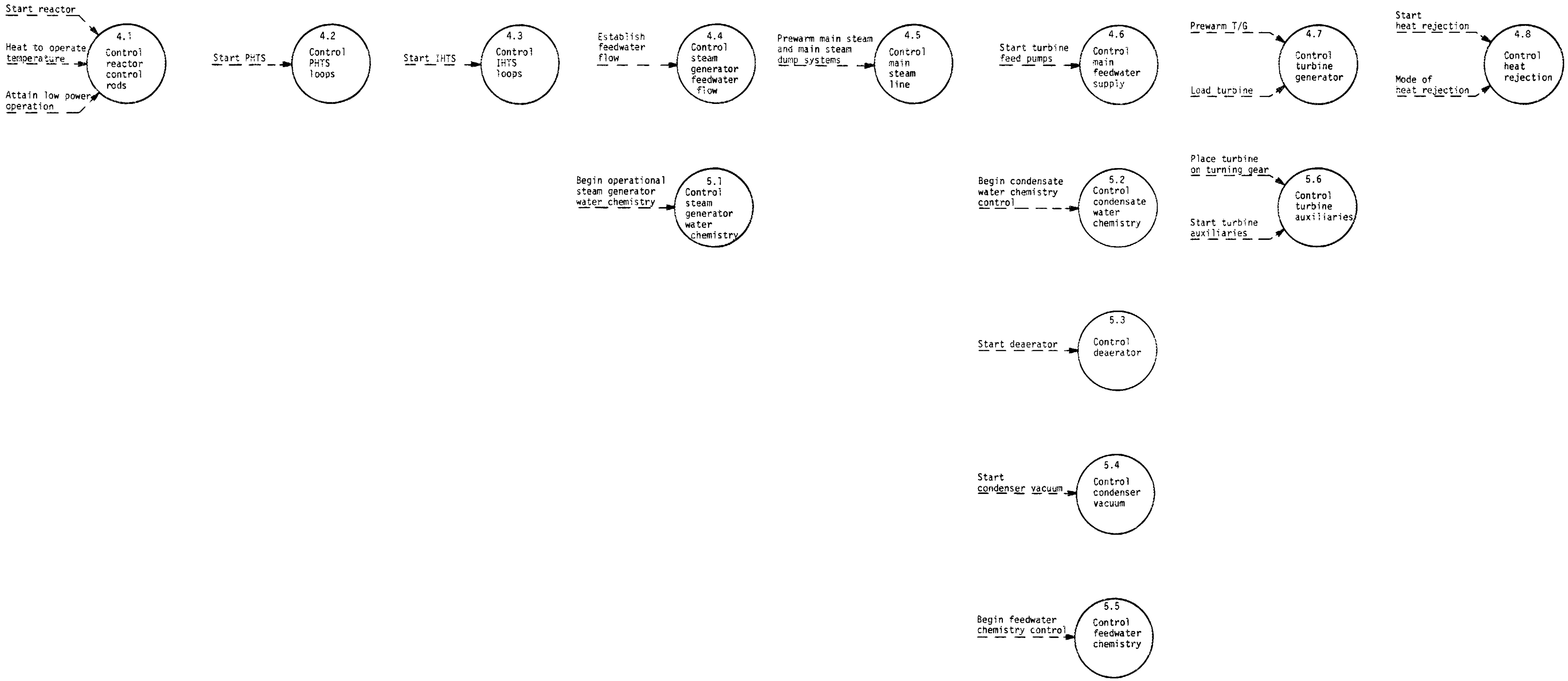

Fig. 3.17. Discontinuous commands (prompts) from configuration Package 2.0 to support and prime packages.

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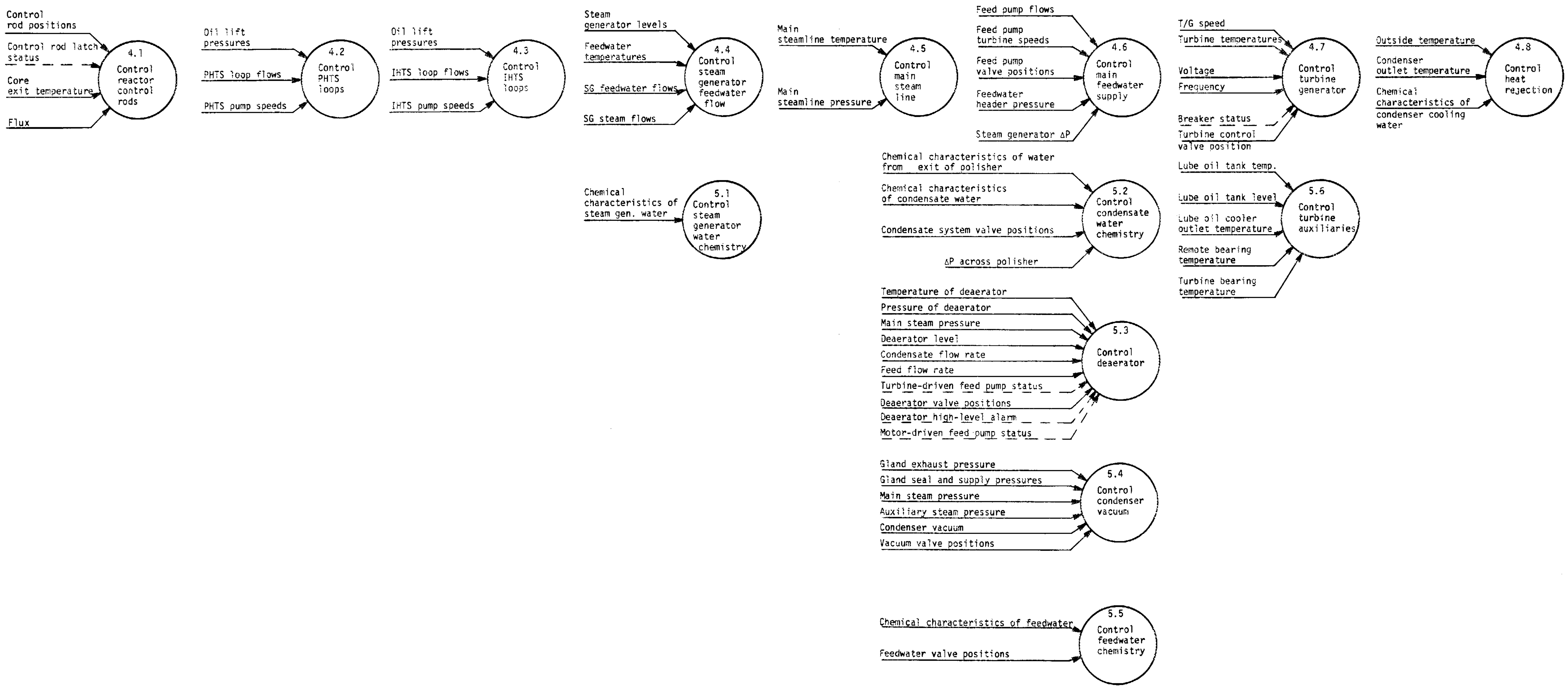

Fig. 3.18. Plant data flows into support and prime packages from data handling system. (See data composition specification for the flow composition.)

Table 3.3. Data composition specification

Control rod positions	{SCRD# + Position} + {Row 4 PCRD# + Position} + {Outer PCRD# + Position}
Control rod latch status	{SCRD# + [latched/unlatched]} + {Row 4 PCRD# + [latched, unlatched]} + {Outer PCRD# + [latched, unlatched]}
Flux	Power-range flux measurement + wide-range flux measurement + source-range count rate
Core exit temperature	[Average fuel exit Na temperature/Average hot leg Na temperature]
Primary heat transport system (PHTS) loop flows	{Loop # + flow rate}
Primary heat transport system pump speed	{Loop # + pump speed}
Intermediate heat transport system loop flows	{Loop # + flow rate}
Intermediate heat transport system pump speed	{Loop # + pump speed}
Steam generator level	{Steam generator # + level}
Steam generator feedwater flow	{Steam generator # + feed flow rate}
Steam generator steam flow	{Steam generator # + steam flow rate}
Feed pump flows	Motor-driven pump flow rate + {turbine-driven pump # + flow rate}
Feed pump turbine speeds	{Turbine-driven pump # + pump speed}
Feed pump valve positions	{Valve # + position}
Steam generator ΔP	{Steam generator # + p across feedwater valve}
Turbine temperatures	{Stage # + Temperature} + {Shell section # + temp.}
Voltage	Generator output voltage + grid voltage
Frequency	Generator frequency + grid frequency
Turbine control valve position	{Turbine inlet valve # + position} + turbine block valve position
Chemical characteristics of condenser cooling water	Chlorine concentration + pH
Chemical characteristics of steam generator water	Sulphite concentration + sulphate concentration + total dissolved solids + conductivity + chlorine concentration + pH + free hydrogen + free oxygen + hydrazene concentration
Chemical characteristics of condensate water	Sulphite concentration + sulphate concentration + total dissolved solids + conductivity + chlorine concentration + pH + free hydrogen + free oxygen + hydrazene concentration
Chemical characteristics of feedwater	Sulphite concentration + sulphate concentration + total dissolved solids + conductivity + chlorine concentration + pH + free hydrogen + free oxygen + hydrazene concentration
Chemical characteristics of water from exit of polisher	pH, conductivity
Deaerator valve positions	{Feedwater valve # + position} + {condensate valve # + position}
Latch control rods	{SCRD # + [latch, unlatch]} + {Row 4 PCRD # + [latch, unlatch]} + {outer PCRD # + [latch, unlatch]}

Table 3.3 (continued)

Secondary control rod drive (SCRD) carriage control	{SCRD # + [run rods in, run rods out]}
Primary control rod drive (PCRD)control	{Row 4 PCRD # + [move rod in, move rod out]} + {outer PCRD # + [move rod in, move rod out]}
Primary heat transport system pump speed	{PHTS loop # + speed demand}
Primary heat transport system inverter breakers	{PHTS loop # + [breaker open, breaker close]}
Primary heat transport system oil lift pump	{Primary heat transport system loop # + [pump on, pump off]}
Intermediate heat transport system pump speed	{Intermediate heat transport system loop # + speed demand}
Intermediate heat transport system static inverter breakers	{Intermediate heat transport system loop # + [breaker open, breaker close]}
Intermediate heat transport system oil lift pump	{Intermediate heat transport system loop # + [pump on, pump off]}
Steam generator startup valve positions	{Steam generator # + startup valve position demand}
Auxiliary feed flow	{Steam generator # + auxiliary feed valve position demand}
Steam generator main feedwater position	{Steam generator # + main valve position demand}
Steam trap bypass valves	{Bypass valve # + [valve open, valve close]}
Steam vent valves	{Vent valve # + [valve open, valve close]}
Dump valve control	{Dump valve # + valve position demand}
Gland seal valve	{Feedwater turbine # + gland seal valve position [open, close]}
Lube oil valve	{Feedwater turbine # + lube oil pump station [on, off]}
Pump valve alignment	{Feed pump # + {valve # + position demand}}
Turbine control valve	{Feedwater turbine # + {valve # + position demand}}
Extraction steam valves	{Extraction valve # + extraction valve position [open, close]}
Steam generator blowdown valve	{Steam generator # + blowdown valve position [open, close]}
Polisher pump	{Polisher system # + {pump # + [on, off]}}
Polisher heater	{Polisher system # + {heater # + [on, off]}}
Polisher valve alignments	{Polisher system # + {valve # + position}}
Turbine auxiliary control	Hydrogen system [start, stop] + stator water cooling [start, stop] + high-pressure hydraulics [start, stop] + exciter [start, stop] + turbine supervisory instrumentation [start, stop] + turbine extraction steam [start, stop] + turbine drain system [start, stop]
Vacuum pump control	{Vacuum pump # + [start, stop]}

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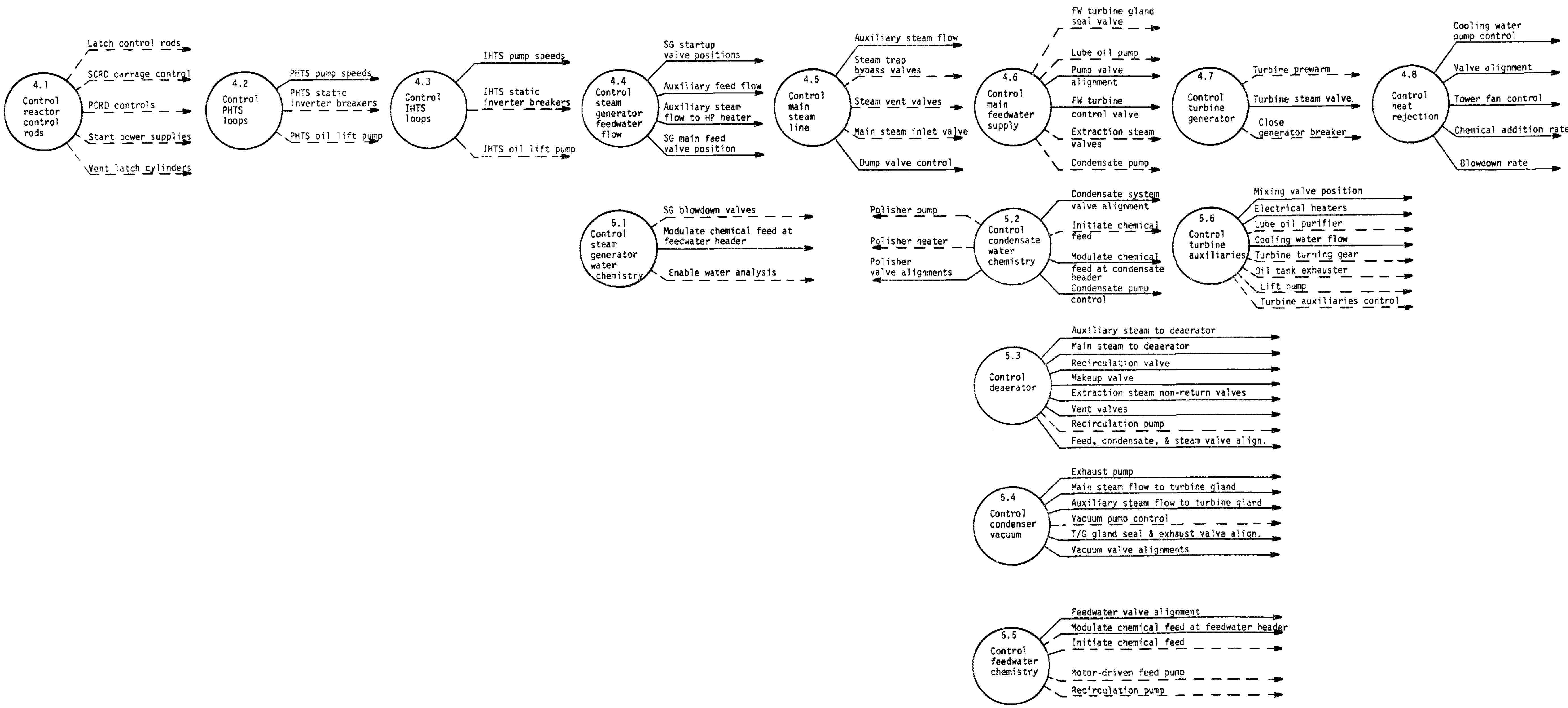

Fig. 3.19. Plant data flows out of support and prime control packages to actuation devices or lower level controllers. (See data composition specification for the elements that constitute these data flows.)

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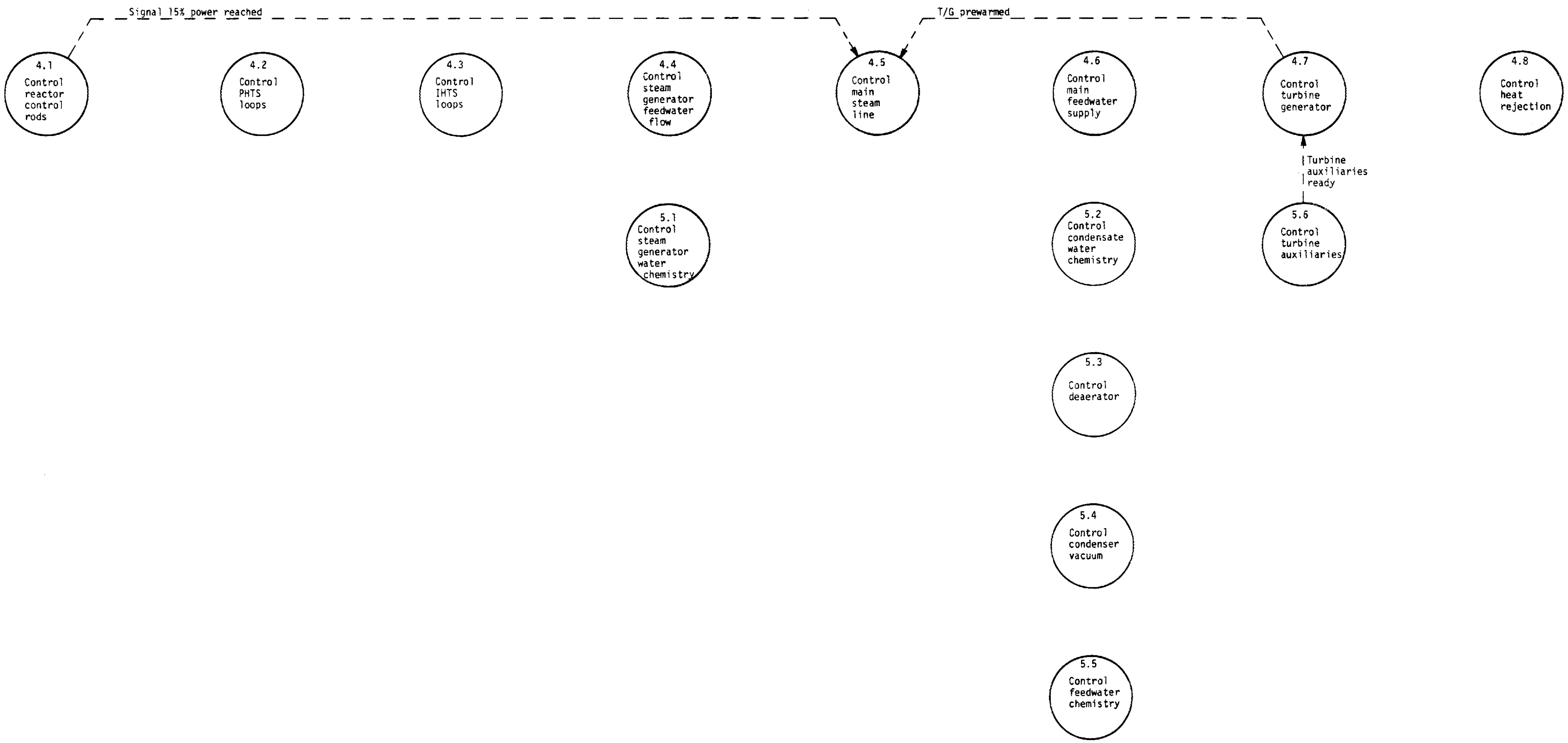

Fig. 3.20. Prime and support control package interconnections for single-bit control communications.

ages. The proper packaging of subsystems minimizes the interfaces between subsystems (especially of control signals and prompts). The scheme used to organize top-level packages 4.0 and 5.0 yielded few cross connections. Not shown on this figure are the inhibits, permits, and other transferent links that are shown in Table 3.1.

The sixth and final figure of the sequence, Fig. 3.21, shows stored data used within the subpackages of 4.0 and 5.0. Some of these data are updated periodically; some remain fixed for the life of the plant. The system for updating these internal stores is not discussed; however, that function could be a part of the data-handling system, package 7.0, or the high-level planner, package 1.0.

Illustrating the techniques to a further level of detail, the subpackages of the prime and support control systems are magnified one more level, and in some cases two more levels of detail. Appendix B contains child diagrams for the 14 packages of Figs. 3.14 and 3.15. At this level, state transition diagrams are packaged with the data flow diagrams, and their interactions are visible. Also a data-conservation rule is observed: each parent package (or bubble) must have exactly the same input and output data and control flows as the child diagram one level below it.

As discussed previously, these diagrams are incomplete; however, they form a framework onto which more plant maneuvers can be mounted until a reasonable Phase 1 system is formed. Then the subsequent phases of designing an intelligent automated control system can be added to the framework.

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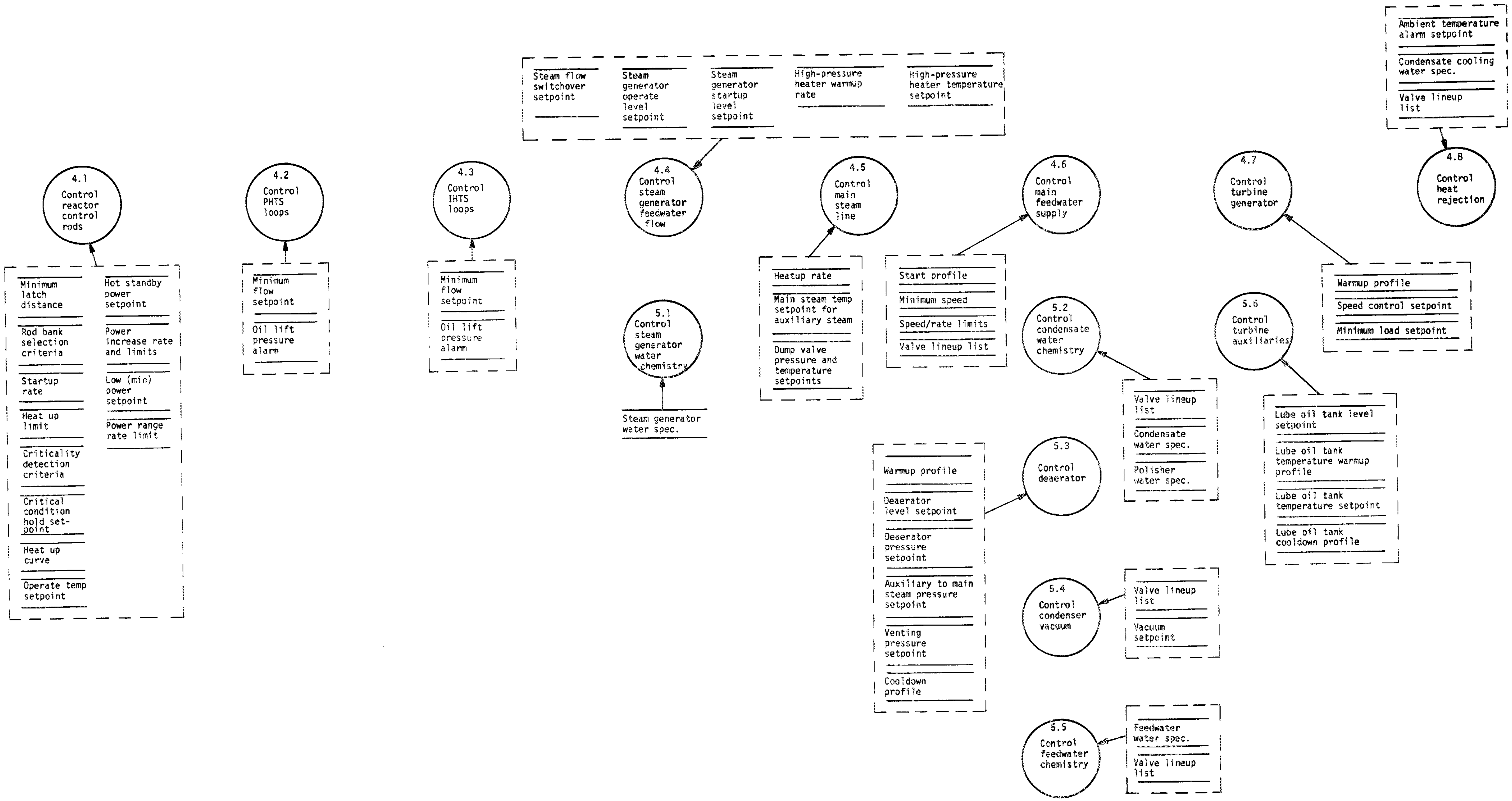

Fig. 3.21. Flows from data stores to support and prime control packages.

4. DISTRIBUTED AND HIERARCHICAL CONTROL TECHNIQUES FOR CONTINUOUS LARGE-SCALE SYSTEMS

4.1 INTRODUCTION

This section develops the continuous-variable control system that comprises package 3.0, supervise prime plant systems for optimal control and coordination, of Fig. 3.4 in Sect. 3.

As previously discussed in Sect. 2, the automated control system should be designed to improve

1. reliability, availability, and robustness of the plant;
2. coordination of plant control during normal operation, low power level operation, and contingencies;
3. efficiency of plant operation through tightened control at the local level; and
4. hardware and software flexibility for later modification.

A distributed and hierarchical control system is outlined to achieve these objectives and to improve overall plant dynamics.

The domain of the continuous-variable control system for the prime plant systems should extend to the various conditions of steady state (used here in the classical sense of an equilibrated system whose variables are essentially stationary), dynamic (contrasted with steady state), disturbances (noise and perturbations in the process variables), and faulted equipment. To cope with the latter condition of faulted equipment, a system must generally exhibit decision-making capability and be capable of discontinuous actions as described in Sect. 3. Thus, major shifts in function and restructuring of the physical process can be made to adapt the system to the failures encountered. Design for failed equipment is a feature that proceeds from Phase 3 efforts as described in Sect. 2. The techniques for Phase 3 design are the same as those for Phase 1, as Phase 3 work is built on Phase 1. The work that follows is restricted to Phase 1 design.

The control system developed in this section reflects the need to improve dynamic performance of the power plant as a whole to meet possible future requirements for maneuvering plants more rapidly. In general, steady-state control of a plant poses no exceptional problems; therefore, the continuous control system configuration presented at the end of this section relies on existing techniques for steady-state control.

The ability to retain control of the process in the midst of either externally or internally generated disturbances is one measure of robustness. The extent and shape of the homeostatic region described in Sect. 2 can be determined partly by the disturbance-handling capability of the control system. Although disturbances are important to include in the system development, this was not done at this time.

In Sect. 4.2, the prime systems of the large-scale prototype breeder are described. Section 4.3 summarizes the linear models necessary for designing advanced control systems. A supervisory control structure, developed using classical control techniques, is proposed for LSPB in Sect. 4.4. This supervisory controller becomes the upper-level controller of the proposed hierarchical system. Both continuous and discontinuous distributed hierarchical control systems and their functions are illustrated in Sect. 4.5. In Sect. 4.6 and 4.7, a philosophy and design of distributed and hierarchical control is given with application to LSPB. The modularization achieved from distributed and hierarchical control increases reliability of the system, improves flexibility for later modification, and facilitates system trouble shooting.

4.2 DESCRIPTIONS OF PRIME SYSTEM FOR THE LARGE-SCALE PROTOTYPE BREEDER REACTOR

The large-scale prototype breeder reactor (LSPB) provides a good example to illustrate the philosophy and structure of the control system developed in this report because of the availability of data from General Electric (GE) and Westinghouse. A plant schematic and heat transport system schematic of LSPB are shown in Figs. 4.1 and 4.2 respectively.

The LSPB is a liquid-sodium-coolant fast-breeder reactor plant containing a reactor, primary and intermediate heat transport systems, a once-through steam generator system, turbine-generator, and feedwater system. The plant is a four-loop configuration, producing 3500 MW(t) and 1350 MW(e) gross output. Load changes are designed to be accommodated at ±3% or less per minute. A step load change of ±10% power also can be accommodated throughout the normal power range of 100 to 40%. The thermal hydraulics are designed such that (1) the nominal turbine inlet steam pressure is at 2200 psig with peak error of 300 psig and a steady-state error of 110 psig and (2) the nominal turbine inlet steam temperature is at 850°F with peak or steady-state error not to exceed 15°F for 10% power demand step.

Brief descriptions and summaries of linearized state equation models for reactor, intermediate heat exchanger, a once-through steam generator are given in Sect. 4.3. Detailed models of these subsystems are given in Appendix C. These models have been adapted to this application of hierarchical control from the work of various researchers. The models for turbine and feedwater systems are not yet final and hence are not included in the report.

A steady-state program for the plant controllers can be obtained from the GE data given in Figs. 4.3 through 4.5. Variations in temperatures and steam pressures as a function of thermal power are plotted in Fig. 4.6, illustrating the steady-state program.

4.3 SUMMARY OF DYNAMIC MODELS

Successful design of control systems implies that a model of the process is needed. A good model is imperative; however, an extensive, high-order model is not necessarily better for control purposes than a lower-order model. A high-order model may be computationally too expensive to run repeatedly, and it also contains more nonmeasured state variables. Developing a good model for a complex plant is usually a major effort. Extensive literature is available on this subject (Atary and Shah 1972; Chen 1976; Davison 1966; Kerlin et al. 1977; Kerlin and Katz 1983).

In classical control design, an input-output description is used, and in advanced control tech-

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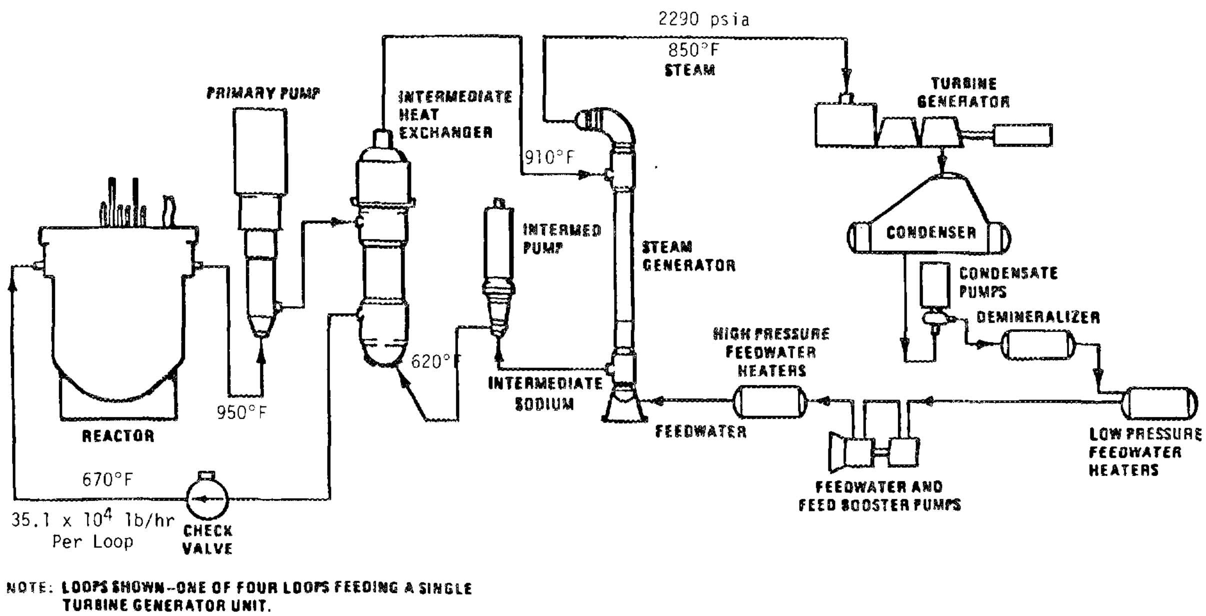

Fig. 4.1. Plant schematic.

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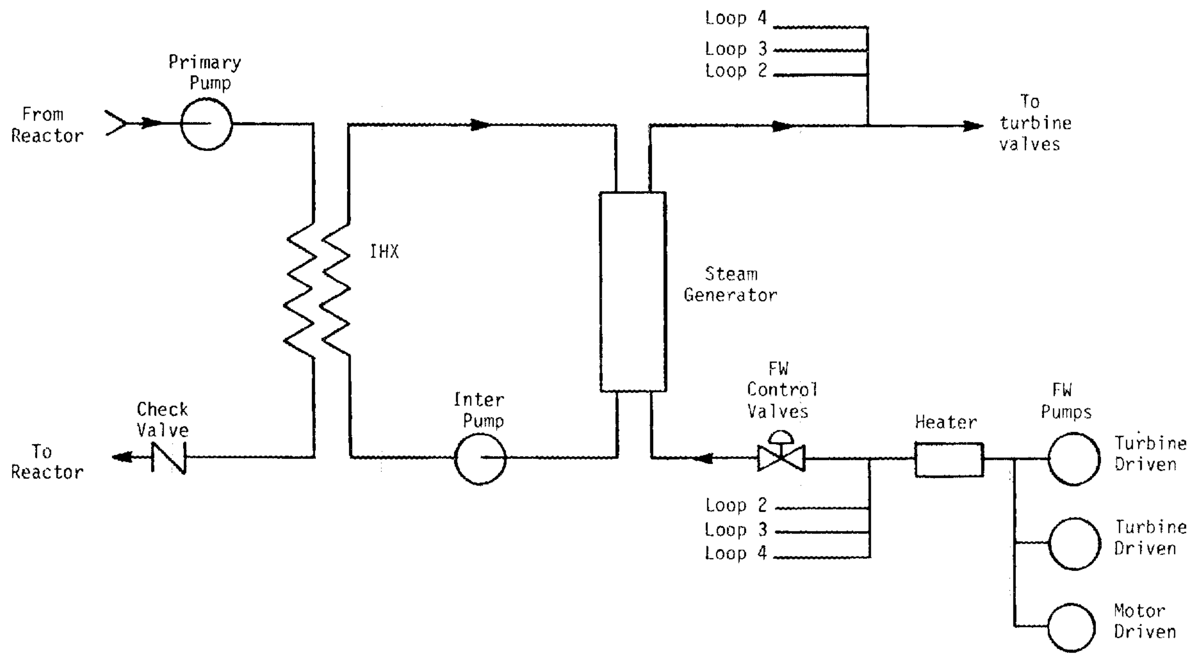

Fig. 4.2. Heat transport system.

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Thermal power	Core exit sodium temp.	Intermed. sodium flow	Primary sodium flow	Throttle valve steam temp.
150	1000	150	150	850
100	950	100	100	850
60	907.1	56.9	60.8	850
40	893.4	33.4	40.8	850
25	888	21.7	26.7	850

Fig. 4.3. Steady-state setpoint feed-forward program (sodium loops and mainstream).

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Thermal power	Steam/feed-water flow	Header pressure	Feedwater valve (ΔP)
150	132.5	2200	110
100	100	2200	110
60	56	2200	110
40	35.8	2200	50
26	22.4	2200	50

Fig. 4.4. Steady-state setpoint feed-forward program (feedwater).

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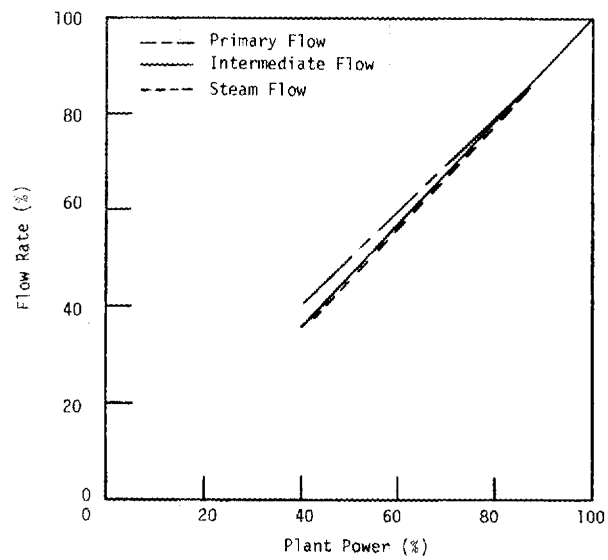

Fig. 4.5. Part load flow profile.

niques, a state variable model that usually requires linear relationship between variables is used. Such linear models may be derived from a set of non-linear equations that describe the process (e.g.,

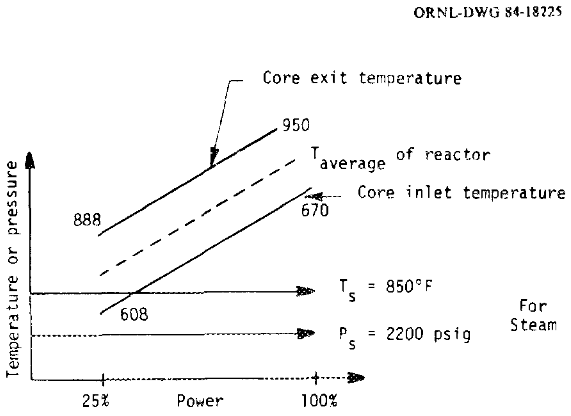

Fig. 4.6. Pressure or temperature variations with power.

LSPB). Consider a model of the process of interest in the form

$$\dot{\bar{X}} = f(\bar{X}, \bar{u})$$

where $\bar{X}$ is the state vector and $\bar{u}$ is the control vector. The object of a control system is to find a u^* which produces the desired (reference) response X^* for the process. The desired response may be obtained in at least two ways: (1) through optimal control techniques and (2) by specifying desired control as a function of specific conditions. Here, a feed-forward reference control, $u^*(P_L)$, as a function of power level demand is specified to obtain the desired steady-state program for the plant. Then $u^*(P_L)$ can be used to find the steady-state reference state vector, $X^*(P_L)$, by solving

$$\dot{X}^* = f(X^*, u^*) = 0 .$$

The feed-forward controller keeps the plant close to the reference values. The desired linear model can be obtained from

$$\dot{X} = AX + Bu$$

where

$$X = \bar{X} - X^*, \; u = \bar{u} - u^*$$

and

$$A = \left.\frac{\partial f}{\partial \bar{X}}\right|_{X^*, u^*}, \quad B = \left.\frac{\partial f}{\partial \bar{u}}\right|_{X^*, u^*} .$$

To obtain distributed and hierarchical control, linear models are needed for the subsystems of the plant. In this section, linear models are described for the three systems: reactor, intermediate heat exchanger and steam generator. The models for turbine and feedwater subsystems are not yet final. These three models, derived from the existing literature, are presented here to illustrate the application of distributed and hierarchical control to LSPB (see Sect. 4.7). A block diagram showing different subsystems of the LSPB plant is shown in Fig. 4.7 with appropriate labeling.

4.3.1 Reactor

A summary description of LSPB is given in Sect. 4.2. The mathematical model presented here, based on Demore and Matta (1975), Huynh (1978), and Weaver (1967), represents the kinetics

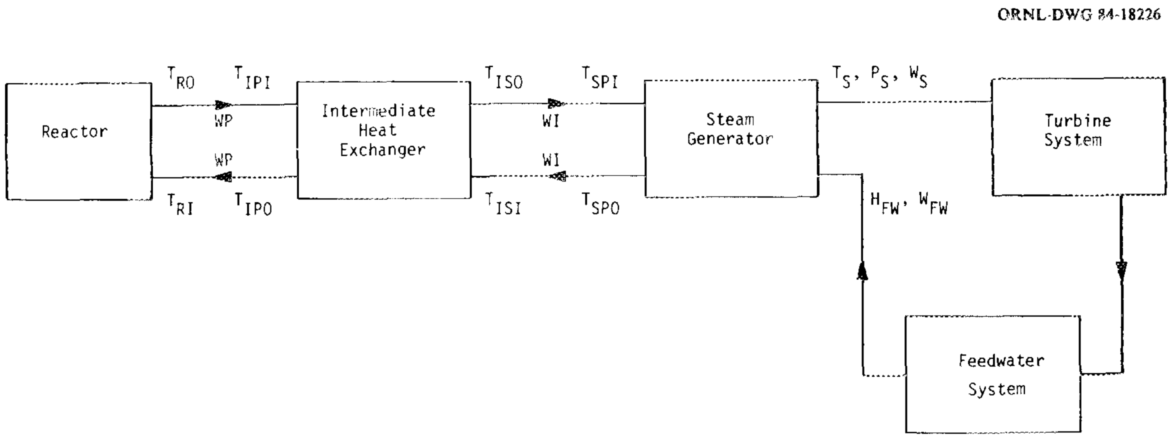

Fig. 4.7. Block diagram of LSPB reactor with different subsystems.

of a point reactor with two groups of delayed neutrons and core thermodynamics. A schematic of the reactor system is given in Fig. 4.8. Mathematical equations representing the reactor are given in Appendix C.1.

The state variables are neutron flux, two precursor concentrations, and temperatures of fuel, clad, coolant (average), plenum metal, and coolant (at core inlet). The inputs included control and interaction variables.

$$X_1 = X_R$$

$$= (\delta n,\ \delta c_1,\ \delta c_2,\ \delta T_f,\ \delta T_c,\ \delta T_N,\ \delta T_m,\ \delta T_{No})$$

The external inputs are rod reactivity, primary flow and reactor inlet temperature.

$$u_1 = u_R = (\delta\rho_{rod},\ \delta_{wp},\ \delta T_{RI})\ ;$$

therefore,

$$\dot{X}_1 = A_1 X_1 + B_1 u_1\ ,$$

where $A_1 = 8 \times 8$ and $B_1 = 8 \times 3$ matrices. The input-output relation can be represented by the block diagram shown in Fig. 4.9.

4.3.2 Intermediate Heat Exchanger

A counterflow intermediate heat exchanger with shell is shown in Fig. 4.10. The response of a counter flow intermediate heat exchanger to inlet temperature and flow rate perturbations is considered (Ball 1964). A lumped model is shown in Fig. 4.11. Both flows in the intermediate heat exchanges are sodium for LSPB. Mathematical equations for an intermediate heat exchanger model are given in Appendix C.2. The linearized state equations take the form

$$\dot{X}_I = A_I X_I + B_I u_I\ ,$$

where the state variables are the temperatures of primary sodium (mean), outlet primary sodium, metal tube, inlet and outlet secondary sodium,

$$X_3 = X_I = (\delta\overline{T}_1,\ \delta T_{IPO},\ \delta\overline{\overline{T}}_T,\ \delta\overline{T}_2,\ \delta T_{ISO})\ ,$$

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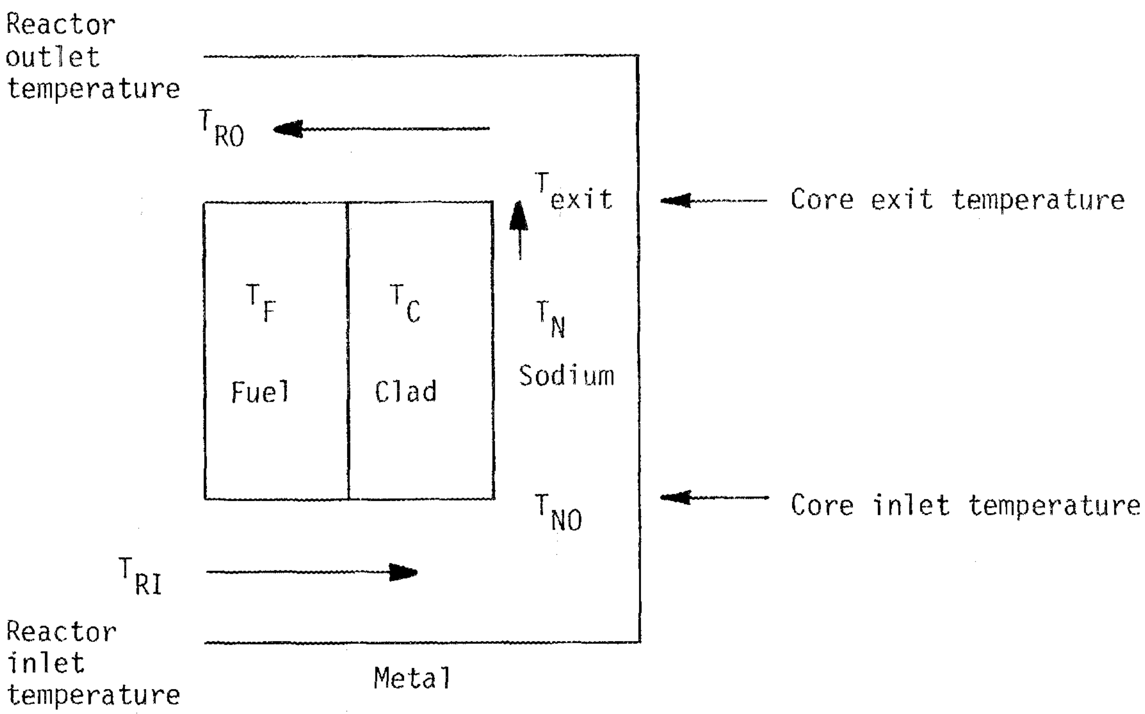

Fig. 4.8. A schematic of reactor subsystem.

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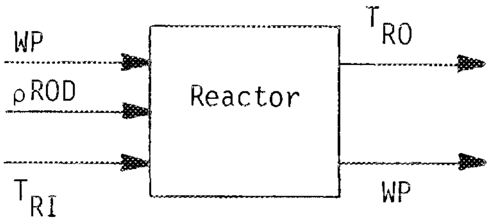

Fig. 4.9. Reactor input-output relation.

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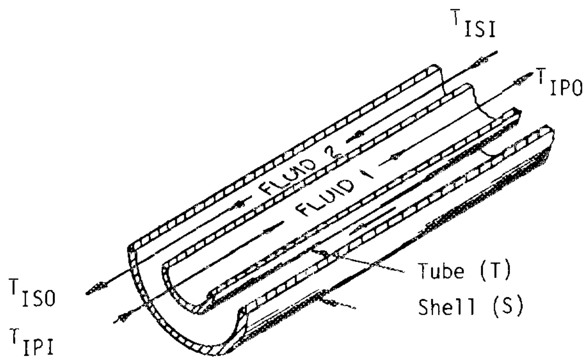

Fig. 4.10. Counterflow heat exchanger with shell.

and external inputs (u_I) are primary and secondary inlet temperatures, primary and intermediate flows,

$$u_I = (\delta T_{IPI},\ \delta w_p,\ \delta w_I,\ \delta T_{ISI}) \ ;$$

$$A_I = 5 \times 5 \text{ matrix and}$$

$$B_I = 5 \times 4 \text{ matrix} \ .$$

An input-output block diagram for an intermediate heat exchanger is given in Fig. 4.12.

4.3.3 Steam Generator

There are several designs for steam generators. In nuclear power plants, recirculation and once-through steam generators (OTSGs) are generally used. In a recirculation generator, the recirculation flow is usually larger than the feedwater flow, and it produces dry or slightly wet saturated steam. Of the recirculation types, the U-tube and drum evaporator are most common. The latter type has an external recirculation loop between the evaporator and the steam-water drum.

Once-through steam generators usually produce superheated steam with the secondary coolant fully evaporated in the upper tube-bundle region. As a consequence of superheating, the OTSGs usually

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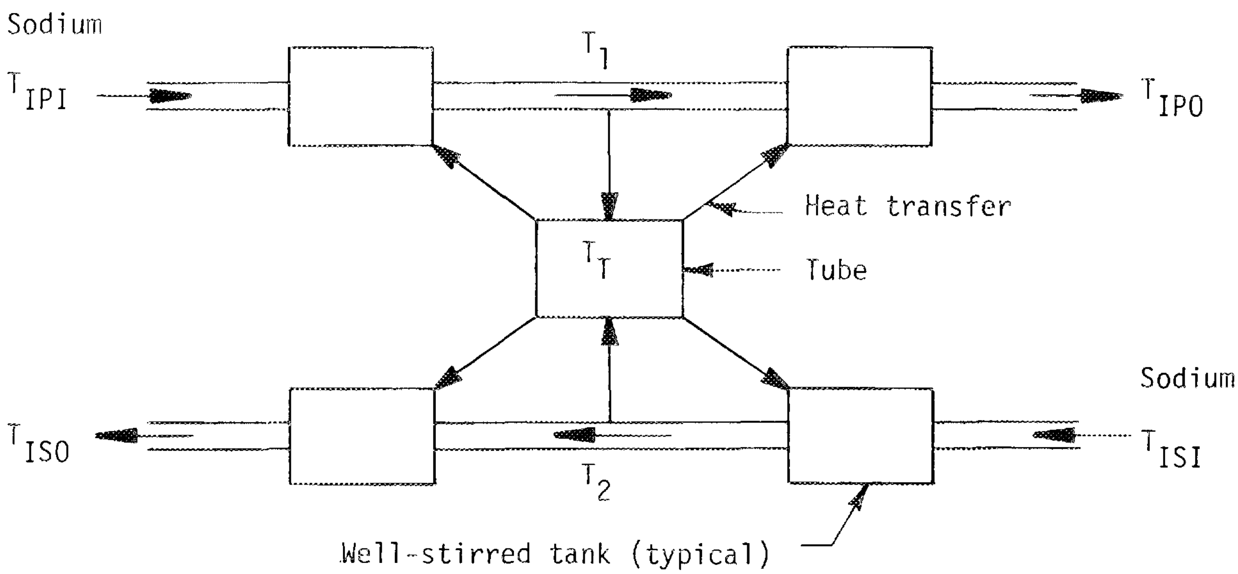

Fig. 4.11. Lumped-parameter approximation of a counterflow heat exchanger.

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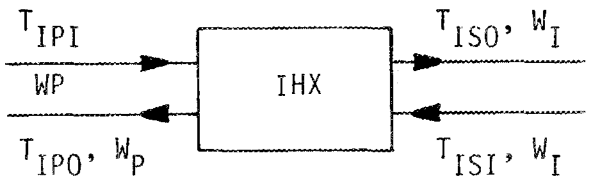

Fig. 4.12. Intermediate heat exchanger input-output relation.

achieve higher thermal efficiency and smaller component size than, for example, U-tube steam generators with comparable capacity. At the same rated power, OTSGs have a lower secondary flow rate and lower mass inventory in the secondary side than systems with a U-tube configuration. This results in less stored energy and faster response to external thermal perturbances for the OTSGs. (Recirculation can also occur in OTSGs with steam aspirated feedwater for feedwater heating.)

In this study, a simplified mathematical model, derived from several sources (Broadwater 1977; Chen 1976; Demore and Matta 1975; Joyner 1984; Kerlin and Katz 1983; Zhiwei and Kerlin 1983), is described for a OTSG. In the steam generator, the subcooled feedwater enters the tube-bundle region, flows upward, and starts receiving heat from the tubes. The secondary coolant reaches saturation and soon boiling starts. Evaporation is completed, then superheating occurs in the upper portion before the steam exits from the generator. Thus, along the secondary coolant path, two important boundaries mark the transitions from subcooled to boiling and from boiling to superheated regions.

The secondary flow exists between the shell and outer tube wall of the steam generator, and the primary flow (sodium) exists inside of the tube. Hence, the OTSG is a counterflow, shell-and-tube heat exchanger.

4.3.4 Steam Generator Model

The two-phase heat transfer and flow problem is quite complex, and many model formulations exist based on different sets of simplifying assumptions to reduce this problem to tractable form. Using a lumped parameter model, Chen (1976) and Broadwater (1977) have modeled a OTSG system. The simplified model presented here is based on the work of Chen and Broadwater and personal conversation with Luther Joyner (1984). A schematic of the steam generator to be modeled is shown in Fig. 4.13. As shown in the figure, the steam generator is divided into subcooled, boiling, and superheat regions on both the primary and secondary sides. To obtain a simplified model, two basic assumptions are made:

1. The outlet temperature of the region (lump) is the representative region temperature.

2. The heat transfer between primary and secondary is instantaneous, thus eliminating lumps for the metal tube.

These assumptions result in a model with three primary coolant lumps: one superheat steam lump, one saturation boiling lump, and one subcooled lump. The mathematical equations describing the model are given in Appendix C.3. A linearized model resulting from the detailed mathematical equations is summarized below. Based on the linearized model, distributed and hierarchical control design is detailed in Sect. 4.7. The linearized model consists of primary temperatures at superheat, boiling and subcooled regions, secondary temperatures at superheat and subcooled regions, boiling length, subcooled length, and steam pressure as state variables

$$X_S = X_s = (\delta T_{PSH},\ \delta T_{PB},\ \delta T_{PSC},\ \delta T_{SH},\ \delta T_{SC},\ \delta \mathrm{L_B},\ \delta \mathrm{L_{SC}},\ \delta \mathrm{P_{SH}}) \ ,$$

and primary input temperature to steam generator, intermediate flow, feedwater enthalphy, feedwater flow, and turbine inlet valve coefficient as external inputs

$$u_s = (\delta T_{SPI},\ \delta W_I,\ \delta H_{FW},\ \delta W_{FW},\ \delta C_v) \ .$$

The linearized state equation is given by

$$\dot{X}_S = A_S X_S + B_S u_S \ ,$$

where A_S = 8 × 8 matrix and B_S = 8 × 5 matrix.

An input-output block diagram for the steam generator is given in Fig. 4.14.

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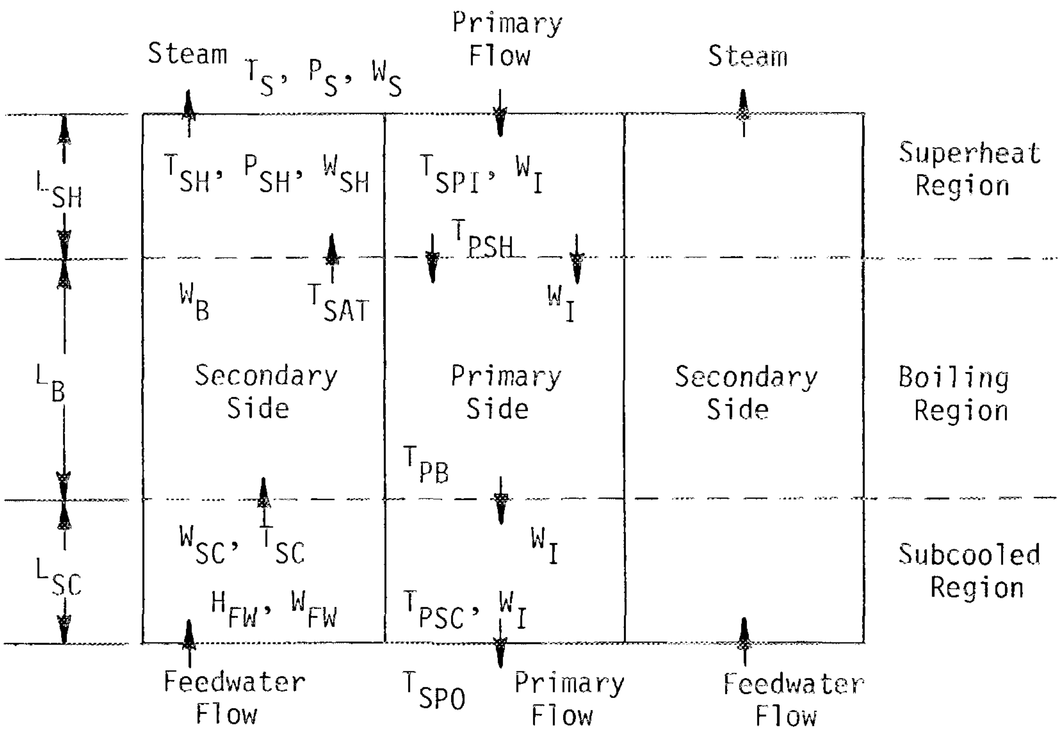

Fig. 4.13. Schematic of once-through steam generator.

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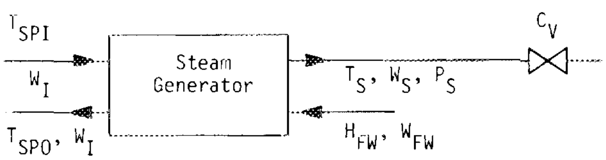

Fig. 4.14. Steam generator input-output relation.

4.4 SUPERVISORY CONTROL USING CLASSICAL CONTROL TECHNIQUES

This section suggests a supervisory control structure using the classical control techniques that are used in the nuclear industry. This qualitative study, based on the existing literature (Chen 1976; Bell, Cook, and Munro 1982; Demore and Matta 1975; Schultz 1961; Ball et al. 1982; and Daniel 1984), offers a philosophy and structure. This section develops the role of the upper-level supervisory controller for the distributed and hierarchical control presented in Sect. 4.7. The classical technique uses both feed foward and regulatory control. The feed forward signal is provided by supervisory control as a function of load demand. The regulatory control is used to control temperature and steam pressure in the system. A proposed supervisory control is shown in Fig. 4.15.

The feed-forward control as a function of load demand (e.g., the load demand signal coming from load dispatcher) is generated by supervisory control using a steady-state program given in Figs. 4.3, 4.4, and 4.6 or through simulation studies.

In the reactor control, the core-exit temperature demand signal speeds up the reactor response to approach the desired core-exit sodium temperature. The core-exit temperature can be tuned to the desired value by using an additional regular control signal that is generated through a dynamic compensation (PID control) of the error signal of the measured steam temperature and 850°F (the setpoint). The primary flow is controlled through the feed-forward primary flow demand without regulatory control. Ball (1982) stated that a regulatory control

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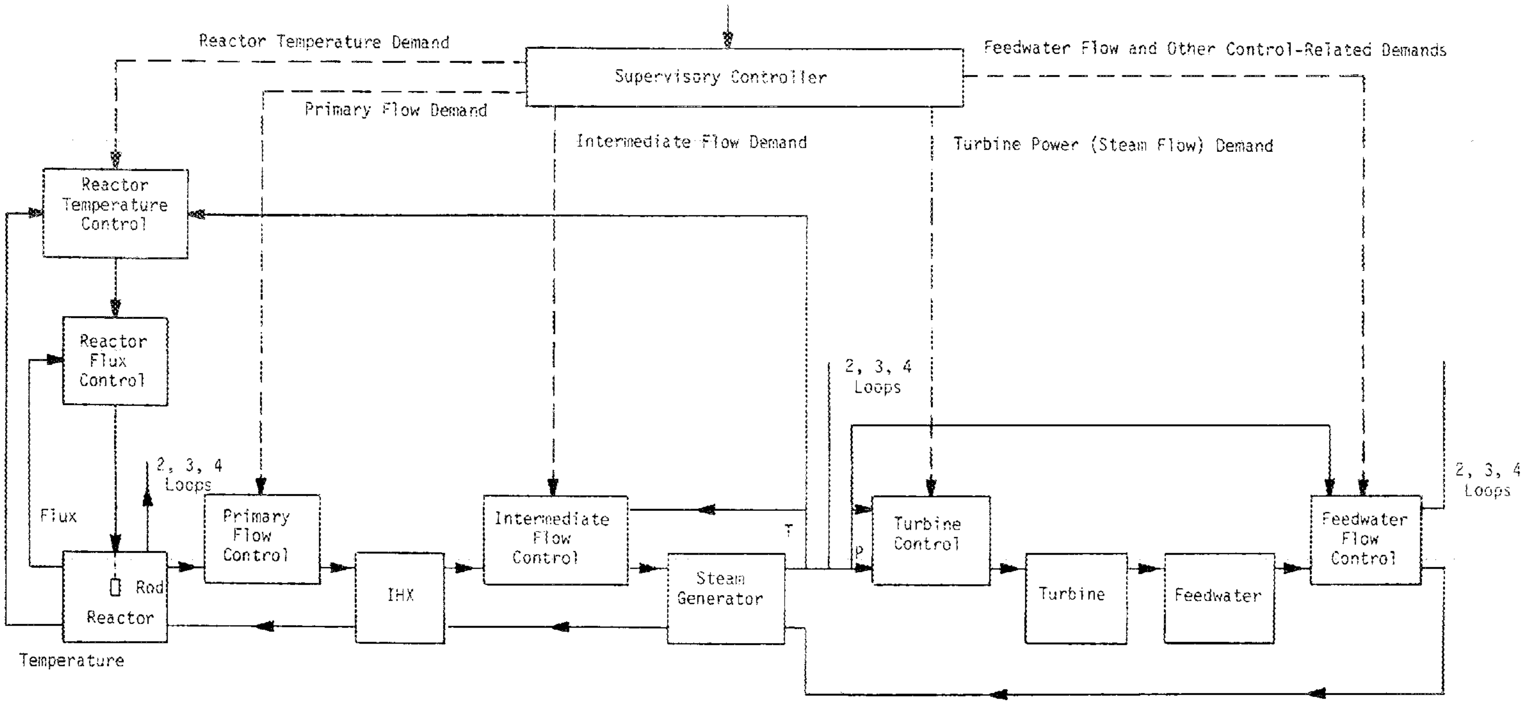

Fig. 4.15. Supervisory control of LSPB reactor with classical control techniques.

of primary flow leads to undesirable interaction problems.

The GE simulation studies (see Figs. 4.16 through 4.19) have shown that the intermediate flow rate perturbation has greater effect on steam generator outlet temperature than on steam pressure. A dynamically compensated (PID control) temperature error signal (the difference between the 850°F setpoint and steam generator outlet temperature) is used as a regulator signal in addition to the feed-forward intermediate flow demand signal from the supervisor in controlling intermediate flow.

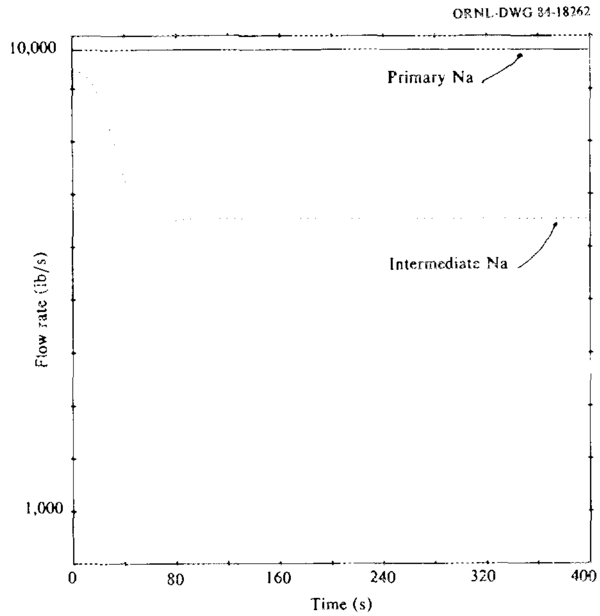

Fig. 4.16. Sodium flow rates affected loop.

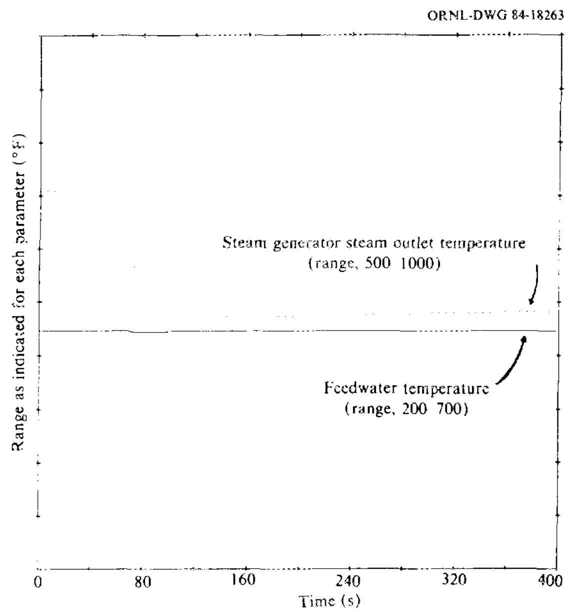

Fig. 4.18. Steam/water temperatures affected loop.

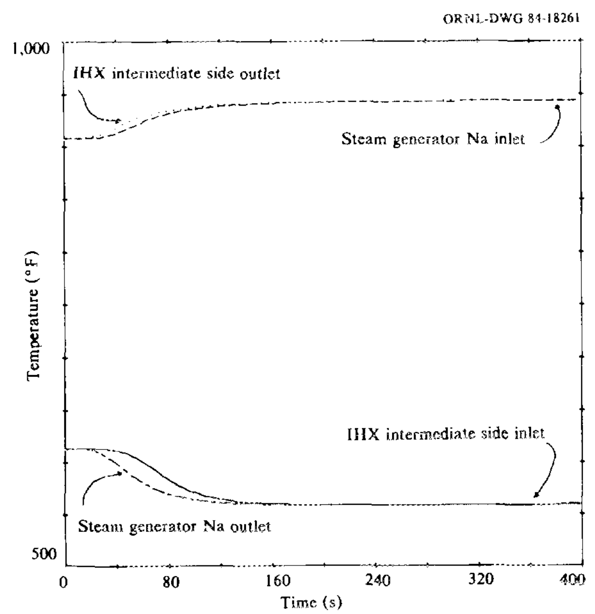

Fig. 4.17. Intermediate sodium temperatures affected loop.

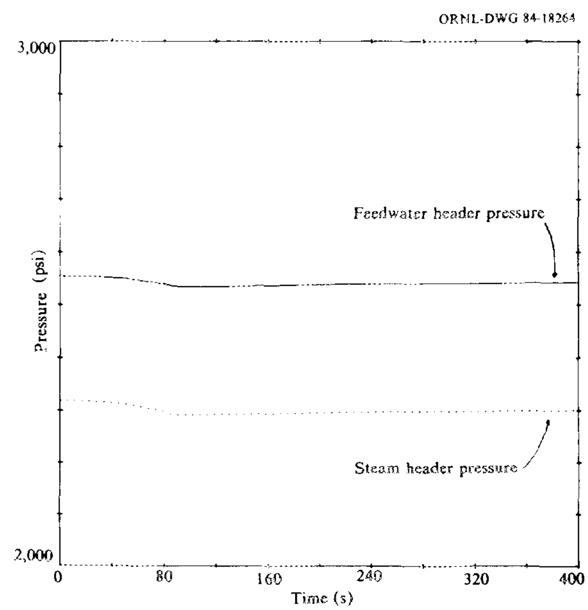

Fig. 4.19. Steam generator pressures.

A feed pump supplies water to the steam generator via the feedwater regulating valves. The steam from the generator passes through the superheater, emerging as superheated dry steam for the turbine supply. Feed flow into the steam generator can be changed both by the feedwater pump speed and by a position adjustment of the feedwater regulating valve. If realistic valve openings are to be maintained, adjustment of the feed valve position alone has little effect on the feed flow because an uncontrolled feed pump acts nearly as a constant flow device. The feed valve positional changes need to be backed up by changes in feed-pump pressure. A backup control is needed to monitor changes in pressure drop across the feed valve and adjust the feed pump to maintain at least a minimum differential pressure across the feed-regulator valve. Constant feed valve differential pressure makes feed flow approximately proportional to feed-valve position.

The output of steam to the turbine, which determines the turbine-generator power output, is controlled by adjusting the turbine inlet control valves. When the power output changes, the feedflow must be changed to match steam flow under transient conditions; the steam pressure greatly influences the operation of the steam generator and turbine. A dynamically compensated pressure error signal (error between the 2200 psig setpoint and actual steam pressure) is used as regulator signals for feedwater flow and turbine power. These regulator signals are superimposed on the respective feedforward supervisory demand signals.

The supervisory controller outlined in this section provides the initial trajectory for power-assent or descent. It does this by pre-establishing operational setpoints in advance of the actual condition of the system. The setpoints are known in advance through off-line simulation analysis. However, these setpoints provide only a coarse adjustment of the system control variables. Trimming of the system is accomplished by minor adjustments of the control variables (e.g., reactor temperature, intermediate loop flow rate, and feedwater flow rate) using both steam outlet temperature and pressure as reference signals.* This controller along with the necessary local loop controls can provide steady-state control of the plant and some degree of control under dynamic conditions; however, improved dynamic response and restraint of the plant parameters (i.e., minimization of parameter excursions under dynamic conditions) is possible by introducing another layer in the hierarchy of control that coordinates the local controllers for minimum error. The coordination layer and combined system of supervisor and coordinator are discussed further below.

*Further details on the supervisory controller outlined in this section are available (Daniel 1984).

4.5 DESCRIPTION OF DISTRIBUTED AND HIERARCHICAL CONTROL OF LARGE-SCALE SYSTEMS

Distributed and hierarchical control systems have evolved over the last few years: (1) as a natural outcome of the need to classify process control functions by process area and the level of control function, (2) because of unreliability of direct digital control (DDC) systems, and (3) because of the availability of microprocessor-based computers for local controllers. This evolution has occurred as processes have become increasingly large and complex, leading to more stringent demands on control system performance. Similar to the management of a large corporation, industrial control systems have acquired the characteristics of distributed and hierarchical organization.

A large-scale system may be described as a complex system composed of a number of constituents or smaller subsystems serving particular functions and governed by interrelated goals and constraints. One of the interactions among subsystems is hierarchical. A subsystem at a given level controls or coordinates the units on the level below it and is, in turn, controlled or coordinated by the unit on the level immediately above it.

A large-scale system can be hierarchically controlled by dividing (decomposing) it into a number of subsystems and then coordinating the resulting subsystems to transform a given integrated system into a multilevel one. A hierarchical control strategy for a large-scale system is shown in Fig. 4.20. The two basic structures in hierarchical (multilevel) systems depend on the model parameters, decision variables, environment, and goals and can be described as follows:

1. *Multiechelon hierarchical structure.* This structure consists of a number of subsystems situated in levels such that each one can coordinate lower-level units and be coordinated by a higher-level one. The distribution of control tasks is horizontal.

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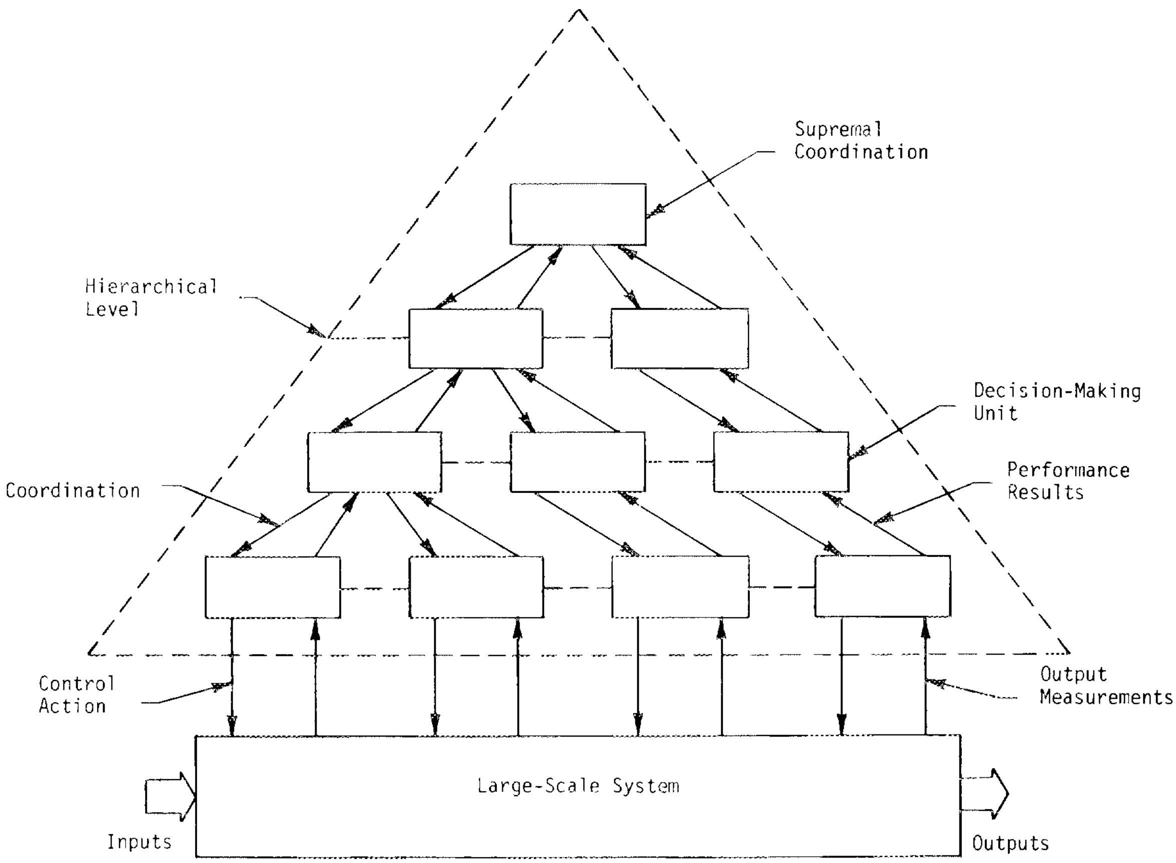

Fig. 4.20. A hierarchial (multilevel) control strategy for a large-scale system.

2. *Multilayer hierarchical structure.* This structure is due to complexities involved in a decision-making process. The control tasks are distributed in a vertical division. For the multilayer structure, regulation (first layer) acts as a direct control action, followed by optimization (calculation of the regulators' optimal control using a decision rule), adaptation (direct adaptation of the control law and model), and self-organization (model selection and control as a function of environmental parameters).

These structures fall within the realm of continuous control. Another important field of control is that of discontinuous control (batch, logical, mode, sequence control, etc.). This, too, has its hierarchy. Electric and mechanical interlocks must be below the process sequence of events control, which in turn is below batch operational directives/supremal coordinator (or supervisor). Some of the concepts of discontinuous control are discussed in Sect. 3.

Figure 4.21 shows a distributed hierarchical system with continuous and discontinuous control.

ORNL-DWG 84-18236

Supremal Coordination		Level 4
Self-organizing and adaptive	Mode, batch and logical control	Level 3
Optimization	Sequence Control	Level 2
Regulation/ Control	Electrical and mechanical interlocks	Level 1
Data Acquisition and Actuation		Level 0
Continuous Control	Discontinous Control	
Large-Scale System (to be controlled)		

Fig. 4.21. Functional and hierarchial distribution of continuous and discontinuous control of a large-scale system.

This distributed and hierarchical structure allows modularization, which increases reliability of the system, improves flexibility for later modification, and facilitates troubleshooting. Also, it is possible that each function can be designed, engineered or programmed, tested, debugged, and documented independently. A possible configuration of a data-acquisition and distributed control is shown in Fig. 4.22.

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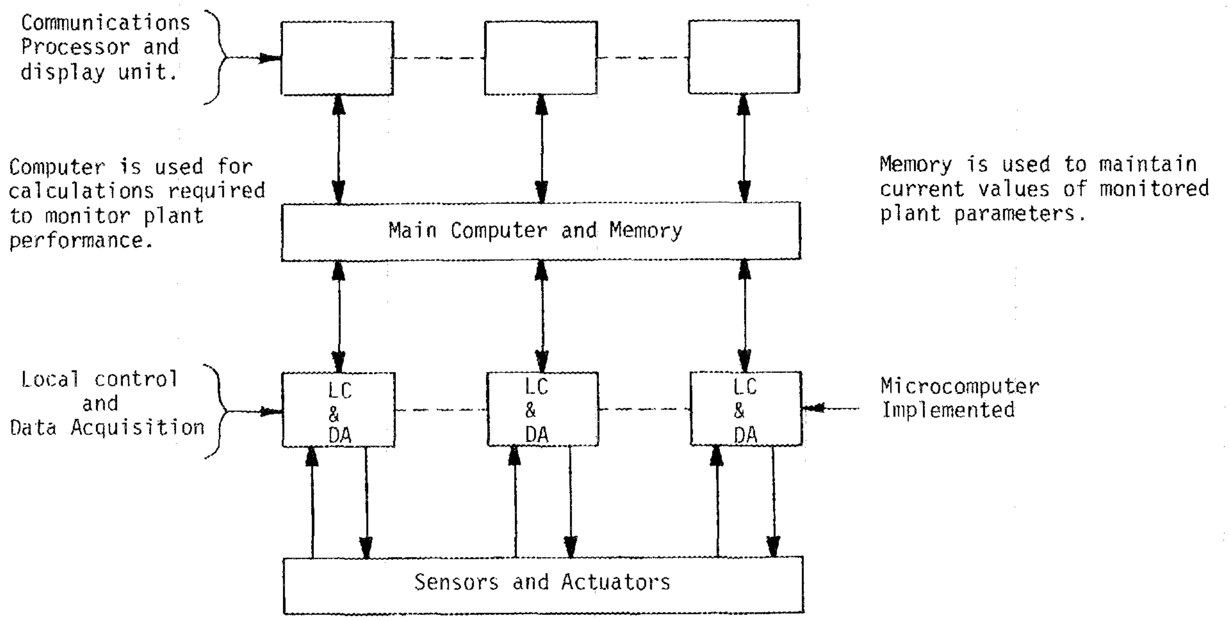


Fig. 4.22. Functional configuration of a distributed control and data acquisition system.

In the context of this report, continuous control implies the use of continuous signals representing physical quantities such as temperature, pressure, and flow. Discontinuous control is defined as a series of monitoring and control functions performed in a predetermined sequence, which may be repeated at prescribed intervals or on demand. This is different from continuous process control, which operates to maintain process variables at or near given trajectory or setpoints as the case may be without direct reference to a sequence of events.

4.6 BRIEF SURVEY OF PREVIOUS OPTIMAL CONTROL DESIGNS FOR NUCLEAR REACTORS

In the past, several optimal control systems have been designed for nuclear power plants. Among them, several studies (Atary and Shah 1972; Bjorlo et al. 1970; Blomsnes et al. 1972; Cummins et al. 1973; Frogner and Grossman 1975; Lipinski and Vacroux 1970; Oguri and Ebizuka 1975) are relevant to the work presented here. In these, a linear dynamic model, a quadratic performance index and a Gaussian stochastic assumption have been used to design a feedback controller.

In the above methods, no hierarchy is used. Hence, the methods are complex in terms of computations involved in the estimation of plant state and implementation of controllers because the problem must be solved globally using all the plant variables. The method used in this study is similar to the ones used in the above references except for the hierarchy. By dividing the nuclear reactor power plant into several subsystems (reactor, intermediate heat exchanger, steam generator, turbine, and feedwater), and using a hierarchical structure, optimal controllers are designed for each subsystem that take into consideration interaction between subsystems. The hierarchy is chosen such that it provides an overall optimal controller for the total plant with greatly reduced computations (i.e., a few multiplications) at higher levels in the hierarchy. At the lower subsystem level, the designing of local optimal controllers is simpler than that of designing the global one because the subsystems are of a lower order than the overall plant order.

The control design currently used in the nuclear industry is based on classical control and is generally implemented by analog circuits. The control system is a collection of single-input, single-output loops with fairly strong interaction between many of the loops, and sometimes with competing control objectives. For a multivariable system, such as a nuclear power plant, a distributed and hierarchical control system seems to offer technical advantages. Local subsystem optimal controllers and sensory data processing can be implemented by microcomputers.

4.7 THE INTERACTION PREDICTION APPROACH FOR DESIGNING DISTRIBUTED AND HIERARCHICAL CONTROL SYSTEMS

The chosen objective is to design a control system for a large-scale nuclear plant with a load-following capability. The basic control approach adopted is to design a regulator control coupled with a feed forward action from the load demand. Then, a distributed and hierarchical control coordinator is designed using an interaction-prediction approach (Findeisen et al. 1980; Jamshidi 1983). This method uses a linear model of the process, which was derived in Sect. 4.3, and a linear quadratic performance criterion (decision rule) to design optimal controllers for the subsystems taking into consideration interaction between subsystems. The interaction prediction method provides an overall optimal control for the total plant with much reduced computations. The linear model described in Sect. 3,

$$\dot{X} = AX + Bu \ , \tag{4.1}$$

is based on the assumption that the feed-forward controller keeps the plant to the desired steady-state program. The matrices A and B are generally dependent on the power level. If A and B are evaluated at a setpoint (operating power level), they are constant matrices. If load following is desired over a broader range, one may have to evaluate the A and B matrices at the middle of the range or at several points along the load range and use those values.

Feed-forward control can speed up plant response, but a regulator control is needed to bring the plant parameters (e.g., steam chest pressure and temperature) to desired values. Thus, a linear feedback optimal controller is designed by minimizing a quadratic performance index of the form

$$J = \frac{1}{2} X^T(T) Q \ X(T) + \frac{1}{2} \int_0^T [X^T Q X + u^T R u] dt \ , \tag{4.2}$$

where T is the terminal time, and Q and R are weighting matrices chosen by the designer from experience or through simulation studies.

The linear feedback controller, designed in such a fashion, will allow the plant to follow the load demand and keep the plant parameters at the desired values.

4.7.1 Method

Consider a large-scale linear interconnected system, described by Eq. (4.1), decomposed into N subsystems, each of which is described by

$$\dot{X}_i(t) = A_i X_i(t) + B_i u_i(t) + C_i Z_i(t) \ ,$$

$$X_i(o) = X_{io}$$

$$i = 1, 2, \cdots N \tag{4.3}$$

where the interaction vector Z_i is

$$Z_i(t) = \sum_{j=1}^{N} L_{ij} X_j \ . \tag{4.4}$$

One can consider that the actuator dynamics are also included in the subsystem model. For LSPB, these subsystems are reactor, intermediate heat exchanger (IHX), steam generator, turbine and feedwater. The optimal control problem at the first level is to find a control $u_j(t)$ which satisfies Eqs. (4.3) and (4.4) while minimizing a quadratic cost function

$$J_i = \frac{1}{2} X_i^T \ (T) \ Q_i X_i(T) + \frac{1}{2} \int_0^T (X_i^T Q_i X_i + u_i^T R_i u_i) dt \ . \tag{4.5}$$

J_i is i^{th} component of J in Eq. (4.2). With the interconnection equation incorporated into a Lagrangian, the Lagrangian becomes

$$L = \sum_{i=1}^{N} \left\{ \frac{1}{2} X_i^T (T) Q_i X_i(T) + \frac{1}{2} \int_0^T \left[X_i^T Q_i X_i + u_i^T R_i u_i + \lambda_i^T \left(Z_i - \sum_{j=1}^{N} L_{ij} X_j \right) + P_i^T(-\dot{X}_i + A_i X_i + B_i u_i + C_i Z_i) \right] dt \right\} \quad (4.6)$$

where P_i is the adjoint vector and λi is the Lagrange multiplier vector. For given $\lambda_i = \lambda_i^*$, $Z_i = Z_i^*$, L in Eq. (4.6) is additively separable, that is

$$L = \sum_{i=1}^{N} L_i = \sum_{i=1}^{N} \left\{ \frac{1}{2} X_i^T(T) Q_i X_i(T) + \frac{1}{2} \int_0^T \left[X_i^T Q_i X_i + u_i^T R_i u_i + \lambda_i^{*T} Z_i - \sum_{j=i}^{N} \lambda_j^{*T} L_{ji} X_i + P_i^T(A_i X_i + B_i u_i + C_i Z_i^* - \dot{X}_i) \right] dt \right\} \quad (4.7)$$

For the purpose of solving the first-level problem, it suffices to assume λ^* and Z_i^* are known. Then, the optimal controller for subsystem i is obtained by Pontriagin's principle

$$u_i = -R_i^{-1} B_i^T P_i(t) \quad (4.8)$$

and

$$\dot{P}_i = -Q_i X_i - A_i^T P_i(t) + \sum_{j=1}^{N} L_{ij} X_j , \quad (4.9)$$

with

$$P_i(T) = Q_i X_i(T) .$$

Let

$$P_i(t) = K_i(t) X_i(t) + g_i(t) , \quad (4.10)$$

$$U_i = -R^{-1} B_i^T [K_i(t) X_i(t) + g_i(t)], \quad (4.11)$$

$$\dot{X}_i = [A_i - S_i K_i(t)] X_i(t) - S_i g_i(t) + C_i Z_i(t) ,$$

$$X_i(o) = X_{io} . \quad (4.12)$$

From the above equations, one can obtain

$$\dot{K}_i(t) = -K_i(t) A_i - A_i^T K_i(t) + K_i(t) S_i K_i(t) - Q_i ,$$

with boundary condition

$$K_i(T) = Q_i , \quad (4.13)$$

which is the matrix Riccati equation, and

$$\dot{g}_i(t) = -[A_i - S_i K_i(t)]^T g_i(t) - K_i(t) C_i Z_i(t) + \sum_{j=1}^{N} L_{ij} \lambda_j(t) , \quad (4.14)$$

$$g_i(T) = 0 ,$$

which is the adjoint equation.

The subsystem optimal controller, u_i, is a function of subsystem state X_i (feedback) and the forcing term $g_i(t)$, that is,

$$u_i = -R_i^{-1} B_i^T K_i(t) X_i(t) - R_i^{-1} B_i^T g_i(t) .$$

The optimal controller derived above can be made a completely closed loop with the procedure given in Appendix D.

The second-level problem is essentially updating the new coordination vector

$$\begin{bmatrix} \lambda_i^T \\ Z_i \end{bmatrix}$$

which can be obtained from Eqs. (4.6) and (4.7),

$$\frac{\partial L}{\partial \lambda_i} = Z_i^* = \sum_{j=1}^{N} L_{ij}X_j$$

$$\frac{\partial L}{\partial Z_i} = \lambda_i^* = -C_iP_i(t)$$

thus, making the coordination rule

$$\begin{bmatrix} \lambda_i^* \\ Z_i^* \end{bmatrix}^{K+1} = \begin{bmatrix} -ci \;\; Pi \\ \sum_{j=1}^{N} L_{ij}X_j \end{bmatrix}^{K} . \qquad (4.15)$$

The technique described is summarized in the next section as a set of procedures that can operate in the software of a control system.

4.7.2 Step-by-Step Procedure

The following step-by-step procedure is suggested for obtaining hierarchical distributed optimal control. Steps 1 and 2 are performed as off-line calculations. The remaining steps (3 through 9) are on-line:

Step 1. Solve N independent matrix Riccati equations, Eq. (4.13) with $K_i(T) = Q_i$ and store $K_i(t)$.

Step 2. For initial λ_i^{*k}, Z_i^{*k}, solve adjoint Eq. (4.14) with $g_i(T) = 0$ and store $g_i(t)$ for all subsystems.

Step 3. Solve state Eq. (4.12) and store $X_i(t)$ for all subsystems.

Step 4. Compute optimal control u_i for each subsystem using Eq. (4.11).

Step 5. Compute $P_i(t)$ using Eq. (4.10).

Step 6. Transmit $X_i(t)$ and $P_i(t)$ to second level.

Step 7. At the second level, update coordination vector $[\lambda_i^*, Z_i^*]^T$ using Eq. (4.15).

Step 8. Repeat the updating of coordination vector several times until the total system interaction error

$$e(t) = \sum_{i=1}^{H} \int_0^T \left(Z_i - \sum_{j=1}^{N} L_{ij}X_j \right)^T \left(Z_i - \sum_{j=1}^{N} L_{ij}X_j \right) dt/\Delta T$$

is sufficiently small. Here Δt is the step size of integration.

Step 9. Transmit updated coordination vector to first level for each iteration so that new optimal control is computed using an updated coordination vector. Figure 4.23 illustrates the interaction prediction method of hierarchical control. Consider that at the second level, the computations involve only a calculation of Eq. (4.15). The lower level does less work because problems of lower mathematical order are solved. The convergence is rapid in the iteration process (five or six iterations).

A large-scale plant model usually includes some variables in X that are not measurable. Furthermore, the measured variables are often corrupted by noise introduced by the sensors. There are bound to be discrepancies between real plant and mathematical models. One is then faced with the problem of obtaining an estimate of state for use in the computation of the optimal feedback controller. Several estimation procedures are available in the literature (Eykhoff 1974; Frogner and Grossman 1975). In the case of distributed and hierarchical control, local filters are used to estimate the subsystem state vector (Findeisen et al. 1980).

4.7.3 Application of Distributed and Hierarchical Control to the Large-Scale Prototype Breeder

A large-scale prototype breeder reactor is described in Sect. 4.2. Mathematical models for a reactor, intermediate heat exchanger, and steam generator are described in Sect. 4.3 and in Appendix C. Other subsystem models have not been developed fully for inclusion in this report. The three subsystem models have helped in developing a hierarchial structure for a large-scale process.

A distributed and hierarchical control structure for LSPB reactor with appropriate signal designations is shown in Fig. 4.24. In this figure, the general structure given in Fig. 4.23 is expanded to include the specific prime plant subsystems of the LSPB. This structure includes a classical supervisory controller described in Sect. 4.4, an optimal coordinator described in Sect. 4.7, and local deci-

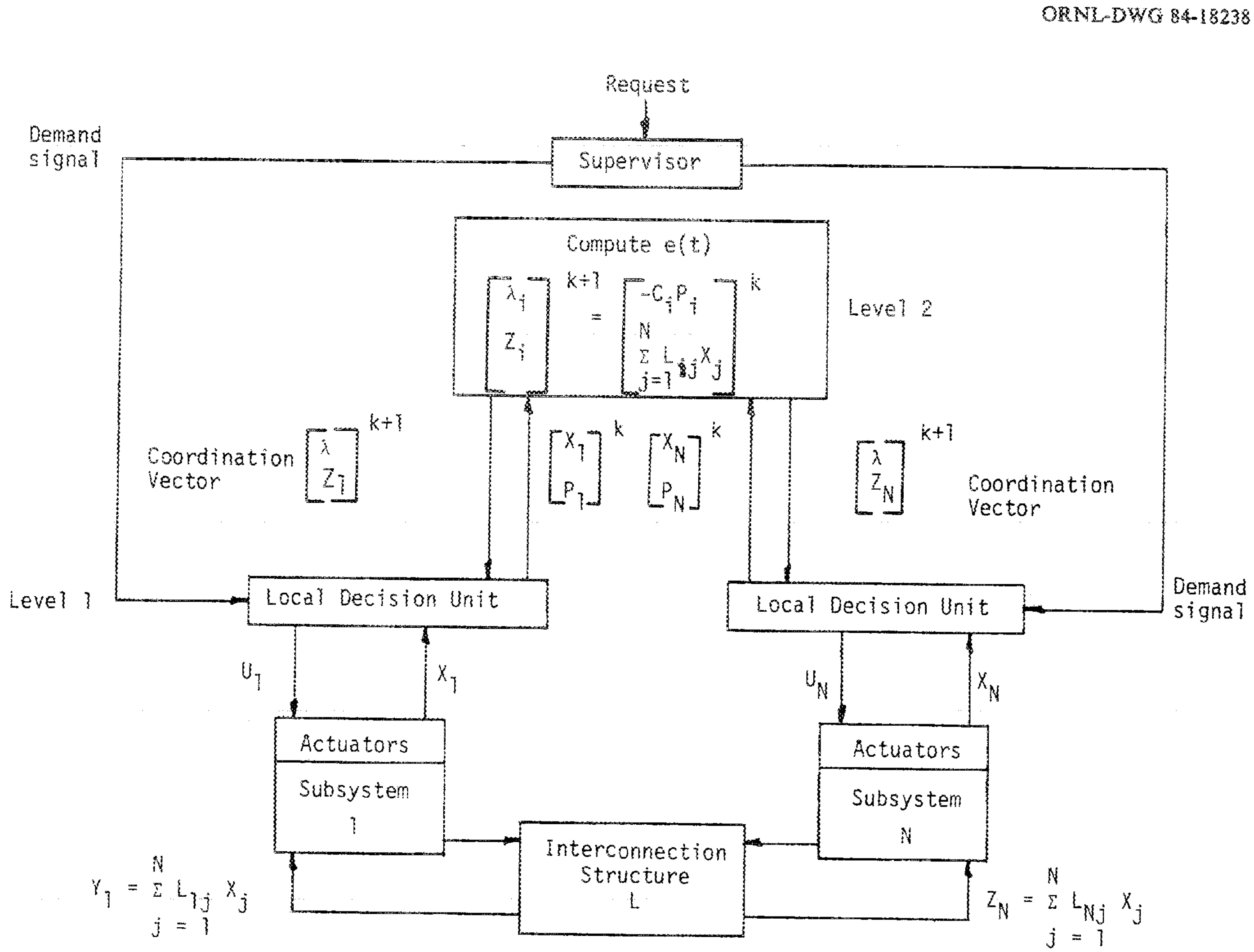
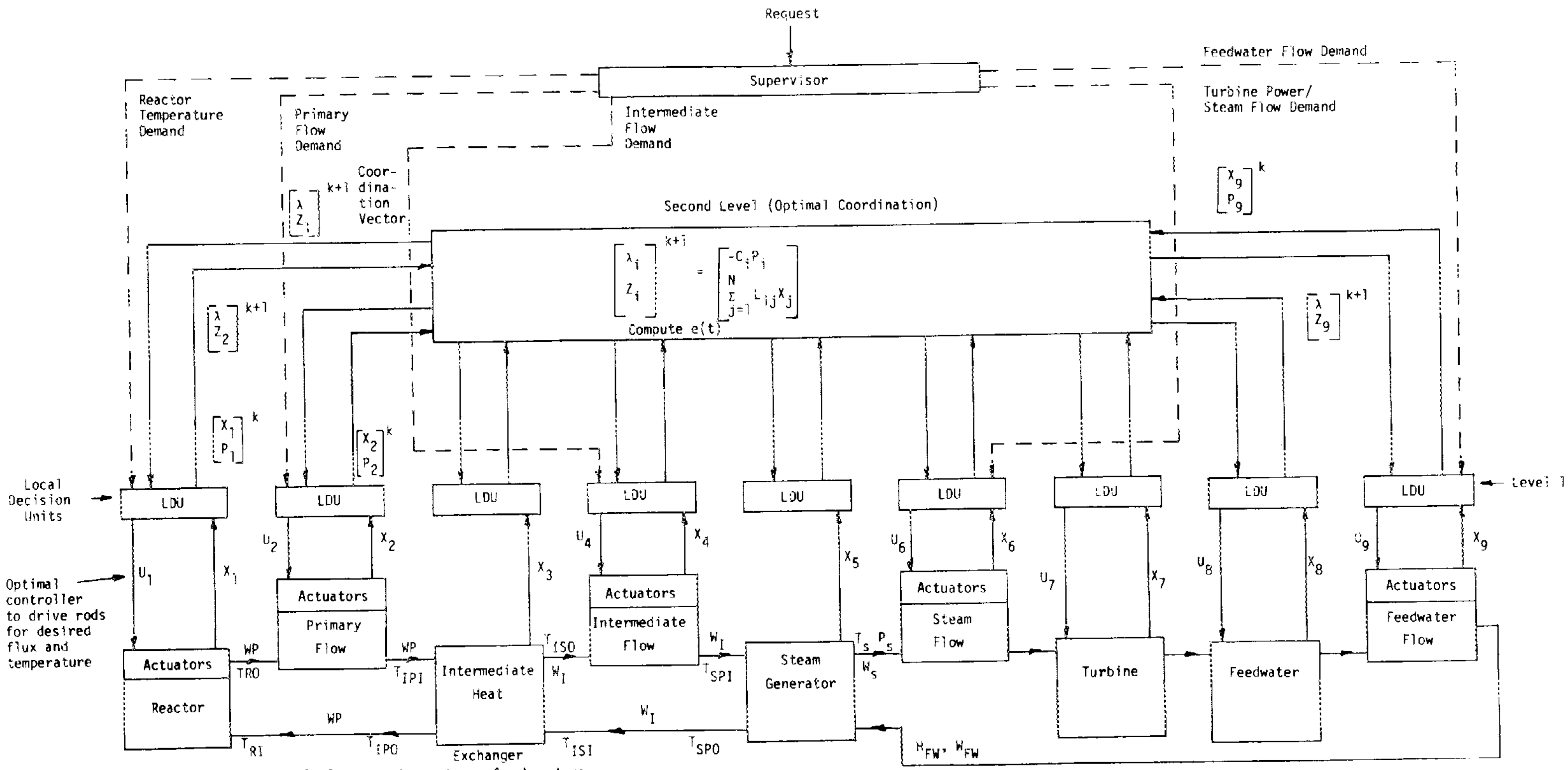


Fig. 4.23. Interaction prediction method hierarchial control.

ORNL-DWG 84-18239



NOTE: X_i = 1, 2, 3, 4, 5, 6, 7, 8, 9 are state vectors of subsystems
U_i = 1, 2, 4, 6, 7, 8, 9 control vectors
Z_i = 1, 2, 3, 4, 5, 6, 7, 8, 9 interaction vectors
λ_i = Largrange multipliers
P_i = Adjoint vectors

Fig. 4.24. A distributed and hierarchial structure for LSPB.

sion units (i.e., local process controllers). Control of the plant can continue with interruption of the optimal coordination function; however, lack of coordination would allow large excursions of the system variables during maneuvering; this would restrict the rates and ranges of key variables.

The supervisor and optimal coordinator constitute the elements of Package 3.0 (supervise prime plant systems for optimal control and coordination) of Fig. 3.4. The local decision units are a part of Package 4.0 (control prime systems) also shown in Fig. 3.4. The request input of the supervisory controller in Fig. 4.24 is the data flow "target parameters for supervisory control system" shown in Fig. 3.4.

4.8 SUMMARY AND RECOMMENDATIONS FOR FURTHER WORK

The focus of the control system function and its structure developed in this section is on improved dynamic performance under normal (or homeostatic as defined in Sect. 2) conditions. The function of the feed-forward supervisory controller and optimal coordinator is to control the minimum error and peak excursion of the subsystem variables. One of the features of the interaction-prediction scheme as it is applied in the report is the minimization of on-line calculations. However, unknown disturbances have not been incorporated explicitly in the approach taken.

To date, the majority of work on the control of electric power generating plants has addressed improved dynamic performance of the normal operational mode. Two approaches that have been considered are based either on linearized state models or linear input-output models. Both models have advantages. This research investigated the state-model approach, although the design can proceed with either. This work is an attempt to break new ground in advanced control system design and should be considered a basis for further development, not as a final solution.

Some general comments on the control issues faced in electric generating plants follow (Broadwater, personal communication, 1984). The hierarchical distributed approach taken addresses only some of these issues. Those issues not addressed are certainly open for further development.

1. A highly nonlinear problem exists in incorporating time-varying parameters, time delays that are a function of load, and other constraints. Thus a control system based on linear models and simple mathematical performance (cost) functions may be either difficult to design, very restricted in operation, or altogether insufficient to the task of controlling the plant. Therefore a tracking constraint monitor is needed.

2. Steady-state feed forward must be incorporated into the design. Dynamic feed forward, which facilitates smooth transititions from one steady state to another, should be included also to improve tolerance to known disturbances. *Known disturbances* should be addressed in the feed-forward portion of the design.

3. Feedback regulation should be used to modify closed-loop dynamics; however, good stability margins should be maintained. If the desired dynamics cannot be obtained with sufficient stability margins when feedback is used, then dynamic feed forward should be used to modify the dynamics. *Unknown disturbances* should be addressed in the feedback portion of the design.

4. Provisions for field tuning of the control system should be provided.

Other control system approaches and structures may offer advantages in coping with disturbances. These approaches may be integrated in various ways with the interaction-prediction approach described here to better meet the control system goals of achieving specific plant performance and availability. Such an approach is possible by extending the ideas developed with state variable linear analysis (Johnson 1976). One extention employs a nonlinear observer system that estimates unknown disturbances entering the plant (Broadwater 1984; Broadwater 1983). Thus, total variable values, not incremental variable values, are used for control.

For all modes of operation of the plant, the nonlinear observer is tuned to track the plant. If such tuning can be accomplished, the steady-state nonlinear model along with known disturbance measurements and unknown disturbance estimates may be used to control the plant for all modes of operation.

A linear quadratic-regulator design with full state feedback or with only output feedback may be used to modify and tune the closed-loop systems dynamics. The robustness of the design can be tested using singular value theory (Zektomaki et al. 1981). To ensure stability of the plant response, the regulator feedback may be disconnected or an entirely different regulator may be enabled during specific contingency modes.

Understanding and effectively operating the observer system, which estimates unknown disturbances, is necessary for applying the state-model approach. The control engineer must understand the process and be able to translate that understanding into a functional and implementable nonlinear observer system.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY OF WORK

This report addresses the problem of designing automatic control systems for large-scale processes such as liquid metal reactor power plants. The scope is limited to the development of a perspective and stating a general philosophy. The goal is to lay the groundwork for the design of integrated, intelligent, and flexible automatic control systems. To provide a good foundation for future design of complex control systems, the structure and function of automated control software are also developed in the text.

Two control topics are emphasized:

1. Design of an hierarchical optimal controller for the LSPB using the interaction prediction approach as an example of continuous control
2. An illustration of the steps involved in bringing LSPB from cold shutdown to 15% power level using structured analysis techniques as an example of discontinuous control.

For the LSPB and other plants in various stages of concept and design, increased automatic action and improved parameter behavior can be accomplished by the approach described. Design errors that result from poor communication between control engineering and software engineering also can be decreased by the approach. Classical and modern control methods have been combined with structured software analysis methods to form a framework for complete system design.

5.2 INTERPRETATION OF RESULTS

The methods presented are highly applicable to other large-scale reactor systems such as advanced LWR and gas-cooled reactors. These methods are also useful when designing systems with a lesser degree of automation than those proposed in the text. In such cases, the methods are useful for integrating human subsystems into the overall plant.

The diagramming techniques used in Sect. 3 are simultaneously aids to control design, instruments for documentation and communication, and the basic input data needed for software design. The multiple uses of the diagramming techniques makes them especially useful. The system model can be further expanded by including models of stored data, a task which was beyond the scope of this report.

The continuous-variable supervisory control system described in Sect. 4 builds on existing classical design to add the capability for optimal control. Thus, local and global minimization of extraneous variation in key parameters is possible during transient conditions.

Some of the methods and techniques described are directly usable; others are developmental. Much of the control system described can be implemented by existing microprocessor technology. However, certain aspects of the high-level, decision-making capabilities of the automated control system, especially for degraded operation, are at the limits of current software capabilities. This not withstanding, an improvement in control system design would result from the implementation of automated control with limited maneuverability in the event of equipment degradation. A plant controlled by a system of the type described in this report should be maneuverable so as to follow power load variation to a greater degree than presently controlled plants.

5.3 RECOMMENDATIONS FOR APPLICATION

The authors believe that the techniques given for discontinuous and continuous control and the integration of both forms of control can be used immediately to increase the automatic responses of LSPB and other plant types and improve their dynamic behavior. The multiphased approach, described in Sect. 2.4, can be realistically applied by currently trained control engineering teams. This approach allows the progressive layering of intelligence and complex control actions upon previously designed control structures.

Following are applications of these techniques that can be implemented now.

1. Develop the continuous hierarchical control system described in Sect. 4 to identify parameters of the LSPB, to consider variations in plant parameters, and to consider disturbances. Then, simulate the plant and hierarchical control system to determine the extent of improvement over other conventional designs.

2. Develop the discontinuous automated control system described in Sect. 3 to form a complete Phase 1 system for LSPB (which includes the hierarchical control system in Sect. 4). Then, simulate the plant with the automated and hierarchical control system to test the plant's response.

3. Complete the next phases of control system design as described in Sect. 2. To implement high-level decision making, analysts will most likely appeal to artificial intelligence for their perspectives and methods. Much simulation of the plant and its automated control system will follow these phases of system design.

4. Develop automated tools that support the methods and techniques described in this report to increase the efficiency of structured design. Currently, no tool is available that supports both the data transform modeling and the state transition modeling and integrates the two of them into the package representation. Further work is needed to create such a tool and design environment. A study has been completed that evaluates the tools available for design of modern continuous control systems (Birdwell 1984). The study lays excellent groundwork for design of an environment to support the design of the continuous aspect of control systems. The existence of structured software analysis tools, continuous control design and analysis tools, a sufficient data base, and a data-base management system would greatly increase the productivity of control system design efforts and the reliability of a control system resulting from such efforts.

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GLOSSARY

Terms in italics are defined elsewhere in the Glossary.

Abnormal—unusual deviation from normal or nominal behavior or characteristics.

Adjoint equation—one of the two canonical equations used in applying *Pontriagin's maximum principle* to obtain *optimal control.* See *state equation.*

Afferent data—data flowing from a *subordinate* module to a *superordinate module within a hierarchical* structure. See also *efferent data* and *transferrent data.*

Alarm—a single bit of information generated as a result of a parameter or variable crossing a pre-established threshold.

Allocation—the process of specifying functions to different systems, subsystems, and equipment.

Analog—a physical variable that remains similar to another variable insofar as the proportional relationships are the same over some specified range; for example, a temperature may be represented by a voltage that is its analog. Contrasted with *digital.*

Anticipatory trip—an immediate shutdown of a *process* or device due to potential loss of *stability*, *viability*, or *integrity*, usually determined by measurement of parameters not directly related to the *process* or device being shut down.

Automation—the operation of a machine, device, or system without direct human intervention. Automation can be applied to several areas: regulating a process, restructuring equipment interconnections, monitoring parameters, and detecting and diagnosing problems.

Availability—the ratio of actual operation of a power plant to theoretically possible operation.

Base-loaded—refers to a plant having fixed power output not responsive to variations in grid load. Contrasted with *load following.*

Bottom-up—proceeding by aggregating specific components into larger general systematic structure. Contrasted with *top-down.*

Cascade—elements, devices, or equipment that are concatenated so that the output of one feeds directly into the input of another.

Child diagram—the next level of *magnification* of a *package* of *data flow* and *state transition diagrams.* The next higher level is the *parent.*

Classical control theory—control techniques based mainly on frequency-response analysis which lead to single-input, single-output implementations of *proportional-integral-derivative* (PID) *control systems.* Compare with *modern control theory.*

Command—a directive to change *mode* or *state* communicated to a *subordinate* module. Compare with *demand.*

Context diagram—a diagram depicting a model of the *control system's* environment in which communications across the boundary between the control system and its environment are clearly shown.

Continuous control system—a *control system* in which the controlled quantity is measured continuously and corrections are a continuous function of the deviation from reference value.

Controller—a device that executes control action for a subsystem. A *control system* may be composed of a hierarchy or network of individual controllers.

Control package—a program to implement a control algorithm constructed of both *data flow* and *state transition diagrams* "packaged" together.

Control system—a general term that refers to a system in which one or more outputs are forced to change in a desired manner as time progresses.

Coordination control—the coordination of local *controller* actions by a higher-level action in the *hierarchical* structure.

Corruption—noise or disturbances that interfere with or obscure the true signal.

Data flow diagram—a diagram depicting a model of the flow and transformation of data within a system. See also *state transition diagram*, *entity relationship diagram*, and *package diagram*.

Data validation—the process of determining the correctness of data by comparison with other data from the system and the application of rules.

Decomposition—the partitioning of a composite system into its subsystems.

Degraded conditions—a *state* within a system in which the normal or nominal state is reduced in quality or distorted, often associated with equipment failure.

Degraded region—a region in the space of a system's *state variables* that surrounds the homeostatic region in which system performance is considered degraded and the control strategy must change to prevent further degradation. Three forms of degradation are possible: *stability*, *viability*, and *integrity*. See also *homeostatic region* and *uncontrollable region*.

Demand—setpoints or other continuous references communicated to a *subordinate* module. Compare with *command*.

Derivative control—a type of control in which the control signal changes at a rate that depends on the speed of increase in the system error.

Destination state—the final *state* that is desired at the completion of a *mode* change.

Digital—pertaining to data in the form of digits or discrete values. Contrasted with *analog*.

Discontinuous control system—a *control system* in which the corrections taken are discrete actions that may be a function of the controlled *process* or external timing, sequence, or logic. Compare with *continuous control system*.

Distributed control—a scheme for decentralization of the control algorithms and decision making that is suitable for multiple and distributed computing modules.

Dynamic compensation—the counterbalancing of a system's natural dynamic behavior by *control system* actions to obtain the desired plant dynamic behavior.

Efferent data—data flowing from a *superordinate* module to a *subordinate* module within a *hierarchical* structure. See also *afferent data* and *transferrent data*.

Entity relationship diagram—a diagram depicting a model of the stored data within a system and their interconnections. See also *data flow diagram* and *state transition diagram*.

Fault tolerance—the ability of a system to withstand a wide range of disturbances, specifically disturbances arising from component failure and external events. Compare with *robustness*.

Feedback control—control in which a portion of an output signal is redirected as an input signal so that the value of the controlled output signal can be held closer to a desired reference value.

Feed-forward control—control in which changes detected at the process input result in generation of an anticipating correction signal that is applied before the process output is affected.

Flexibility—the capability to adapt to change. Here it refers to the case of implementing future modification to the *control system* as replacement and other upgrades are required.

Hierarchical system—a collection of subsystems configured as a *multilevel* or *multilayer structure*. See also *multilevel hierarchy* and *multilayer hierarchy*.

High-order model—a detailed model described by high-order differential or difference equations. Contrasted with *low-order model*.

Homeostatic region—a region in the space of a system's *state variables* in which the system is considered *robust* so that given a disturbance, which causes a deviation bounded within the homeostatic region, the *control system* returns the system to the normal value. See also *degraded region* and *uncontrollable region*.

Initial conditions—the conditions that exist in the *process* prior to the beginning of operation of the *process*.

Initial state—the natural *state* that exists prior to the beginning of operation of a system or at the beginning of a *mode* change. Compare with *destination state*.

Input-output model—a model in which a physical system is described by its inputs and outputs.

Integral control—a type of control in which the control signal changes at a rate proportional to the integral of the error signal.

Integrity crisis—within the *degraded region*, a case in which the controlled system's integrity is violated; thus, equipment damage is imminent. No operation is possible. See also *stability crisis* and *viability crisis*.

Interaction-prediction method—a method used in hierarchical *optimal control* which avoids second-level gradient type iterations.

Large-scale system—in general, refers to a complex collection of smaller subsystems each of which serve particular functions and are governed by interrelated goals and constraints.

Linear system—a system in which the inputs and outputs are related by linear functions. Compare with *nonlinear system*.

Load following—proportional response of generated output of a power plant to grid load. Contrasted with *base-loaded*.

Logical model—an implementation-free model of the functionality of the *control system* based on data flow and transformation, dynamic behavior, and stored data. Compare with *physical model*.

Low-order model—a model in which a system is approximated by low-order differential or difference equations. Contrasted with *high-order model*.

Magnification (zooming)—reversal of the information- hiding process by looking within a *package diagram* to find its constituent packages and interconnections. The package can be magnified to the level of the primitive *data flow* and *state transition diagrams* which are the bottom-most level.

Maneuverability—the capability of accomplishing a wide range of potential changes to manipulate the system into a desired position or to move toward a predetermined goal.

Mathematical model—a model in which a system is described in terms of mathematical equations.

Mode—one of several alternative conditions or methods of operation of a system or component.

Modern control theory—control techniques based on frequency- and time-response analysis and that use matrix notation which lead to multiple-input, multiple-output implementations of *optimal* and adaptive control. Compare with *classical control theory*.

Multilayer hierarchy—a structure originating out of the complexities involved in decision-making processes in which layers of control actions are constructed. Each next higher layer controls aspects of the system that correspond to longer time horizons of the system.

Multilevel hierarchy—a structure that consists of a number of subsystems situated in levels such that each one can coordinate lower-level units (*subordinate*) and be coordinated by a higher-level one (*superordinate)*.

Network graphics tools—Diagrammatic tools that provide a visually oriented method for the development and analysis of complex systems. These tools include *data flow diagram*, *state transition diagram*, *entity relationship diagram*, and *package diagram*.

Nonlinear system—a system in which the inputs and outputs are related by functions of which some are nonlinear. Compare with *linear system*.

Off-line system—a computer system that is operated in batch mode. Contrasted with *on-line system*.

On-line system—a computer system operating continuously in real time in step with the process. Contrasted with *off-line system*.

Optimal control—the generation of a control signal that optimizes the chosen performance index for a system.

Package diagram—a diagram containing both *data flow diagramming* and *state transition diagramming*. See also *control package*.

Parameter identification—the determination of actual system parameters by direct or indirect measurement techniques; may be needed as systems age.

Parent diagram—the next higher level of data flow and *state transition diagram*. The next lower level is the *child*.

Path—a course to follow in a system's state space.

Pathological coupling—an automatic data processing term that refers to a connection between functional modules that bypasses the "normal" hierarchical data flows. Such coupling allows one module to reach inside another and access an entity that would otherwise be hidden within its module.

Physical model—a model of the implementation environment including the data processors, software architectures, and coding architectures. Compare with *logical model.*

Pontriagin's maximum principle—a theorem giving a necessary condition for the solution of *optimal control* problems.

Prime system—a plant system that contributes directly to the production of a plant's principal product. See also *support system* and *utility system.*

Process—a system or series of continuous or regularly occurring actions taking place in a predetermined or planned manner; for example, the heat-generating process in a nuclear reactor.

Process configuring—the restructuring of the flow of material or data within a *process* or reordering of the operation of a *process* as a result of changes in the objectives and functions of the overall system.

Process control—the control of a real-time physical system by the manipulation of conditions to bring about a desired change on the output characteristics of the system.

Process diagnosing—the detection and anticipation of anomalies, identification of their cause, prediction of their propagation and consequences, and determination of the proper response with respect to the mission of the overall system.

Process monitoring—the measurement and transfer of process parameters and variables.

Proportional control—a type of control in which the amount of corrective action is proportional to the amount of error, as in a *controller* in which an error signal (the difference between measured output and reference input) is amplified by a constant gain to form an output.

Quadratic cost function—another term for *quadratic performance index.*

Quadratic performance index—a cost function which is an integral of the weighted sum of the squares of the system's response and the input to the system. The cost function is minimized to obtain an *optimal control* input to the system.

Real-time system—a system in which the physical time constants are short enough to require reaction to events as they are occurring. The designation of real time may depend to some extent on the capability of the implementing technology.

Regulator control—refers to continuous *feedback control* of a *process.*

Riccati equation—a matrix differential (or algebraic) equation the solution of which leads to the calculation of *optimal control.*

Robust controller—a *controller* in which satisfactory regulation or tracking occurs in spite of arbitrarily large variations in plant parameters.

Robustness—the ability of a system to withstand large, normally unstructured parameter changes without serious degradation in performance. Compare with *fault tolerance.*

Security defects—losses in redundancy of equipment.

Stability crisis—within the *degraded region,* a case in which the controlled system is exhibiting unstable behavior. See also *integrity crisis* and *viability crisis.*

State—the total condition of a system. The term state can refer to the collective value of a system's measured variables or its *mode* of operation including the condition of the equipment that constitutes the system.

State equation—a vector differential equation relating the *state* of the system and the input to the system. One of two canonical equations used in applying *Pontriagin's maximum principle* to obtain *optimal control.* See *adjoint equation.*

State model—a model in which a physical system is represented by *state variables.*

State transition—a change in the *state* of a system over time; a discrete change in the *mode* of a system.

State transition diagram—a diagram depicting a model of the dynamics of a *control system* in terms of the *modes* that the system exhibits when the need to change behavior is recognized. See also *data flow diagram*, *entity relationship diagram*, and *package diagram*.

State variables—one of a minimum set of numbers which contain enough information about a system's history to enable computation of its future behavior.

Status—the *state* of a system at a given instant.

Steady-state program—the overall relationship of a subsystem's setpoints (e.g., temperature and pressure) to the system's output (e.g., thermal power of reactor) to achieve the equilibrated condition.

Structural defects—equipment faults or faults in the interconnection of equipment.

Subordinate—referring to a mode or module that responds to command (*efferent*) *data* from a higher-level one relative to it within a hierarchical structure.

Superordinate—referring to a mode or module that generates command (*efferent*) *data* for lower-level ones relative to it within a hierarchical structure.

Supervisory control—generally, control in which individual *controllers* are interconnected in a hierarchy that resembles the organization of a business. In some instances, supervisory control refers to the *superordinate* function of *feed-forward control* for subsystems under its scope of control.

Support system—a plant system that contributes necessary functions and services to the *prime systems* of the plant. See also *prime system* and *utility system*.

Target state—a virtual point within the *homeostatic region* that is the current desired operating point for the system.

Termination—systems external to the *control system* represented in a *context diagram*.

Top-down—proceeding by breaking large general aspects of a system into smaller, more detailed constituents. Contrasted with *bottom-up*.

Transferrent data—data flowing laterally at the same level within a hierarchical structure usually in the form of inhibiting or permissive signals. See also *afferent data* and *efferent data*.

Uncontrollable region—a region in the space of a system's *state variables* that surrounds the *degraded region*, the entry into which is an indication that the control strategy or means of its implementation were ineffective against the disturbance or failure. The system has become uncontrollable. See also *homeostatic region* and *degraded region*.

Utility system—a form of *support system* that supplies bulk materials, energy, or data to the *support* and *prime systems* of the plant. See also *prime system* and *support system*.

Viability crisis—within the *degraded region*, a case in which the controlled system has no stable state, and thus normal continued operation is impossible. See also *stability crisis* and *integrity crisis*.

Appendix A

STRUCTURED SYSTEM MODELING TOOLS

A.1 MODELING TRANSFORMATIONS

ORNL-DWG 84-18240

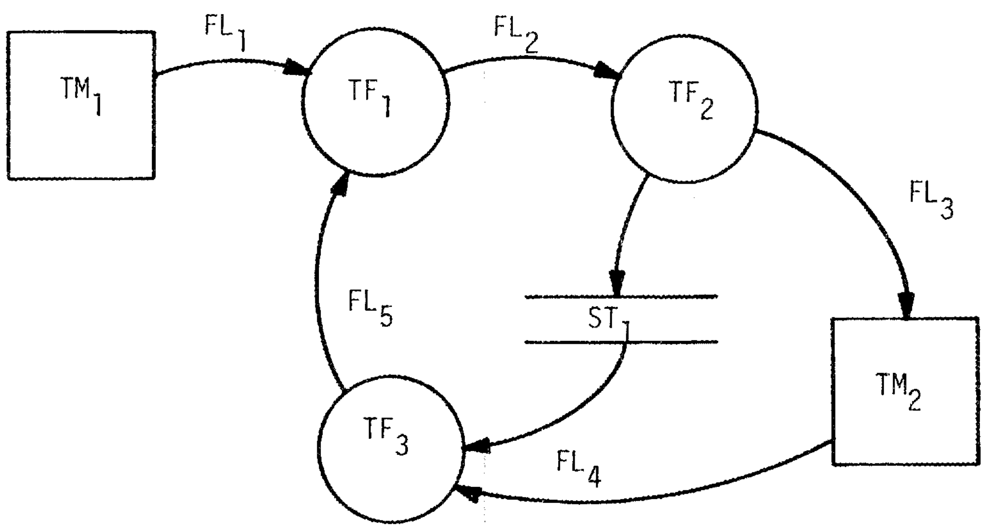


Fig. A.1. Data flow diagram.

Data Flow (FL)	A pipeline through which streams or packets of known composition flow.
Transformation (TF)	Changes incoming flows to outgoing flows.
Data Store (ST)	Retains (or delays the flow of) data for later use by the transformations.
Termination (TM)	Marks the edge of the model (a system outside of the system under study).

A.2 MODELING DYNAMICS

ORNL-DWG 84-18241

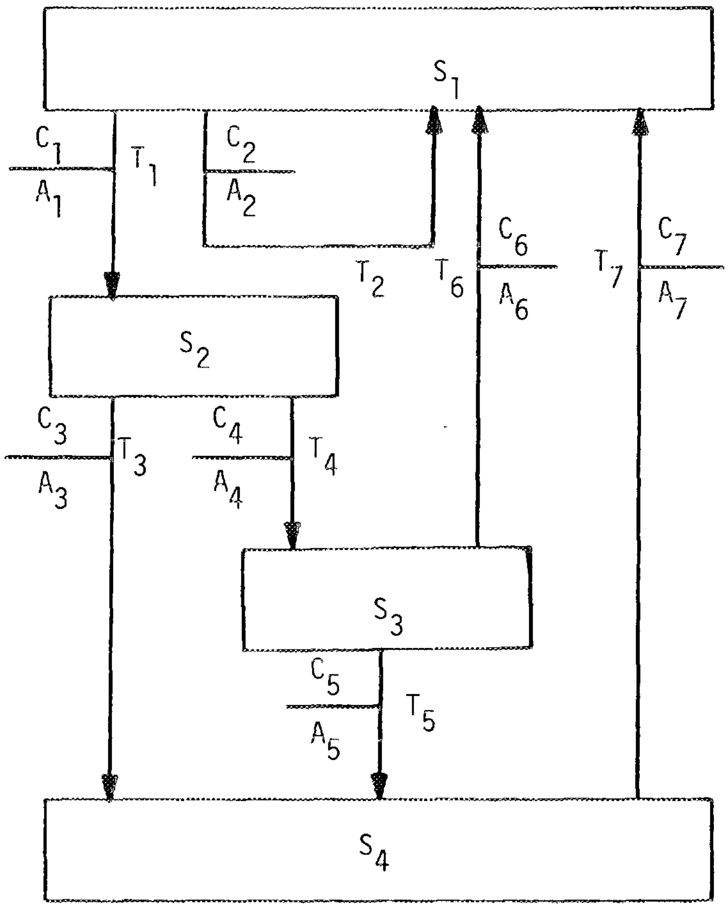


Fig. A.2. State transition diagram.

State (S) — A mode of behavior of the system that has a unique combination of conditions and destination states. The state is passive because the control system is waiting for conditions to occur.

Transition (T) — The movement of the system from one state to another.

Condition (C) — Cause for the system to move from one state to another. Conditions may be generated internally or externally to the system or by time period.

Action (A) — Carried out by the system as it moves from one state to another. An action can enable/disable a transformation, trigger a "one-shot" transformation, signal a specific condition, set a timer, or issue a control signal.

Appendix B

DETAILS OF TOP-LEVEL PACKAGES

ORNL-DWG 84-18242

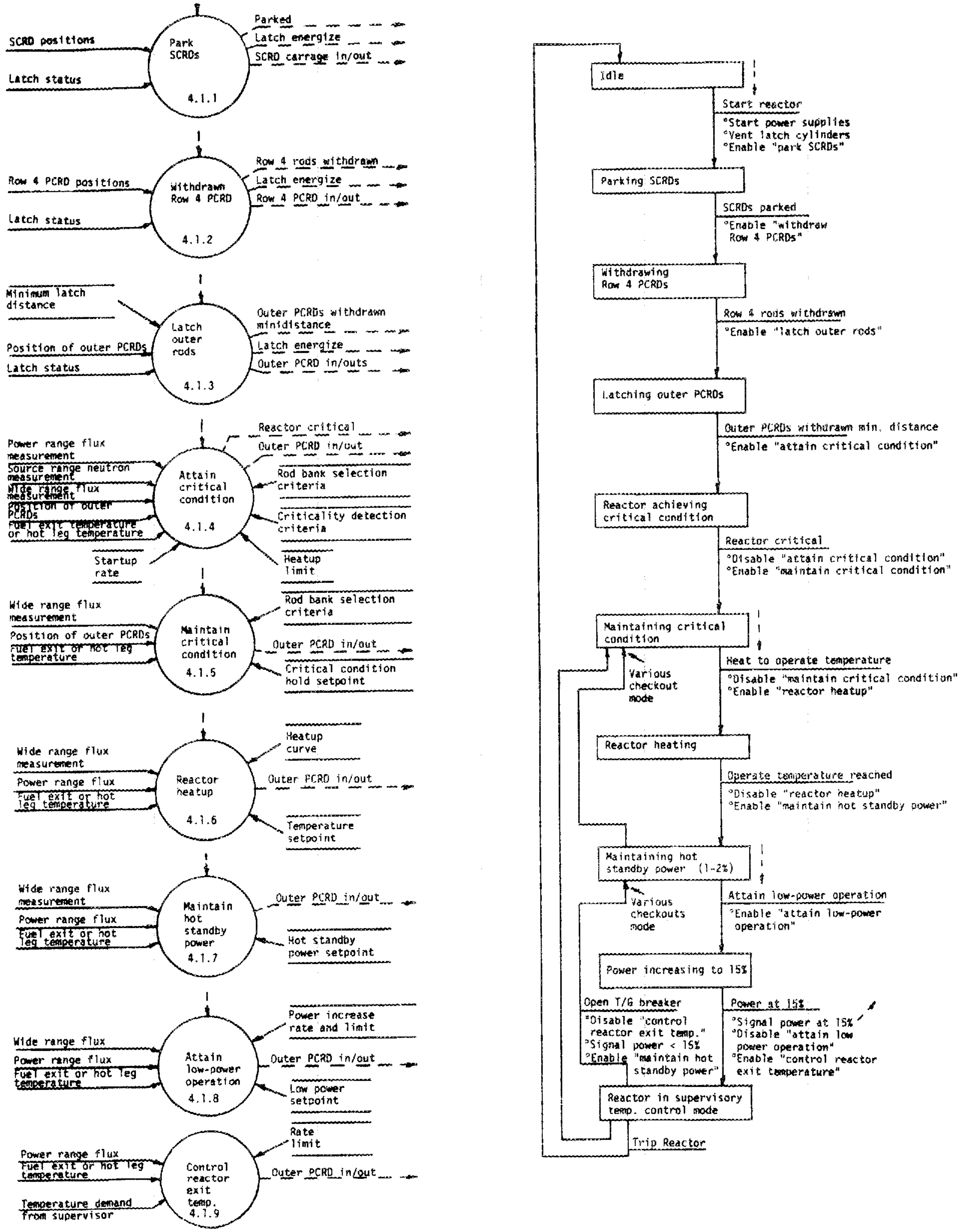


Fig. B.1. Control reactor control rod system (Package 4.0).

ORNL-DWG 84-18243

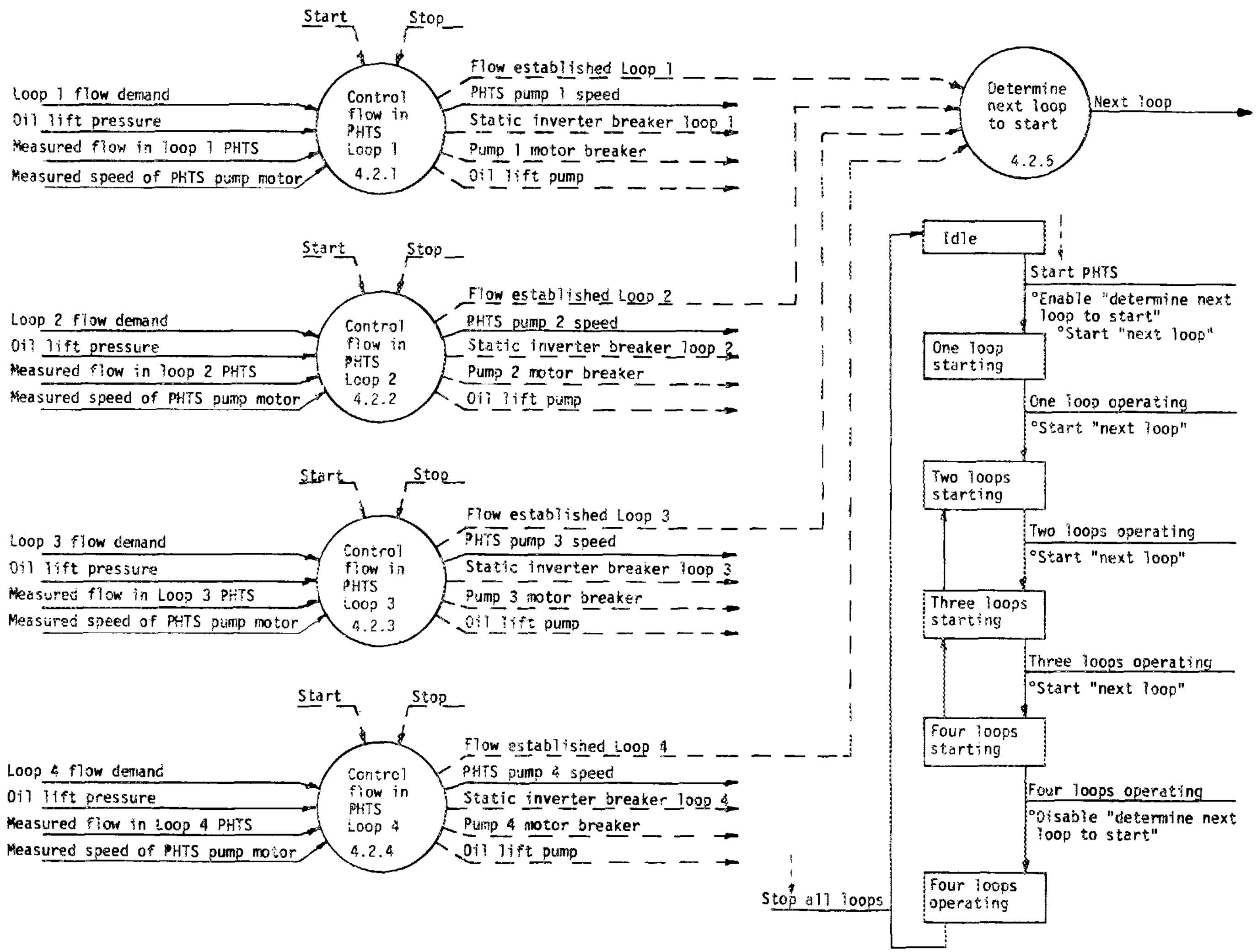


Fig. B.2. Control PHTS loops (Package 4.0).

ORNL-DWG 84-18244

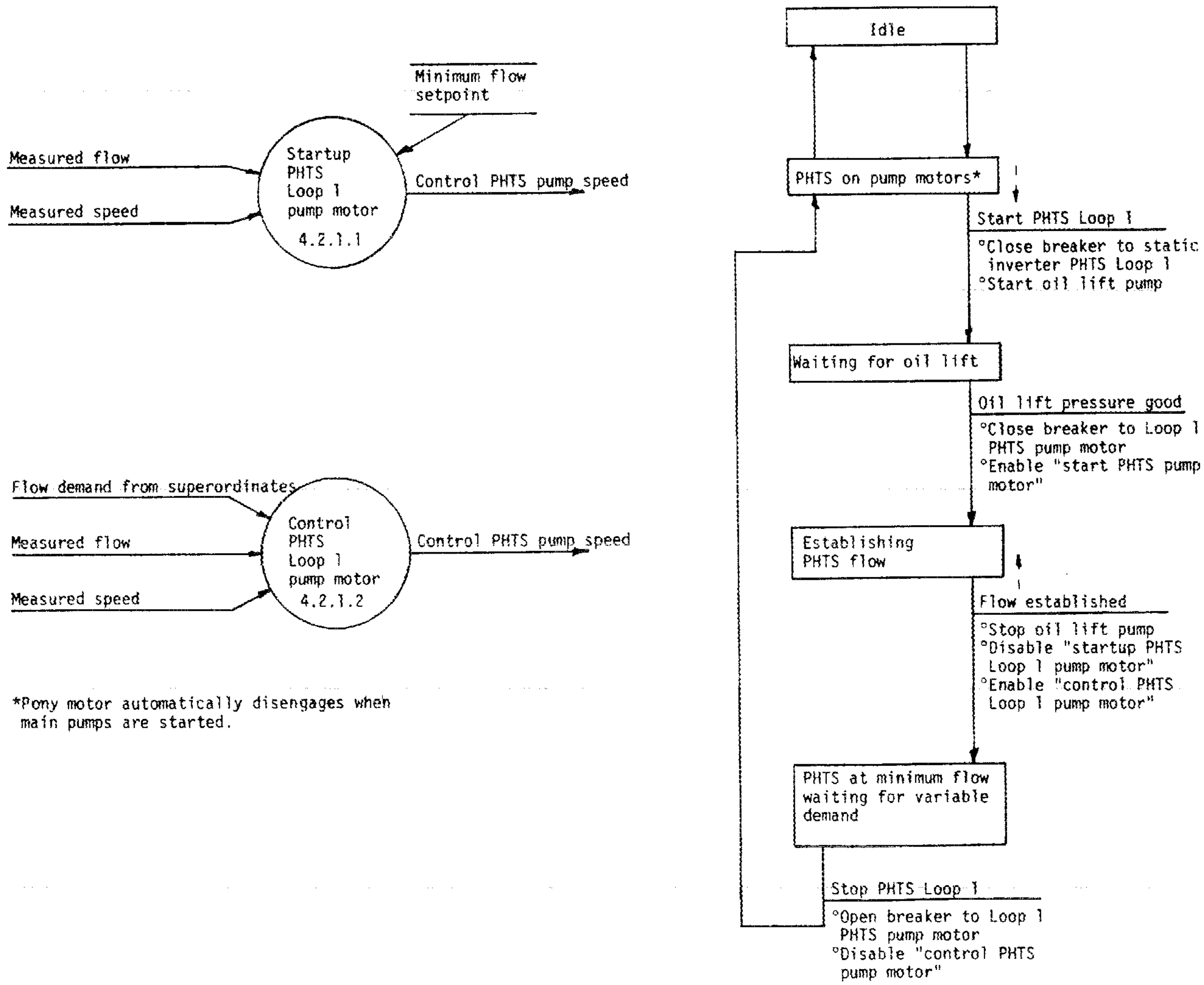


Fig. B.3. Control flow in PHTS loop 1 (Package 4.0).

ORNL-DWG 84-18245

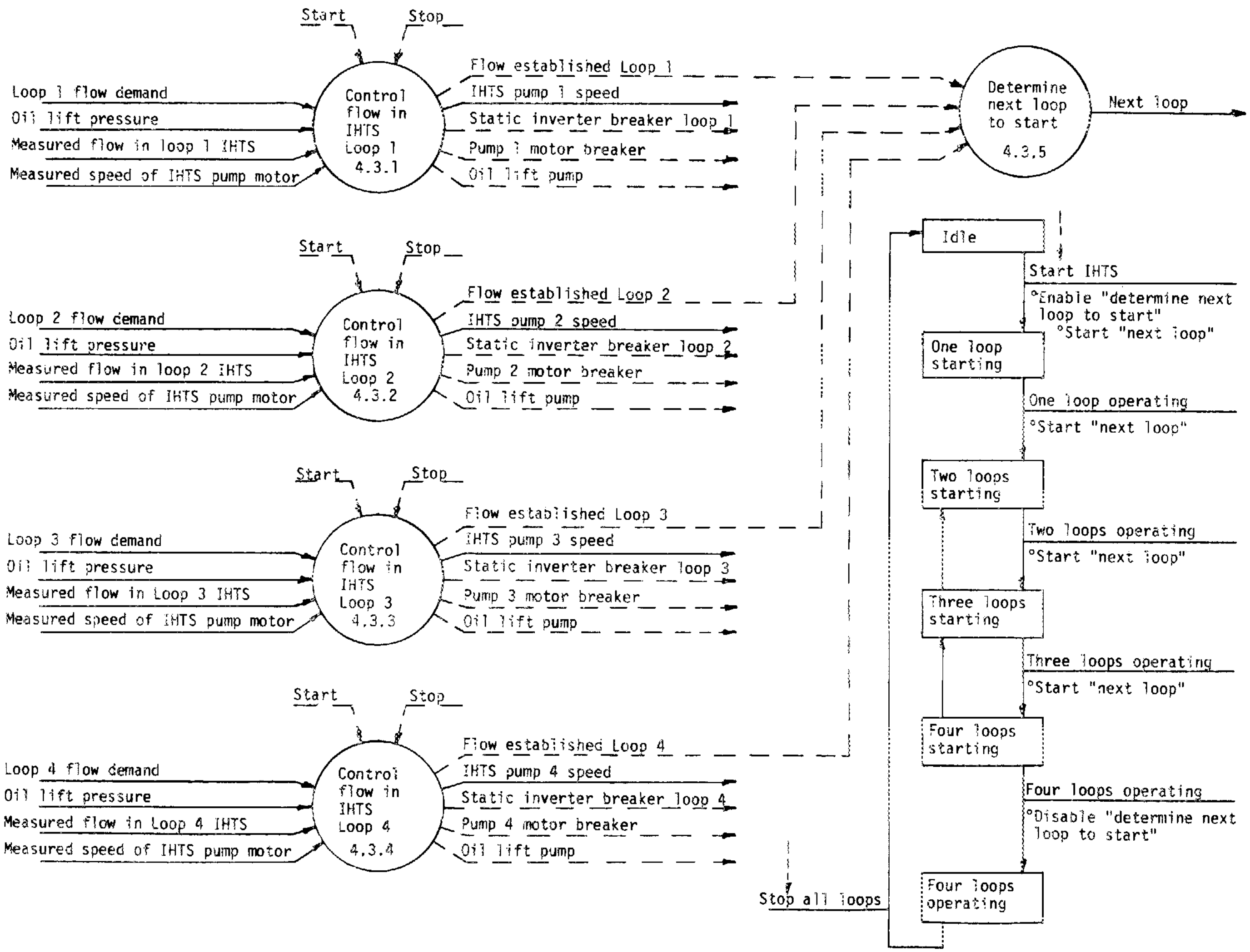


Fig. B.4. Control IHTS loops (Package 4.0).

ORNL-DWG 84-18246

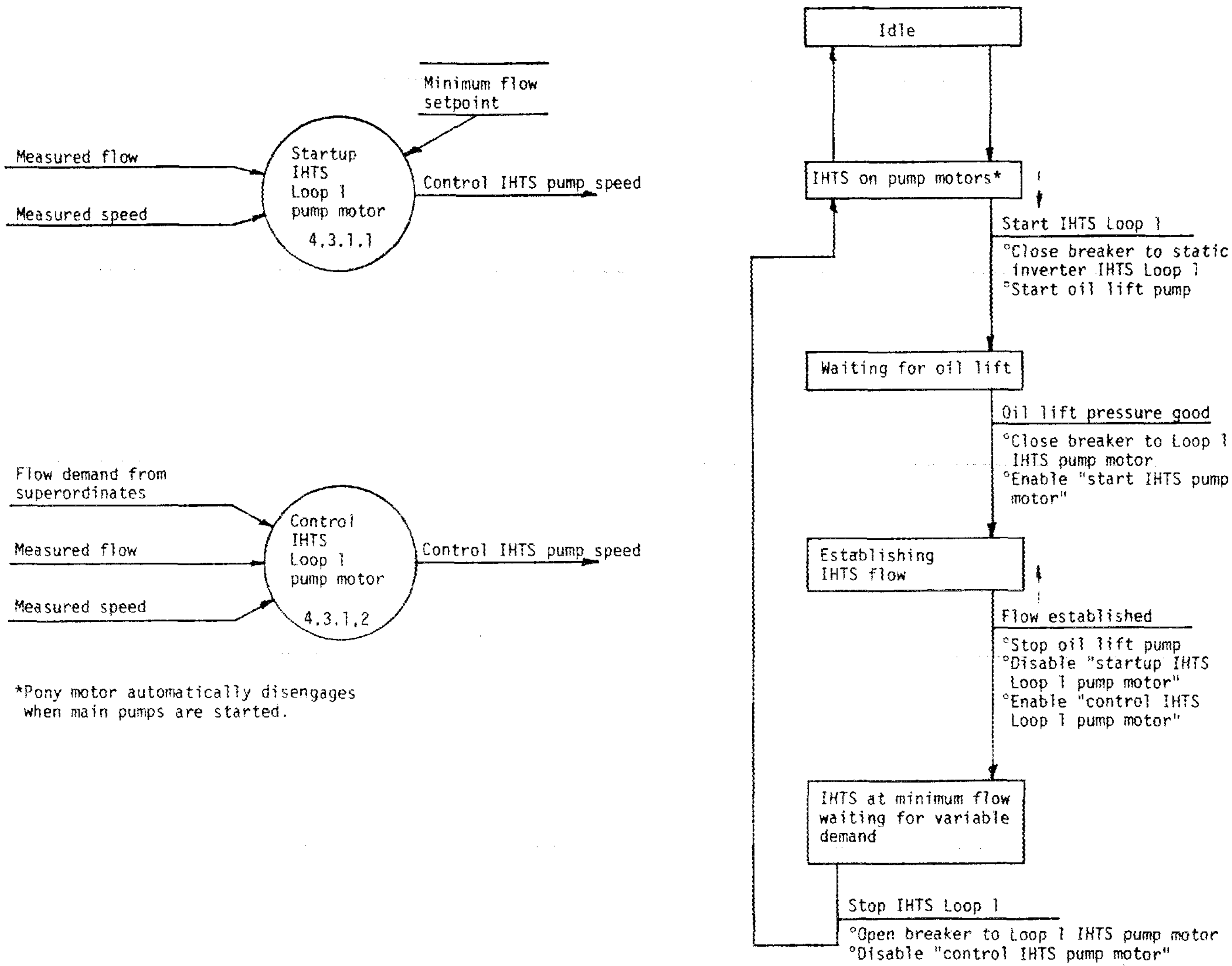


Fig. B.5. Control flow in IHTS loop 1 (Package 4.0).

ORNL-DWG 84-18247

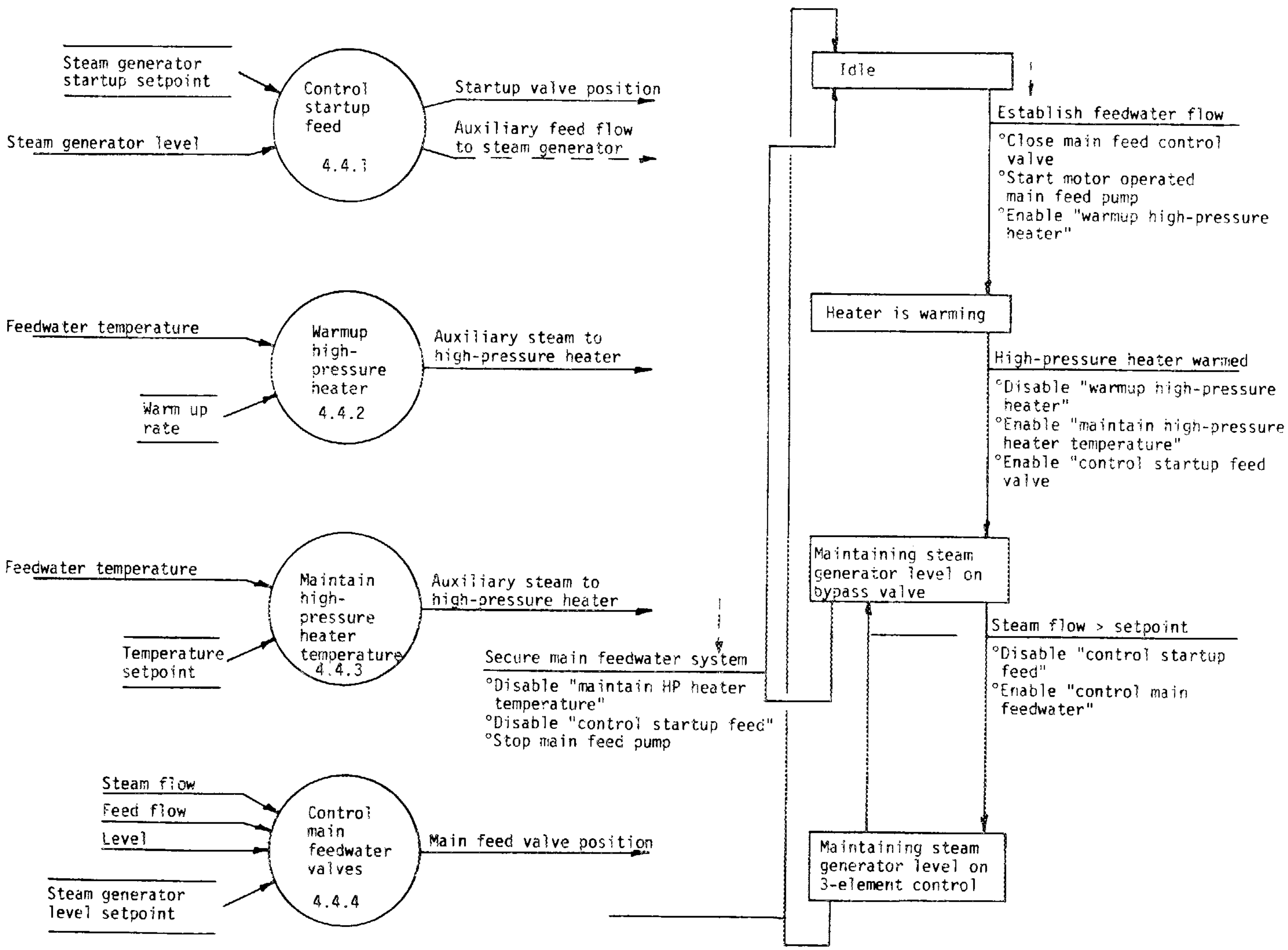


Fig. B.6. Control steam generator feedwater flow (Package 4.0).

ORNL-DWG 84-18248

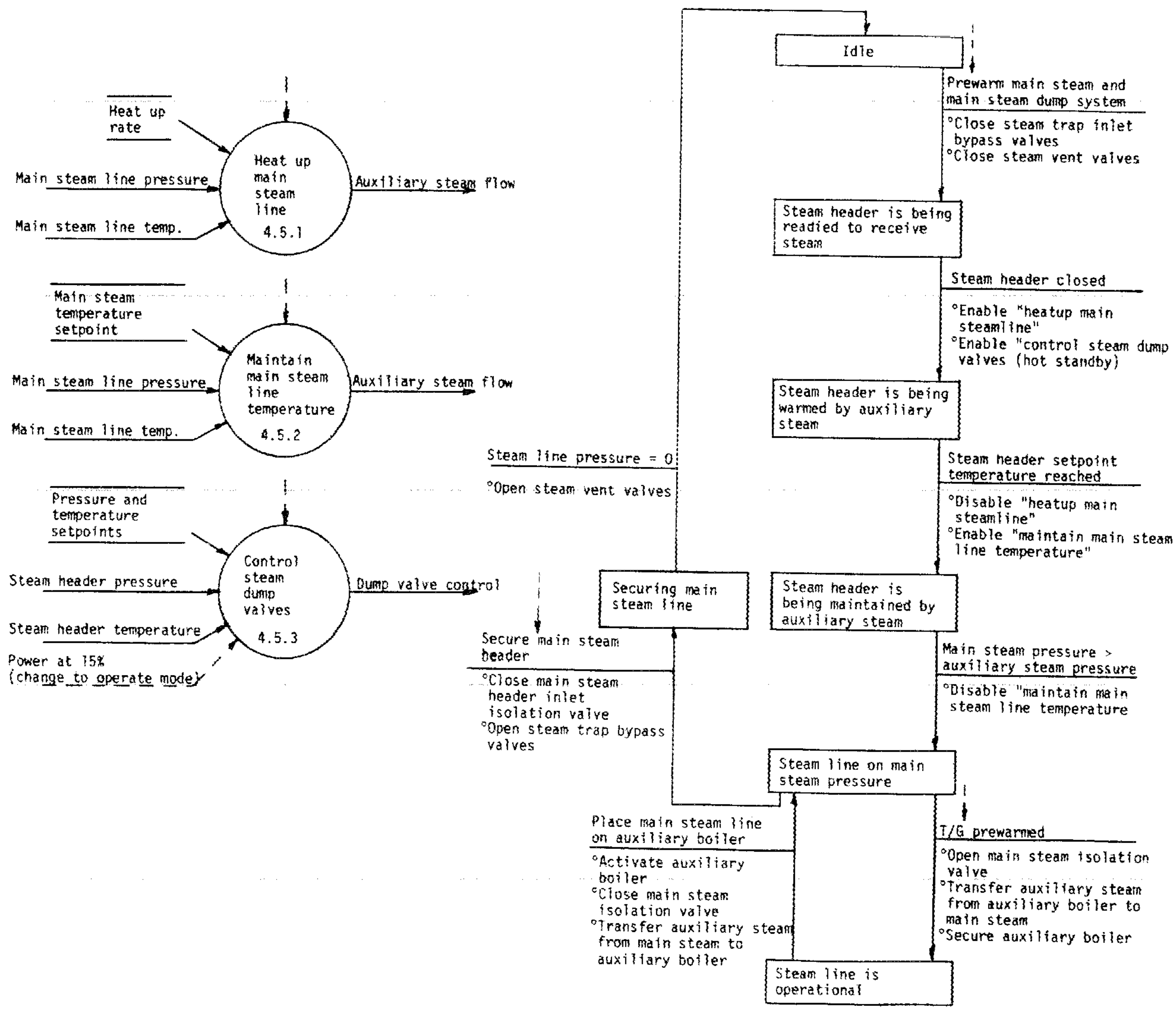


Fig. B.7. Control main steam line (Package 4.0).

ORNL-DWG 84-18249

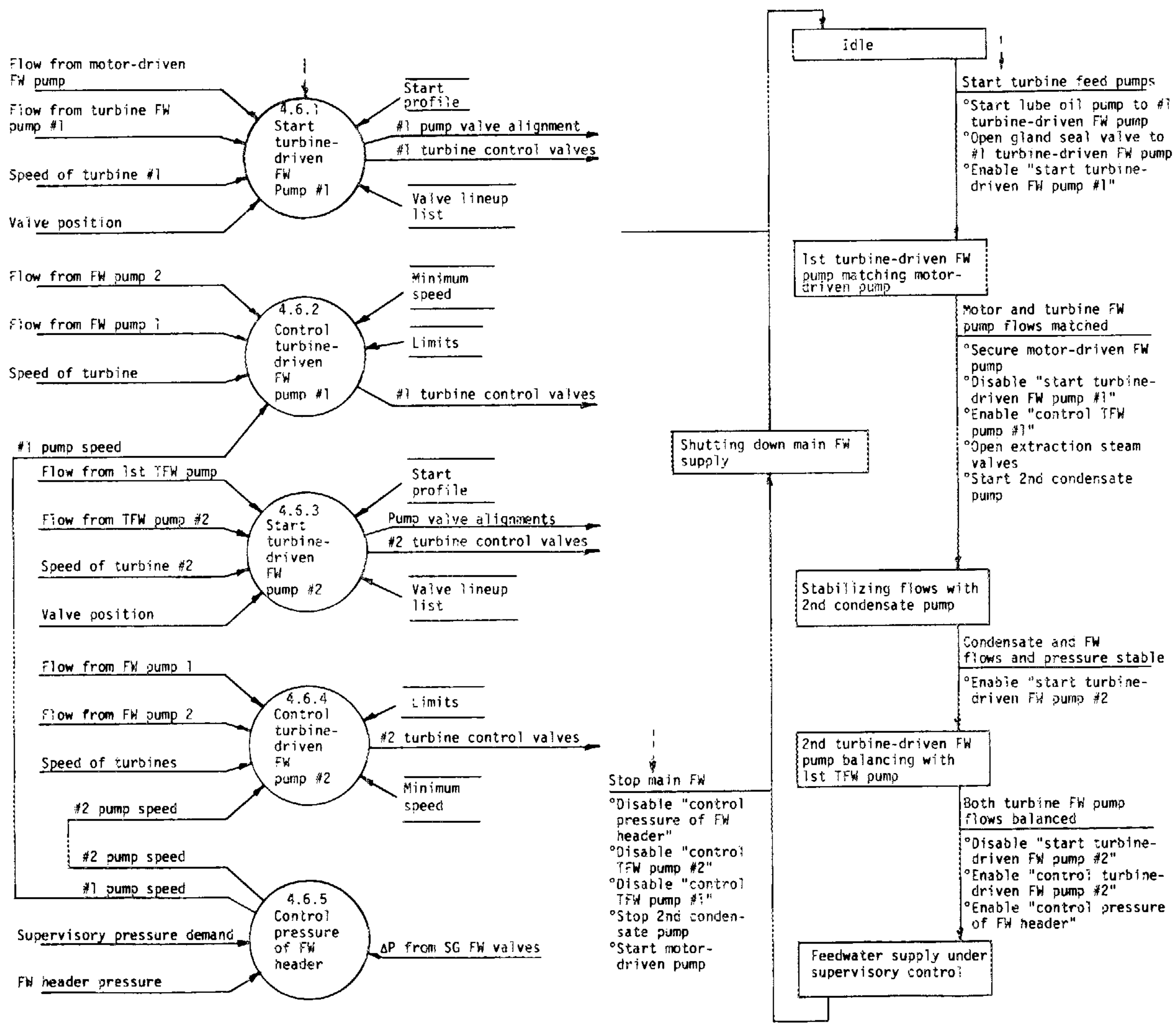


Fig. B.8. Control main feedwater supply (Package 4.0).

ORNL-DWG 84-18250

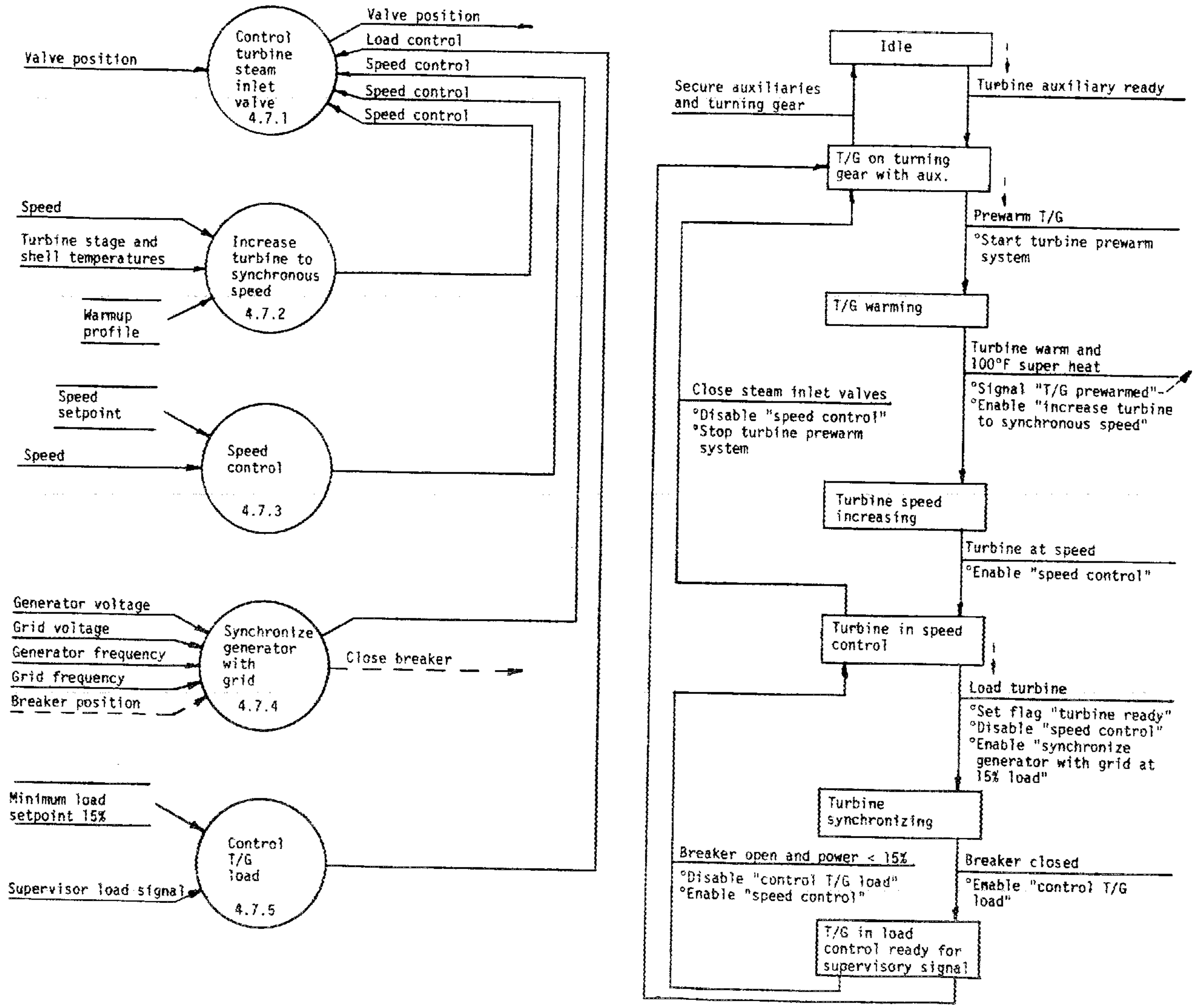
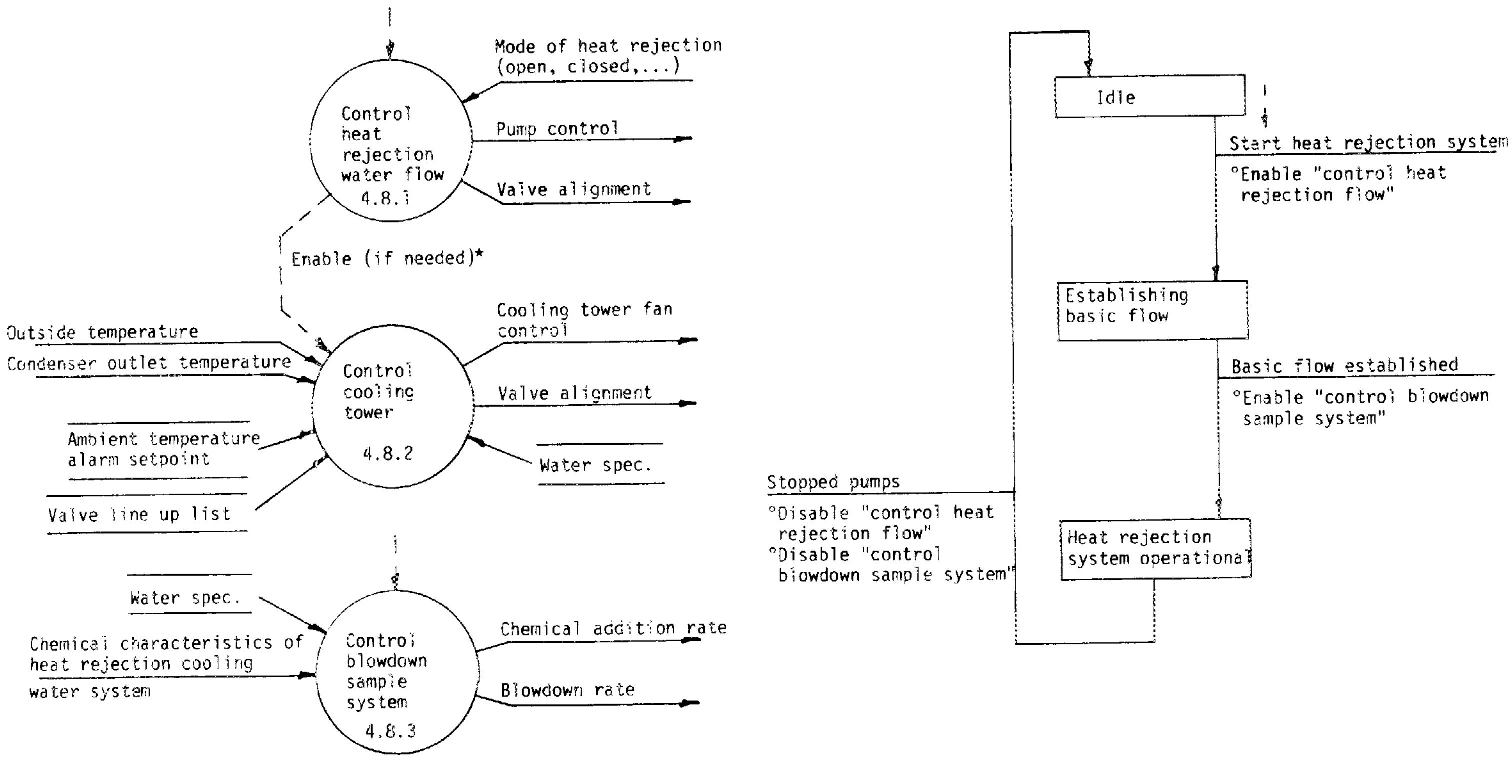


Fig. B.9. Control turbine-generator (Package 4.0).

ORNL-DWG 84-18251



NOTE: Plant may or may not be built with a cooling tower

Fig. B.10. Control waste heat rejection (Package 4.0).

ORNL-DWG 84-18252

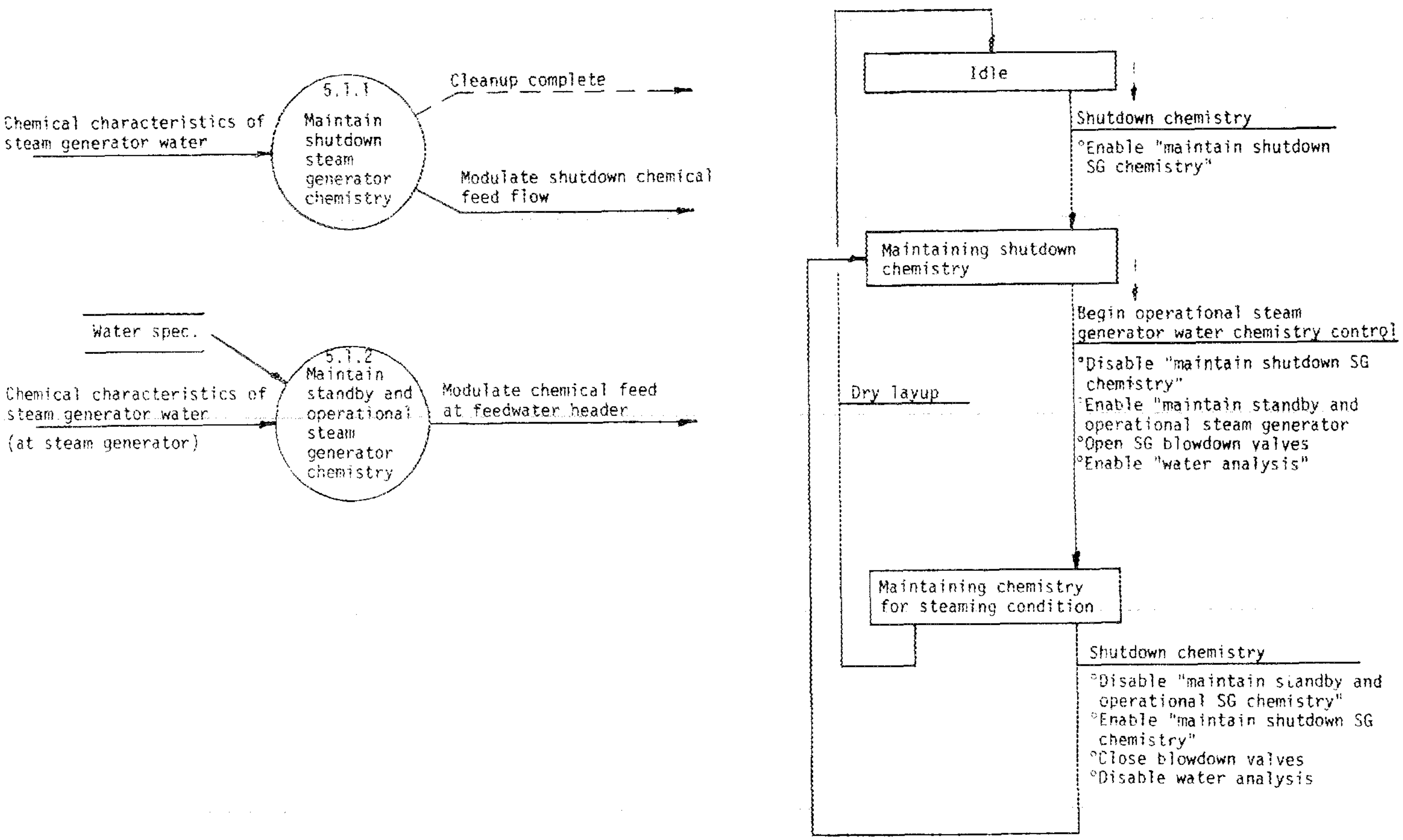


Fig. B.11. Control steam generator water chemistry (Package 5.0).

ORNL-DWG 84-18253

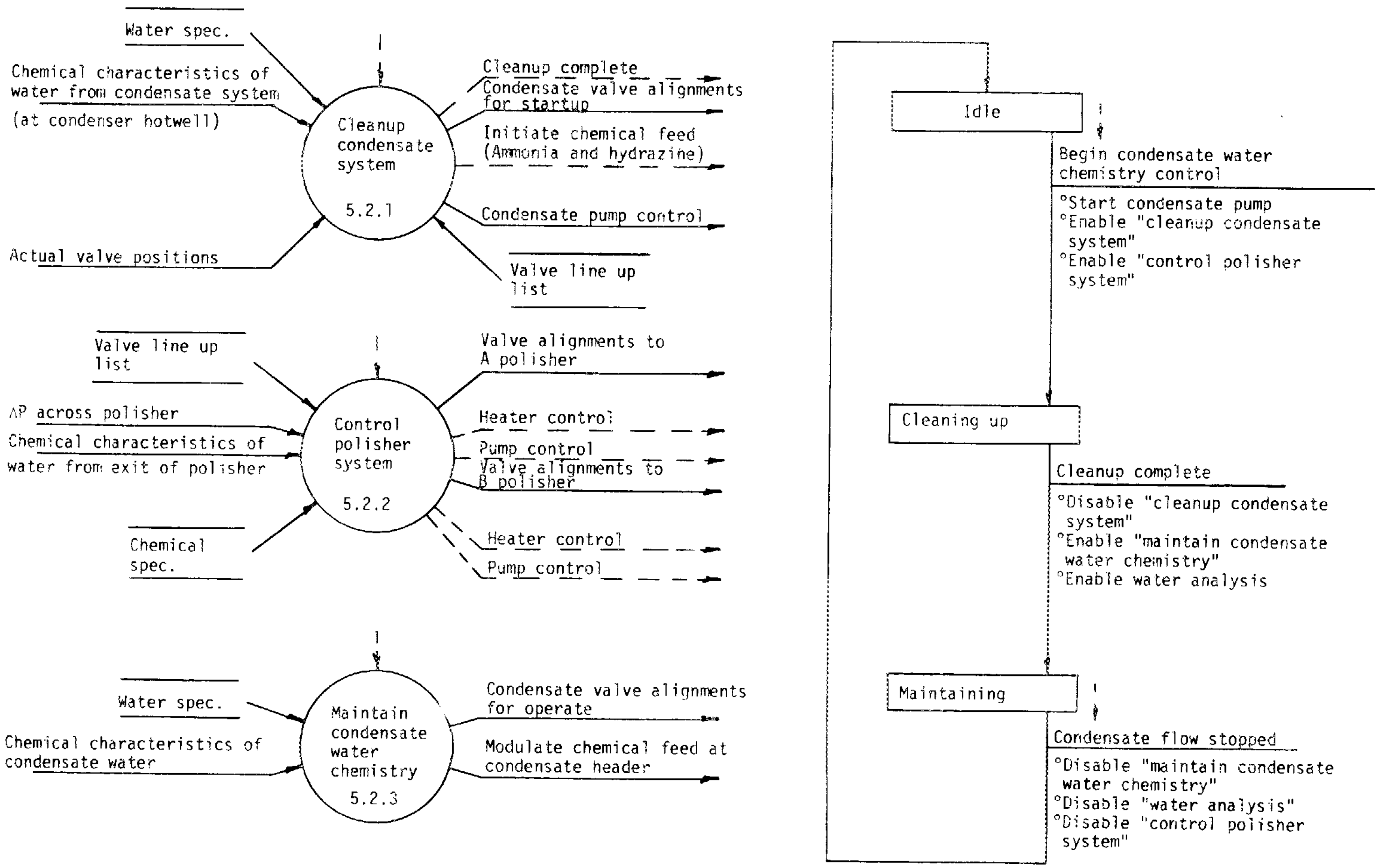


Fig. B.12. Control condensate water chemistry (Package 5.0).

ORNL-DWG 84-18254

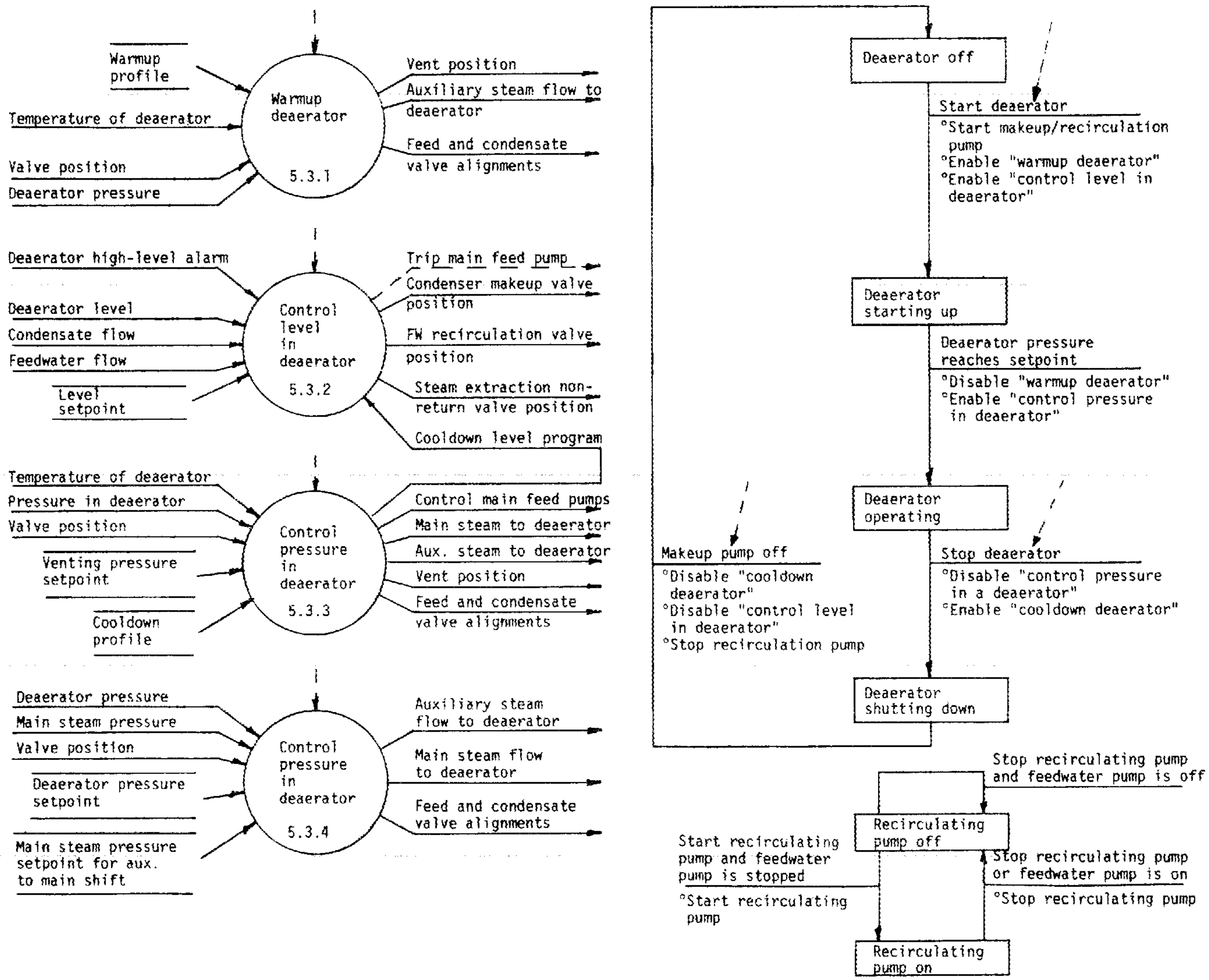


Fig. B.13. Control deaerator (Package 5.0).

ORNL-DWG 84-18255

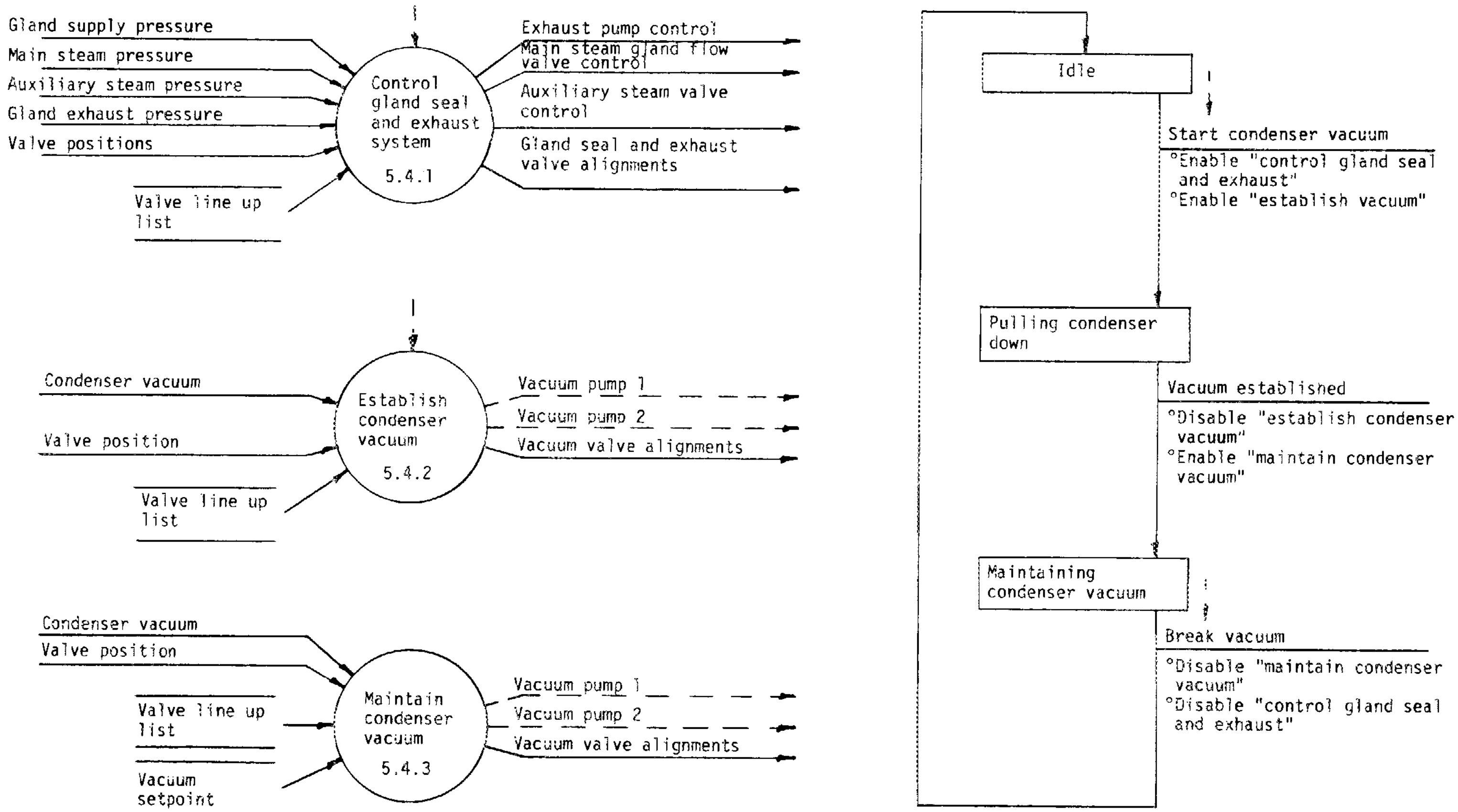


Fig. B.14. Control condenser vacuum (Package 5.0).

ORNL-DWG 84-18256

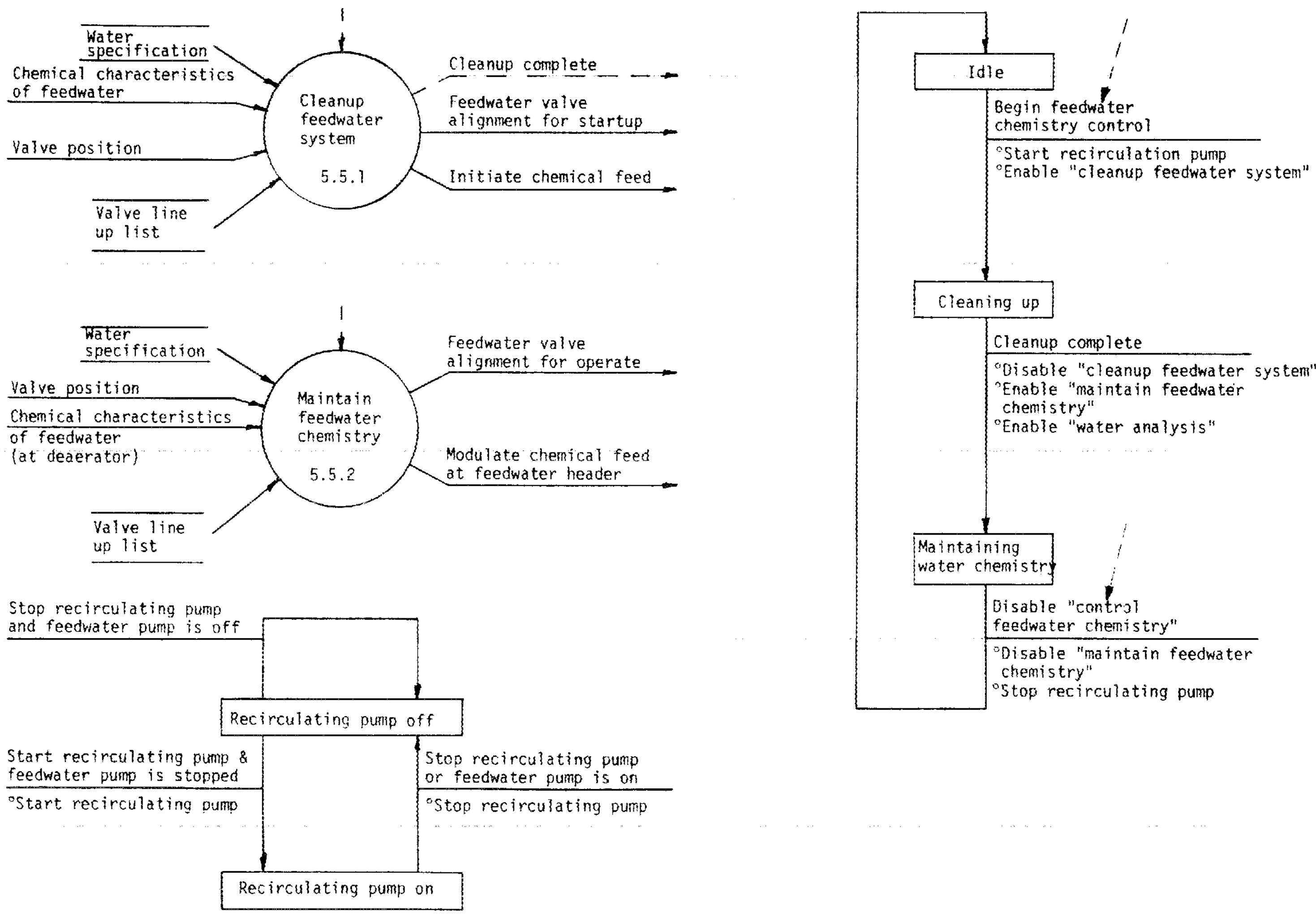


Fig. B.15. Control feedwater chemistry (Package 5.0).

ORNL-DWG 84-18257

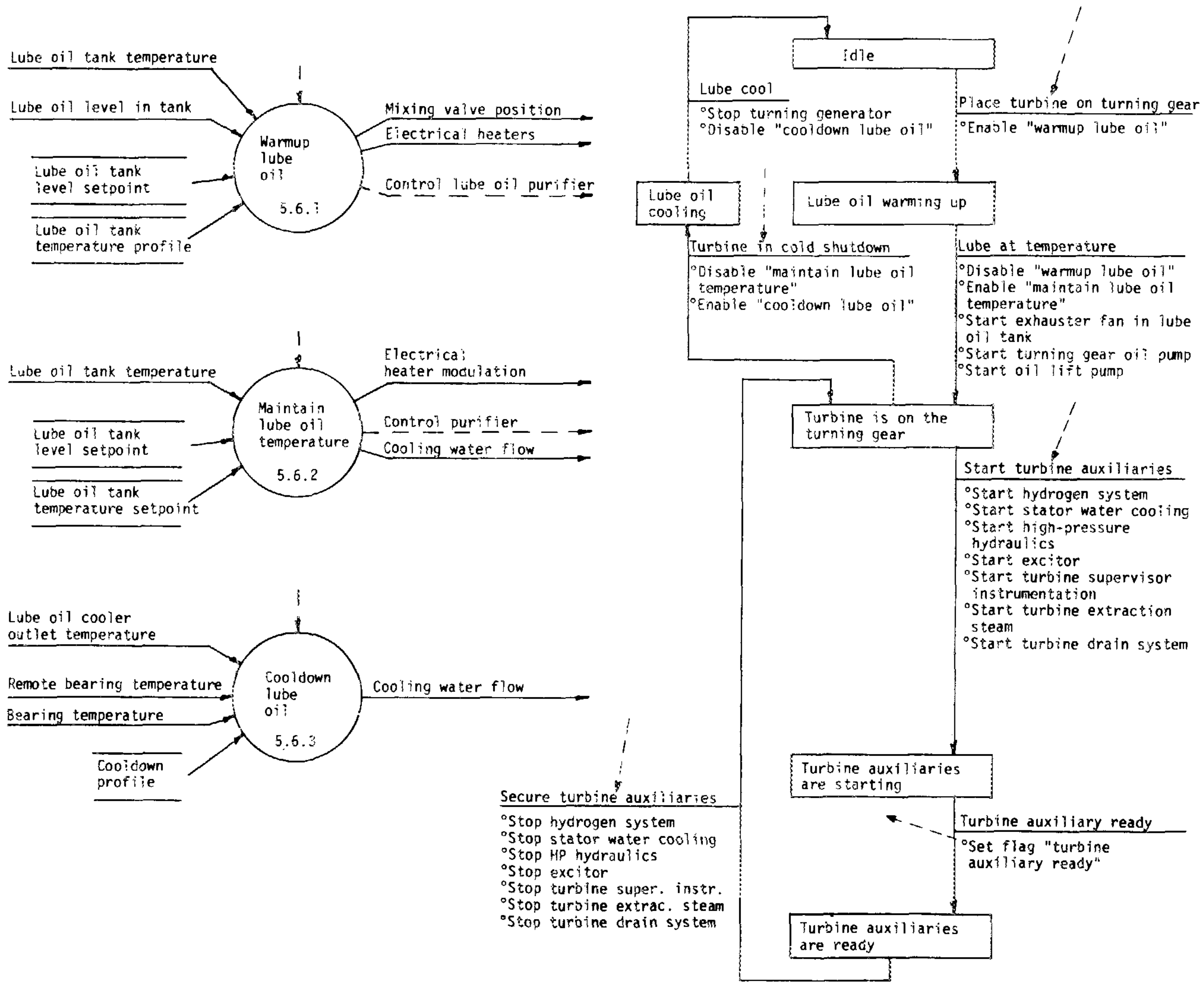


Fig. B.16. Control turbine auxiliaries (Package 5.0).

Appendix C

SELECTED MODELS FOR A LARGE-SCALE PLANT

APPENDIX C. SELECTED MODELS FOR A LARGE-SCALE PLANT

C.1 REACTOR MODEL

The model presented here represents the kinetics of a point reactor with two groups of delayed neutrons and core thermodynamics. The kinetics are given by:

$$\dot{n} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{2} \lambda_i c_i \tag{C.1}$$

$$\frac{dc_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i c_i, \quad i = 1, 2 \tag{C.2}$$

where

n = neutron flux
ρ = reactivity
β_i = fractional yield of delayed-neutron precursor group i
β = $\Sigma\beta_i$
λ_i = decay constant of precursor group i
c_i = precursor concentration of group i

The core thermodynamic equations represents the dynamic behavior of fuel, clad and coolant temperature. These equations are given by

$$\dot{T}_f = A_{RI} n - A_{R2} T_f + A_{R2} T_c \tag{C.3}$$

$$\dot{T}_c = A_{R3} T_f - (A_{R3} + A_{R4}) T_c + A_{R4} T_N \tag{C.4}$$

$$\dot{T}_N = \frac{2W_p}{5} A_{R5} \left[T_{NO} - T_N\right] + A_{R6} T_c - A_{R6} T_N, \tag{C.5}$$

$$\dot{T}_m = A_{R11} T_{NO} - A_{R11} T_m, \tag{C.6}$$

$$\dot{T}_{NO} = A_{R13} T_m - (W_p A_{R12} + A_{R13}) T_{NO} + W_p A_{R12} T_{RI}, \tag{C.7}$$

where

T_F = average fuel temperature,
T_c = average clad temperature,
T_N = average coolant temperature,
T_m = plenum metal temperature,
T_{NO} = inlet core coolant temperature,
T_{exit} = core exit temperature,
W_p = sodium flow.

The average coolant temperature is given by

$$T_N = \frac{T_{NO} + T_{exit}}{2} \text{ or } T_{exit} = 2\,T_N - T_{NO}. \tag{C.8}$$

The reactivity is given by

$$\rho = \rho_{rod} - K_d T_f - K_N T_N. \tag{C.9}$$

Linearizing the above equations about reference values, yields

$$\delta\dot{n} = \frac{-\beta}{\Lambda} \delta n + \sum_{i=i}^{2} \lambda_i \delta c_i + \frac{n^*}{\Lambda}\left[\delta\rho_{rod} - K_d \delta T_f - K_N \delta T_N\right], \tag{C.10}$$

$$\delta\dot{c}_i = \frac{\beta_i}{\Lambda} \delta n - \lambda_i \delta c_i, i = 1, 2, \tag{C.11}$$

$$\delta\dot{T}_f = A_{R1}\delta n - A_{R2}\delta T_f + A_{R2}\delta T_C, \tag{C.12}$$

$$\delta\dot{T}_C = A_{R3}\delta T_f - \left[A_{R3} + A_{R4}\right] \delta T_C + A_{R4}\delta T_N, \tag{C.13}$$

$$\delta\dot{T}_N = \left[A_{R6}\delta T_C - A_{R6} + \frac{2w^* A_{R5}}{5}\right] \delta T_N + \frac{2w^* A_{R5}}{5} \delta T_{NO} - \frac{1}{5} \Delta T_O A_{R5} \delta w_p, \tag{C.14}$$

$$\delta \dot{T}_m = A_{R11}\delta T_{NO} - A_{R11}\delta T_m \,, \tag{C.15}$$

$$\delta \dot{T}_{NO} = A_{R13}\delta T_m - \left[w^* A_{R12} + A_{R13}\right] \delta T_{NO} + w^* A_{R12}\delta T_{Ri} \,, \tag{C.16}$$

where

ΔT_O = $(T_{exit} - T_{NO})^*$,
$(T_{RI} - T_{NO})^*$ = 0 at steady state (operating point).
T_{RI} = reactor inlet sodium temperature, and
δ = deviation of the variable from reference value.

With state vector and external input vector defined as

$$X_R = (\delta n, \delta c_1, \delta cz_2, \delta T_f, \delta T_c, \delta T_N, \delta T_m, \delta T_{NO}) \,,$$

$$u_R = (\delta \rho_{rod}, \delta_{wp}, \delta T_{RI}) \,,$$

the linearized state equation becomes

$$\dot{X}_R = A_R X_R + B_R u_R \,, \tag{C.17}$$

where $A_R = 8 \times 8$ and $B_R = 8 \times 3$ matrices.

$$Note\ that\ \delta T_{exit} = 2\delta T_N - \delta T_{NO} \,, \tag{C.18}$$

and for constant inlet temperature,

$$\delta T_{NO} = O;\ 2\delta T_N = T_{exit} \,. \tag{C.19}$$

C.2 INTERMEDIATE HEAT EXCHANGE MODEL

The differential equations describing the heat balance are

$$\frac{d\overline{T}_1}{dt} = \frac{2w_p}{M_p}\left[T_{IPI} - \overline{T}_1\right] + \frac{(hA)_p}{M_p C_p}\left[\overline{T}_1 - \overline{T}_T\right] , \tag{C.20}$$

$$\frac{d\overline{T}_{IPO}}{dt} = \frac{2w_p}{M_p}\left[\overline{T}_1 - T_{IPO}\right] + \frac{(hA)_p}{M_p C_p}\left[\overline{T}_T - \overline{T}_1\right] , \tag{C.21}$$

$$\frac{d\overline{T}_T}{dt} = \frac{(hA)_p}{M_T C_{pT}}\left[\overline{T}_1 - \overline{T}_T\right] + \frac{(hA)_s}{M_T C_{pT}}\left[\overline{T}_2 - \overline{T}_T\right] . \tag{C.22}$$

$$\frac{d\overline{T}_2}{dt} = \frac{2w_I}{M_s C_p}\left[T_{ISI} - \overline{T}_2\right] + \frac{(hA)_s}{M_s C_p}\left[\overline{T}_T - \overline{T}_2\right] , \tag{C.23}$$

and

$$\frac{dT_{ISO}}{dt} = \frac{2w_I}{M_s C_p}\left[\overline{T}_2 - T_{ISO}\right] + \frac{(hA)_s}{M_s C_p}\left[\overline{T}_T - \overline{T}_2\right] , \tag{C.24}$$

where

w_p = primary flow rate,
M_p = mass of sodium in primary,
M_s = mass of sodium in secondary,
C_p = specific heat of sodium,
w_I = intermediate flow rate,
M_T = mass metal tube,
C_{pT} = specific heat of tube metal,
h = heat transfer coefficent which is a function of flow rate,
A = heat transfer area.

The subscripts p, s, and T refers to primary, secondary, and metal tube, respectively.

Also

T_{IPI} = inlet primary sodium temperature,
$\overline{T}_1$ = primary sodium mean temperature,
T_{IPO} = outlet primary sodium temperature,
$\overline{T}_T$ = metal tube temperature,
$\overline{T}_2$ = secondary sodium mean temperature,
T_{ISI} = inlet secondary sodium temperature,
T_{ISO} = outlet secondary sodium temperature,
δ = variation of the variable from reference value.

The linearization of the above equations yields

$$\delta\dot{\overline{T}}_1 = \frac{2}{M_p}\,\delta w_p\left[T_{IPI} - \overline{T}_1\right] + \frac{2w_p}{M_p}\left[\delta T_{IPI} - \delta\overline{T}_1\right]$$

$$+\frac{A_p}{M_pC_p}\frac{\partial h_p}{\partial w_p}\,\delta w_p\left[\overline{T}_1-\overline{T}_T\right]$$
$$+\frac{(hA)_p}{M_pC_p}\left[\delta\overline{T}_1-\delta\overline{T}_T\right] \tag{C.25}$$

$$\delta\dot{T}_{IPO}=\frac{2}{M_p}\,\delta w_p\left[\overline{T}_1-T_{IPO}\right]+\frac{2w_p}{M_p}\left[\delta\overline{T}_1-\delta T_{IPO}\right]+\frac{A_p}{M_pC_p}\frac{\partial h_p}{\partial w_p}\,\delta w_p\left[\overline{T}_T-\overline{T}_1\right]+\frac{(hA)_p}{M_pC_p}\left[\delta\overline{T}_T-\delta\overline{T}_1\right], \tag{C.26}$$

$$\delta\dot{\overline{T}}_T=\frac{A_p}{M_TC_{PT}}\frac{\partial h_p}{\partial w_p}\,\delta w_p\left[\overline{T}_1-\overline{T}_T\right]+\frac{(hA)_p}{M_TC_{PT}}\left[\delta\overline{T}_1-\delta\overline{T}_T\right]+\frac{A_s}{M_TC_{PT}}\frac{\partial h_s}{\partial w_I}\,\delta w_I\left[\overline{T}_2-\overline{T}_T\right]+\frac{(hA)_s}{M_TC_{PT}}\left[\delta\overline{T}_2-\delta\overline{T}_T\right], \tag{C.27}$$

$$\delta\dot{\overline{T}}_2=\frac{2}{M_sC_p}\,\delta w_I\left[T_{ISI}-\overline{T}_2\right]+\frac{2w_I}{M_sC_p}\left[\delta T_{ISI}-\delta\overline{T}_2\right]+\frac{A_s}{M_sC_p}\frac{\partial h_s}{\partial w_I}\,\delta w_I\left[\overline{T}_T-\overline{T}_2\right]+\frac{(hA)_s}{M_sC_p}\left[\delta\overline{T}_T-\delta\overline{T}_2\right], \tag{C.28}$$

$$\delta\dot{T}_{ISO}=\frac{2\delta w_I}{M_sC_p}\left[\overline{T}_2-T_{ISO}\right]+\frac{2w_I}{M_sC_p}\left[\delta\overline{T}_2-\delta T_{ISO}\right]+\frac{A_s}{M_sC_p}\frac{\partial h_s}{\partial w_I}\,\delta w_I\left[\overline{T}_T-\overline{T}_2\right]+\frac{(hA)_s}{M_sC_p}\left[\delta\overline{T}_T-\delta\overline{T}_2\right]. \tag{C.29}$$

With the state variables

$$X_I=(\delta\overline{T}_1,\delta T_{IPO},\delta\overline{T}_T,\delta\overline{T}_2,\delta T_{ISO}), \tag{C.30}$$

and external inputs (pertubations)

$$u_I=(\delta T_{IPI},\delta w_p,\delta w_I,\delta T_{ISI}) \tag{C.31}$$

defined, the linearized state equations can be put in the form

$$\dot{X}_I=A_IX_I+B_Iu_I, \tag{C.32}$$

where $A_I = 5\times 5$, $B_I = 5\times 4$ matrices.

C.3. MATHEMATICAL MODEL OF STEAM GENERATOR (see Fig. 4.13)

C.3.1 The Conservation Laws of Mass and Energy

$$\frac{d}{dt}(\rho V)=W_i-W_o, \tag{C.33}$$

$$\frac{d}{dt}(\rho VU)=\frac{d}{dt}(MU)=W_iH_i-W_oH_o+Q-W^*, \tag{C.34}$$

or

$$\frac{d}{dt}(MH-PV)=(WH)_i-(WH)_o+Q-(P\dot{V}), \tag{C.35}$$

or

$$(M\dot{H}+H\dot{M}-V\dot{P})=(WH)_i-(WH)_o+Q, \tag{C.36}$$

or

$$(M\dot{H}-V\dot{P})=W_i(H_i-H_o)+Q, \tag{C.37}$$

$$\Delta H=C_p\Delta T,\ \dot{H}=C_p\dot{T}, \tag{C.38}$$

where

- ρ = density in the volume
- V = volume of lump
- W = mass flow rate
- W^* = work done by the fluid inside the lump
- i, o = subscripts for inlet and outlet of a lump
- U = internal energy
- H = enthalpy
- P = pressure
- Q = heat transfer rate across the boundaries
- M = ρV = mass of the lump
- C_p = specific heat capacity

C.3.2 Single-Channel Conservation Equations for the Primary Coolant

$\dot{M}_{pi} = W_i - W_o$ neglecting $\dot{P}_p$ and assuming flow rate is same in all lumps of primary, from Eq. (C.37) yields

$$M_{PSH}\,C_{PSH}\,\dot{T}_{PSH}=W_I\,C_{PSH}(T_{SPI}-T_{PSH})-Q_{TSH} \tag{C.39}$$

for the superheat region.

$$M_{PB}\,C_{PB}\,\dot{T}_{PB} = W_I\,C_{PB}\,(T_{PSH} - T_{PB}) - Q_{TB} \qquad \text{(C.40)}$$

for the boiling region, and

$$M_{PSC}\,C_{PSC}\,\dot{T}_{PSC} = W_I\,C_{PSC}\,(T_{PB} - T_{PSC}) - Q_{TSC} \qquad \text{(C.41)}$$

for subcooled region.

C.3.3 Single-Channel Conservation Equations for Secondary Side

For superheated steam, the enthalpy is a function of both temperature and pressure.

$$\Delta H_S(T_S,P_S) = \left.\frac{\partial H_S}{\partial T_S}\right|_{P_s = \text{constant}} \Delta T_S + \left.\frac{\partial H_S}{\partial P_S}\right|_{T_s = \text{constant}} \Delta P_S \qquad \text{(C.42)}$$

$$= Cp_{SSH}\,\Delta T_S + \left[\frac{\partial H}{\partial P_S}\right] \Delta P_S \qquad \text{(C.43)}$$

$$\dot{M}_{SH} = W_B - W_{SH}\,. \qquad \text{(C.44)}$$

From Eqs. (C.36) and (C.44), we have

$$M_{SSH}\left[C_{PS}\,\dot{T}_{SH} + \frac{\partial H_{SH}}{\partial P_{SH}}\,\dot{P}_{SH}\right] + H_{SH}\left[W_B - W_{SH}\right] - V_{SH}\,\dot{P}_{SH} = (WH)_B - (WH)_{SH} + Q_{TSH}$$

and,

$$M_{SSH}\,C_{PSH}\,\dot{T}_{SH} + \left[M_{SSH}\frac{\partial H_{SH}}{\partial P_{SH}} - V_S\right]\dot{P}_{SH} = W_B(H_B - H_{SH}) + Q_{TSH}\,.$$

Let $H_B - H_{SH} \simeq C_{PSH}\,(T_{Sat} - T_{SH})$,

and

$$M_{SSH}\,C_{PSH}\,\dot{T}_{SH} + \left[M_{SSH}\,\frac{\partial H}{\partial P_{SH}} - V_S\right]\dot{P}_{SH} = Q_{TSH} + W_B\,C_{pS}\left[T_{Sat} - T_{SH}\right]. \qquad \text{(C.45)}$$

The steam pressure in the superheating lump can be described by the compressibility-adjusted ideal gas state Eq. (C.33).

$$P_{SH}V_{SH} = Z^*\,M_{SSH}\,\frac{RT_{SH}}{M_{stm}} \qquad \text{(C.46)}$$

$$\dot{M}_{SSH} = W_B - W_{SH}\,,$$

where

Z^* = compressibility factor,
R = universal gas constant, and
M_{stm} = molar weight of steam.

For the boiling lump,

$$\dot{M}_b = \frac{d}{dt}(\rho_b\,A_b\,L_b) = A_b\,\rho_b\,\dot{L}_b + A_b\,L_b\,\frac{\partial \rho}{\partial P_{sat}}\,\dot{P}_{sat} = W_{SC} - W_b\,. \qquad \text{(C.47)}$$

For the subcooled region,

$$M_{SC}\,C_{PSC}\,\dot{T}_{SC} + H_{SC}\,\dot{M}_{SC} - V_{SC}\dot{P}_{SC} = W_{FW}\,H_{FW} - W_{SC}\,H_{SC} + Q_{TSC}\,, \qquad \text{(C.48)}$$

$$\dot{M}_{SC} = \frac{d}{dt}(\rho_{SC}\,A_{SC}\,L_{SC}) = \rho_{SC}A_{SC}\,\dot{L}_{SC} + A_{SC}\,L_{SC}\,\frac{\partial \rho_{SC}}{\partial P_{SC}}\,\dot{P}_{SC} = W_{FW} - W_{SC}\,, \qquad \text{(C.49)}$$

$$A_{SC}\,\rho_{SC}\,L_{SC}\,C_{PSC}\,\dot{T}_{SC} + C_{PSC}\,T_{SC}\left[\rho_{SC}\,A_{SC}\,\dot{L}_{SC} + A_{SC}\,L_{SC}\,\frac{\partial \rho_{SC}}{\partial P_{SC}}\,\dot{P}_{SC}\right] - V_{SC}\,\dot{P}_{SC} = (W_{FW}\,H_F - C_{pSC}\,W_{SC}\,T_{SC}) + Q_{TSC}\,, \qquad \text{(C.50)}$$

$$Q_{TSH} = U_{SH}\,L_{SH}\,(T_{PSH} - T_{SH}) = h_{SH}\pi RL_{SH}\,(T_{PSH} - T_{SH})\,, \qquad \text{(C.51)}$$

$$Q_{TB} = U_B L_B\,(T_{PB} - T_{Sat}) = h_B\pi RL_B\,(T_{PB} - T_{Sat})\,, \text{ and} \qquad \text{(C.52)}$$

$$Q_{TSC} = U_{SC}\,L_{SC}\,(T_{PSC} - TSC) = h_{SC}\pi RL_{SC}(T_{PSC} - T_{SC})\,, \qquad \text{(C.53)}$$

where h = heat transfer coefficient, R = radius of tube.

$$L_{SH} = L_{Total} - L_{SC} - L_B \,. \qquad (C.54)$$

The critical flow relationship is given by

$$W_{SH} = W_{steam} = W_S = C_V P_{steam} = C_V P_{SH} \qquad (C.55)$$

$$\delta W_{SH} = C_V \delta P_{SH} + P_{SH} \delta C_V \qquad (C.56)$$

where C_V = valve coefficient and $C_V \propto$ valve opening which is controlled by a control system.

Equations (C.39) through (C.41) and (C.45) through (C.49) form the system equations for the steam generator. The linearization of system equations will provide the linear model of the steam generator. The state variables include

$$X_S = (\delta T_{PSH}, \delta T_{PB}, \delta T_{PSC}, \delta T_{SH}, \delta T_{SC}, \delta L_b, \delta L_{SC}, \delta P_{SH}) \,.$$

The external inputs include

$$u_S = (\delta T_{SPI}, \delta W_I, \delta H_{FW}, \delta W_{FW}, \delta C_V) \,.$$

The δ represents variation of the variable from reference value. In linearized equations, some variations of system parameters are not chosen as state variables, but they can be expressed as a linear combination of state variables.

The linearized system equations for the steam generator can be put more conveniently into the form

$$T\dot{X}_S = MX_S + Nu_S \qquad (C.57)$$

where T and M are two 8×8 coefficent matrices and N is a 8×5 perturbation matrix,

$$\dot{X}_S = T^{-1}M\,X_S + T^{-1}N\,u_S$$

or

$$\dot{X}_S = A_S\,X_S + B_S\,u_S \,.$$

The linear models for turbine and feedwater subsystems are not finalized and are not included in this report.

Appendix D

PROCEDURE FOR CLOSED-LOOP OPTIMAL CONTROL

APPENDIX D. PROCEDURE FOR CLOSED-LOOP OPTIMAL CONTROL

One can make optimal controls completely closed loop with the following procedure:

Substituting Eq. (4.15) in Eq. (4.14), one obtains

$$\dot{g}_i = -(A_i - S_i K_i)^T g_i(t) i - K_i C_i \sum_{i=1}^{N} L_{ij} X_j - \sum_{j=1}^{N} T_{ji}^T C_j^T (K_j X_j - g_j(t))$$

or

$$\dot{g} = -(A - SK + CL)T_g - (K C L + L^T C^T K)X, \; g(t_f) = 0$$

which has a solution

$$g(t) = \Phi_1(t,t_o) g(t_o) - (t,\gamma)[K(\gamma)CL + L^T C^T K(\gamma)X(\gamma)]d\gamma = M(T,t)X(t).$$

For complete derivation, please see Jamshidi 1983.

For an infinite time regulator, M is constant whereas X and g are not. Thus, if the values of X and g are recorded at first n time points very close to t_o, M can be determined as follows:

Form the matrices $G = [g(t_o, g(t_1),\dots g(t_n)]$ and X $= [x(t_o),\dots X(t_n)]$, $G = MX$ or $M = GX^{-1}$. These computations can be done off line.

Note that if a time-varing M is desirable (for finite terminal time T), it is possible to solve the problem with n initial conditions, that is $X(t_o)$, $X(t_o + 1),\dots$ and from $n \times n$ time dependent matrices G(t) and X(t) to find M(t) for each integration step.

The closed-loop control for the composite system can be formulated by

$$u = -R^{-1} B^T K X - R^{-1} B^T MX$$

$$= -R^{-1} B^T (K + M)X = -FX$$

The matrices R, B, K, and M are obtained from decentralized calculations. The gains are computed off-line, the on-line calculations for real-time closed-up loop control is minimal.

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