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Prepared for the
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A METHODOLOGY FOR ALLOCATING NUCLEAR POWER PLANT CONTROL FUNCTIONS TO HUMAN OR AUTOMATIC CONTROL

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ABSTRACT

This report describes a general method for allocating control functions to man or machine during nuclear power plant (NPP) design, or for evaluating their allocation in an existing design.

The research examined some important characteristics of the systems design process, and the results make it clear that allocation of control functions is an intractable problem, one which increases in severity with the increasing complexity of systems. The method is reported in terms of specific steps which should be taken during the early stages of a new system design, and which will lead to an optimal allocation at the functional design level of detail.

The procedures described are not expected to provide an ultimate solution to the allocation-of-functions problem. However, these procedures can at least assure that allocation of control functions is considered during design in an orderly and rational way. They should substantially advance the general understanding of this problem and the ability of the design community to allocate control functions to humans or automation in complex systems.

1. INTRODUCTION

This report and a companion literature review (ref. 1) report the results of two years of research by BioTechnology, Incorporated, under the direction of the Oak Ridge National Laboratory, to explore the problem of allocating functions to human or automatic control, with particular reference to nuclear power plant control rooms.

The report focuses on the allocation of control functions to humans and automatic devices in a nuclear power plant (NPP). In a NPP control room (CR), all instrumentation and control devices are operated remotely. For each control function, the key question considered is whether that function should be exercised by a human operator, by automatic devices, or by some interactive combination of the two. The allocation methodology reported here can be applied during the overall design of an NPP system or during the development of a design modification.

The scope of this report is limited to the specialized problem of choosing between man and automation in remote process control, and specifically excludes certain other considerations which may be important in the broader context of whole-system design.

1.1 HISTORICAL PERSPECTIVE

This report concerns men and machines. Machines are built to serve the needs of man. This is more than simply an obvious point, since it is a point too often lost during system design. Especially as technology becomes more complex and as designers focus on technical problems, the needs of those who use, operate, and maintain the machines can quickly be forgotten, until finally the engineering objectives of a new system are pursued at the expense of the economic or social objectives which the system was originally intended to serve.

1.1.1. The Evolution of Technology

Early, simple technologies tended to forgive designers who neglected the role of man. This was true in part because man is, within limits, very adaptable. Furthermore, early technologies developed slowly, providing time for many cycles of experiment and test. Finally, early designers usually were themselves experienced operators of the type of machines they designed, and thus they were naturally sensitive to the needs of users. Although the early designers felt a benign lack of concern for what we now call human factors, their inventions fueled the industrial revolution and were often remarkably satisfactory to use. Early technology was forgiving so far as human factors were concerned.

The history of the automobile provides an illustration: A full 30 years of development elapsed between the time Otto Benz sold his first car in 1887 and the arrival of mass auto production in the 1920s. The early automobiles were awkward things to drive, modeled after horse-drawn vehicles and railway engines. But by the 1920s a rather satisfactory control configuration had developed, essentially identical to the one in use today, and this occurred without any formal advocacy of human factors in design.

This achievement was possible because the automobile was a relatively simple technology. A new design could be developed from concept to road test within 6 to 18 months. During those 30 years of early development, several hundred automakers put thousands of different models on the road. Those models were designed by people who themselves drove cars, and a single person could direct the design effort and know the entire design in detail. Few instruments and controls were required, and the dynamics of the control system were easy for an operator to understand.

These conditions made it possible, in both the automobile and other industries, to design moderately satisfactory machines in spite of the fact that the design teams had little formal organization and included only design engineers. Any problems people might have with the machines were viewed as problems in training. And because people are adaptable, they could generally learn to use the machines.

By contrast, more complex technologies are not so forgiving. Consider the conditions of a modern nuclear power plant (NPP) or a chemical process plant: (1) An NPP is highly complex, and each new plant is to some extent unique; (2) The industry is young in the sense that there have been few generations of redesign; (3) It takes years to place each design in operation; (4) The designers are not the users; (5) Many specialists are involved, and no one designer can know the entire system in detail--in fact, several different contractors are usually employed; and (6) Thousands of instruments and thousands of controls are required to operate and maintain each plant.

Not surprisingly, it is hard to coordinate the design of a complex system such as an NPP. Even though there is usually some formal planning for the human elements of the system (or at least for a human organization and a training program), many complex systems are delivered with embedded design shortcomings which compromise their operability and safety. These shortcomings often originate as errors in the allocation of roles between human and automatic control.

1.1.2 System Design

World War II was a watershed in system design. For the first time it was recognized that large systems would require new design disciplines if they were to be made to work. Out of this concern came systems theory and human factors disciplines such as ergonomics, engineering psychology, and training design. Complex systems were recognized to include a human subsystem which, like the engineering subsystem, required professional attention during design. Careful coordination of the parts and subsystems of a design was required to assure that those elements were mutually supportive and would each be delivered at the appropriate time. In fact, by the 1960s federal procurement regulations required formal planning for these considerations as a part of the procurement process.

This man-machine system approach was generally effective, and it made complex system designs more readily achievable than had been the case previously. But in spite of some great successes, a few problems continued to worsen as technology became more complex. These problems include allocation of control functions, the problems of fault diagnosis, and control system design. The particularly intractable one was the question of allocation of control functions: Which system and task responsibilities should be assigned to man, which to a machine, and which to some combination of human and automatic control?

This problem is now widely recognized in the military and aerospace fields and by most developers of complex systems, including those in the nuclear power community. It is generally understood that man is actually the more complex of the two componenets in a man-machine system, and it therefore makes sense to base a system design on the characteristics of man as much as on those of the machine, and to allocate control functions on the same basis. It is the purpose of this project to provide a general methodology for allocating control functions to man or machine, with emphasis on automation and on the nuclear power industry.

1.1.3. Automation

The research reported here is partly in anticipation of a continuing increase in automation. Automation* is already a basic tool of NPP and process control, and its role is expected to expand. However, automation brings with it an increased importance for the appropriate allocation of functions. In fact, automated control is expected to produce a dramatic change in the role of the NPP operator. The authors are convinced that this change will be for the better; that automation may provide the best capability for mastering the complexity of NPP control; and that 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 rush to automation has not always produced desirable results (ref 2). In fact, many automated systems are not as satisfactory as the manual systems they replaced. Each new system creates some new tasks for the human as it alleviates others, and each new system possesses new possibilities for human error. Automated systems are often considered less "user friendly" by operators, and frequently the users either resist automation, seek to override the automatic system, or continue to do by hand what the system was designed to do automatically.

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*The term "automation," as it is used in this report, refers loosely to the delegation of tasks to machine or computer systems, thus freeing human operators from vigilance tasks.

One of the principal causes of poor man-machine design has been the absence of deliberate consideration of which tasks and decisions are best performed by man and which by machine. There is an ever-present tendency for system designers to automate to the limits of affordable technology without asking if a function or task should be automated. Unfortunately, automation decisions usually are based primarily on design (equipment) engineering grounds. They soon are firmly cast into hardware (and software), after which they limit the flexibility of the human role. When functions are automated, the human operators may be unable to monitor events or to exercise useful control when needed. On the other hand, when functions are delegated to man, the users may be required to perform unnecessary chores or to do tasks for which humans are poorly adapted. To a large extent the failure to allocate tasks appropriately occurs because there has been no established procedure for making such decisions during system design.

1.2 ALLOCATION OF CONTROL FUNCTIONS

The seven steps of the model outlined in this report provide an orderly decision sequence for allocating functions. But more important than the particular sequence of steps is the commitment to a deliberate allocation process. In the past, when designers have achieved good man-machine designs, that success has been due in part to an intuitive consideration of human factors. Designers try to foresee how users will interact with the machine. They may themselves have experience as hands-on users, and they may think about human factors considerations intuitively. Unfortunately, the more frequent case has been one in which the equipment designers pursued an engineering solution without any consideration, deliberate or otherwise, of what should be automated. The objective of this model is to suggest a methodology for the structured consideration of man-machine roles as part of the system design process.

1.2.1. Background

The problem of proper allocation of functions was recognized by the U.S. Nuclear Regulatory Commission (NRC) several years ago, and in 1980 NRC sponsored a project under the direction of Oak Ridge National Laboratory (ORNL) which examined the problem, developed a methodology, and lead to this study (ref. 1). Earlier (in 1979-80) BioTechnology, Inc. (BTI) had undertaken a study for the Department of Defense (DOD) to examine the literature and the histories of recent systems procurements (ref. 3). In spite of DOD regulations which specifically require allocation of functions as a step in the design cycle, no case was found in the literature in which the allocation of control functions had been determined in an orderly manner on a system-wide basis.* This was true notwithstanding

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*Note findings of the 1982 NASA Space Human Factors Workshop: "There is currently no systematic, widely applied technology for allocating functions between automated systems and the pilot. . ." (Montemerlo and Cron, ref. 4).

the fact that several methodological models had been developed and were available to guide the allocation of functions. Many obstacles were responsible, but central among them was the absence of an accepted general method and of a professional tradition for the allocation of functions. Accordingly, BTI recommended the development of a practical framework and set of methodological tools which a design team could use in allocating functions.

1.2.2. Methodology Development

In 1982, under NRC sponsorship, BTI began developing an allocation-of-function methodology for the nuclear power industry. Initially a conceptual method was developed for allocation of control functions (or for assessing existing allocations) in NPP control rooms. This method is applicable both to earlier technology using electromechanical process control and to more recent technology involving computers.

BioTechnology, Inc., first examined the history of control technology, then reviewed major models and methods proposed for the allocation of functions. These begin with the "listing" approach. In 1951, Fitts (ref. 5) proposed a table listing the differing capabilities of machines and humans, to be used in support of automation decisions. Since then, more elaborate lists have been put forward, for instance by Mertes and Jenny (ref. 6), Edwards and Lees (ref. 7), and Swain (ref. 8). More elaborate simulations, procedural guides, and information support systems have also been developed, including HEFAM (ref. 9), CAFES (ref. 10), SYSSIM (ref. 11), SAINT (ref. 12), and HOS (ref. 13).* Several of these systems include features which might be applied in determining functions for nuclear power plant control, but most of them either were never developed in an operational form or were predicated on the availability of large bodies of human engineering reference data which do not yet exist. Thus, in spite of widespread concern over this problem, at this time there appears to be no reported instance of a proven methodology for allocating control functions to man or machine, and certainly not one which can be applied to the allocation of cognitive tasks.

Findings of the preliminary research included a recommended rule-based, iterative procedure for allocating functions in the design of NPP control rooms, a procedure based on the hypothetical-deductive model of Price and Tabachnick (ref. 14).

1.2.2.1. The Hypothetical-Deductive Model

The hypothetical-deductive model provided a practical, step-by-step, reproducible method by which allocation could be made. This method was later developed into the operational form reported in Sect. 3.

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*These systems are described in detail in NUREG/CR-2623 (Ref. 1)

The procedure differs from earlier schemes in at least one major feature: earlier procedures provided hypothetical solutions only--however sound they were, they provided only an untested hypothesis as to the correct allocation--whereas the BTI procedure added deductive (or empirical) tests of the hypothetical solution. Furthermore, in the revised procedure specific tests are followed by closed feedback loops so that the designer can search heuristically toward an optimimum man-machine interaction. The method is designed to be applied continuously throughout the system design process, and to provide a series of iterative approximations approaching the goals expressed in a system requirements statement.

Figure 1.1 illustrates principal steps of the recommended method. Note the dashed line, which separates an initial hypothetical phase from the evaluation phase. This second phase is called the "deductive" phase when deductive rather than empirical tests are employed, as must be the case during the early (concept or preliminary) phases of design.

The hypothesis procedure

In the hypothetical-deductive model, initial decisions identify those functions which for obvious reasons must be allocated to man or machine. Such allocations must be made to automation (Step 1), for instance, when regulation or policy requires it, when hostile environments preclude the presence of man, or when the required system reaction times exceed human response limitations. Allocations to human control (Step 2) may be mandatory when there is a requirement to develop strategies or detect patterns or trends, or when meaning or values must be assigned to events. Additional tests are applied for economic and technical feasibility (Step 3), and in some cases a tentative decision may have to be fed back for reconsideration at the system requirements level.

Steps 1 and 2 are repeated first at the whole-system level, then for subsystems, and finally for portions of subsystems, until those parts of the system which clearly must be controlled by man or by computer have been partitioned off and properly assigned. Normally this will leave substantial portions of the system and the operating procedure to be allocated either to man, to machine, or to some combination of the two. At Step 3 these functions are classified according to a performance taxonomy and allocated on a best-choice basis.

At each point in this process decision aids are provided, but the actual decisions remain judgmental. It is suggested that the procedure be applied by a team including at least one experienced human factors engineer and one design engineer experienced in the type of subsystem being considered. The method provides an orderly decision procedure and a set of decision aids. More importantly, it provides for documentation of the decision process, which makes it possible for allocation decisions to be communicated widely within the systems design organization. It also provides a basis for the evaluation steps which follow. Finally, it provides a basis for iterative improvement and elaboration of detail in the man-machine relationship, and interaction with engineering design decisions as the system design evolves.

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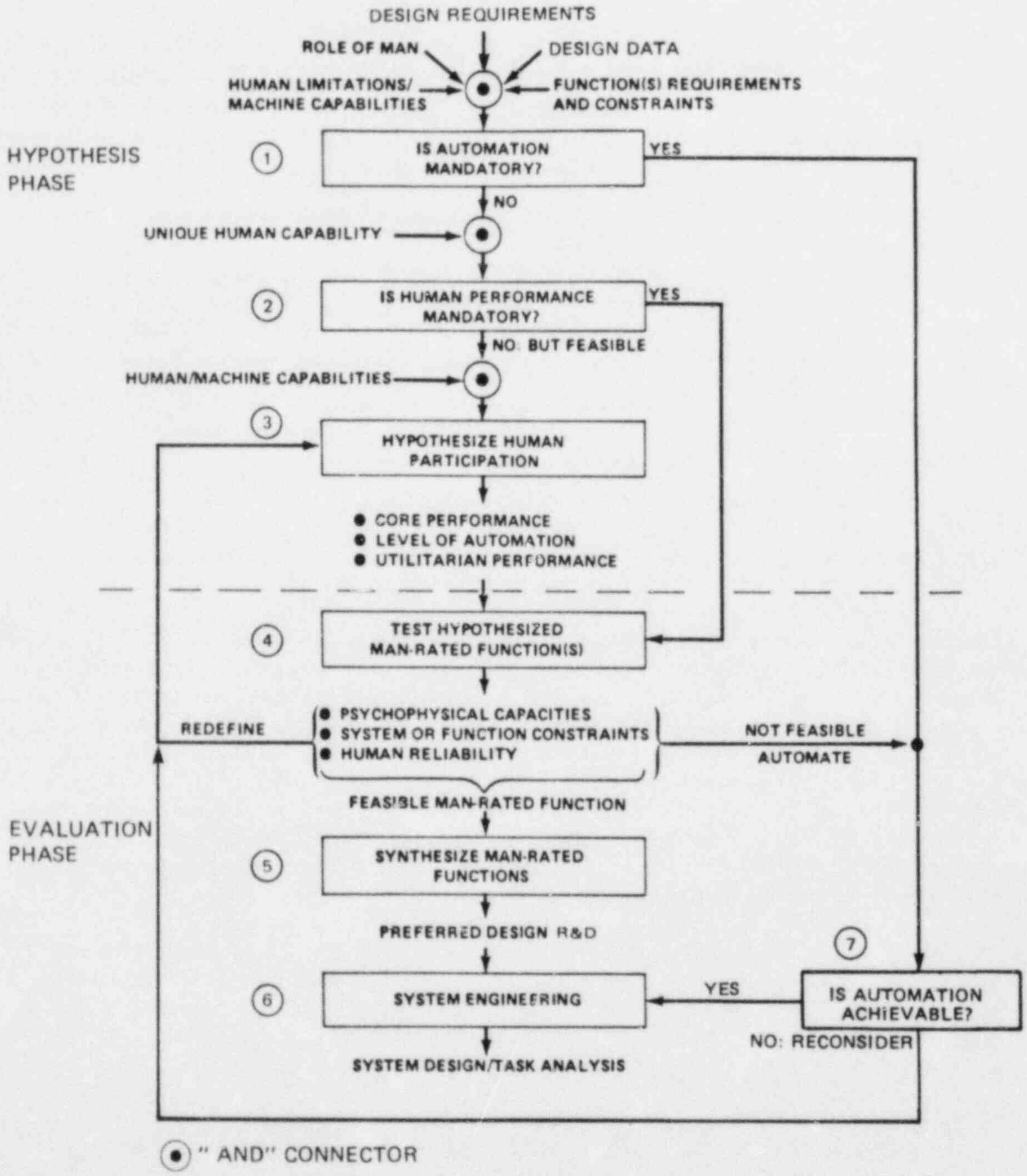

Fig. 1.1. The hypothetical-deductive model.

The deductive evaluation procedure

At this point in each cycle of the system design, an allocation of functions to man or machine has been hypothesized. In a design which has reached the mockup or prototype phase, an empirical test is appropriate. The hypothetical-deductive model also provides a set of deductive tests which can be used during concept formulation and other early design phases.

In Step 4, those functions hypothesized as "man-rated" are reviewed in detail against the known psychophysical capabilities of man, against system constraints, and against reliability requirements. If these requirements are met, Step 5 forces the analysis team to ask whether the human job, as it is emerging, is acceptable to an operator. At this point modifications are made to ensure that operators will feel supported and important, that the job is coherent, and that it will fit into a reasonable authority and social structure. Depending on test results (Steps 4 and 5), elements of a preferred man-machine design are provided for systems engineering (Step 6) or are fed back to other steps of the design process. Finally, if any function hypothetically allocated to automation proves technically infeasible, it is looped back for reconsideration (Step 7).

1.2.3. Implementing the Method

Having identified the hypothetical-deductive model as a concept, the next step is to make it an operational method by relating it to the normal design practice.

The detailed methodology developed by BTI for the allocation of functions is designed to be applied during the original design of an NPP system or during the development of a design modification. This methodology is an operational form of the hypothetical-deductive model, and it fits easily into the iterative cycles of inventive hypothesis, integration, and test which are features of good design practice. The method is described (in Sects. 2 and 3) in terms of 26 steps, steps normal to systems design which are linked to the allocation-of-function decision. The method is not intended to be prescriptive, but is adaptable to the many variations of design practice in industry.

It was considered useful to develop a means by which the methodology could be applied to evaluate the allocation of functions in existing designs (including existing NPP control rooms). Such a method was developed and subjected to a preliminary test, which is reported in Sect. 4.

1.3. REPORT OUTLINE

This report consists of seven sections and three appendices: Section 2, "Defining the Problem," reports lessons learned during research, defines the terms to be used, and describes significant characteristics of the design process which affect the allocation of functions. Section 3, "The Design Process," outlines that process in terms of 25 steps plus the data base (Step 26). It explains how allocation-of-function decisions are embedded in other design decision processes. Section 4, "The Allocation of Functions," expands on Steps 11 and 19 (see Sect. 2), in which an allocation of functions is first hypothesized and then tested. Section 5, "Evaluating an Existing Design," describes the procedure for evaluating an existing control room or NPP design. Section 6, "Quantifying Goodness of Allocation," describes a procedure for formulating a quantified score--a "goodness of allocation" rating of either an existing design or a design under development. Section 7, "Conclusions," summarizes the conclusions of this study and identifies useful directions for continued research.

The three appendices contain reference materials and tabular data which may assist designers in performing an allocation of functions.

2. DEFINING THE PROBLEM

This section discusses a series of problems which confront the designers of systems, with special emphasis on the allocation of functions in the design of NPPs. Some of these problems are familiar ones with recognized solutions, requiring only adaptation to the nuclear power industry. Others are problems for which there are no generally agreed solutions, or which have not even been identified as questions.

This section might have been called "lessons learned," because it reports what was discovered during two years spent developing a method for allocating control functions to man or machine. This section defines the problem of allocating functions, discusses some issues involved in that problem, and clarifies the terms used in this report. In addition, it will describe certain basic principles of complex systems and of the system design process. These principles, although sometimes not recognized or fully understood, are essential to the making of appropriate allocation decisions during design.

In general, our concerns are for the allocation of process control functions and tasks to man or machine, and especially the NPP control room, which is a specialized case within process control. In designing a control room the operational question is whether control actions shall be automated or manual; in most cases both man and machine are mutually involved to some degree.

2.1 DEFINING ALLOCATION OF CONTROL FUNCTIONS

What does the phrase "allocation of control functions" mean? The surface answer is obvious: In any process control system the operator is required to do certain things and certain things are done automatically. Allocation of functions is the apportionment of the control functions, which is determined by the design of the plant and the control system. It is often an issue when human problems arise.

The design procedure in which the allocation-of-function methodology is embedded represents an extension of the practices found in other process control industries. There is, for instance, a system analysis taxonomy by which functions of a projected system are allocated among four resources: men, data (computer programs and procedures), equipment, and facilities. Such a taxonomy is a useful one where it applies to whole-system design. In the control room, however, the facilities are mostly predetermined and data, not being independent of other resources, resides variously in man, in software, in documents, and in instrumentation. Furthermore, system analysis taxonomy does not provide tools for deciding the central question of whether logical functions shall be performed by human cognitive function or by automated system logic. When used in this report, therefore, the phrase "allocation of function" will mean specifically the allocation of control functions or tasks to man or machine in a remote process control operation.

2.1.1 Allocation is a Visible Problem

Designing existing systems adapted for human control requires more effort than pure equipment design. Design decisions originally made on engineering grounds alone become fixed in hardware and software, and may limit the flexibility of the human role. With automated functions, human operators may be unable to observe the process or to exercise useful control. To the obverse, they may be required to perform chores that are unnecessary or tasks for which humans are poorly adapted. To a large extent these design oversights occur because during the design phase no explicit consideration was given to which functions should be allocated to man and which to automation.

2.1.2 Allocation is Part of the Design Decision Process

Once a design engineer selects a tentative engineering design for any part of the plant, it includes certain implicit or explicit control requirements to control off-on conditions, to alter configuration, or to change engineering parameters in order that the plant can perform its mission under all conditions. As a next step in design, someone must decide whether the required control should be manual or automatic.

In conventional design practice that decision may often be reached by default. Many designers, not being consciously aware of the decision, proceed to design controls based on past practice or on purely equipment engineering considerations. When designers do consider automation as an option, the tendency is to automate all functions which are easy to automate, including tasks which may be better done by humans. There is a corresponding tendency (at least statistically) not to automate those tasks most burdensome to the operating crew. The needs and characteristics of man are seldom considered unless the designer has had personal experience as an operator. At best, the question is usually addressed intuitively rather than systematically.

2.1.3 Allocation Defines a Subsystem Interface

Industrial systems can be considered to consist of two major elements: a mechanical subsystem (the plant) and a human subsystem (the organization). The plant is established to perform an economic mission (generate electricity). The human organization provides direction, control, and maintenance.

Within that system, allocation of control functions defines the boundary between the things done by man and those done by machine. In general, *it is our objective to maximize the proportion of the mission accomplished by the machine*. That is the purpose of machines--to unburden man, and to increase his productivity. There always remain things, however, which man should do himself, either because he does them better, because he must retain control, or for other reasons which will be examined later. Allocation of functions is the logical step in system design at which to draw the boundary between the mission of the physical plant and that of the operating crew.

2.1.4 Allocation is an Invention Process

Control function allocation requires invention, as do other elements of system design. Each design decision is composed of three closely interacting parts: (1) an engineering system decision, (2) a human system decision, and (3) an allocation of functions decision. The engineering system decision identifies specific hardware to accomplish a function; the human system decision determines who will operate the hardware; and, finally, the allocation of functions decision determines which control actions will be performed by man and which by machine.

The three parts of the design decision are made as inventive hypotheses. In all three the designers call on their knowledge of past technology, compare it to a present problem, and hypothesize that a particular solution will solve the problem.

2.1.5 Allocation Responds to an Engineering Hypothesis

The steps in the design process that follow represent an extension of the traditional approach to system design taken by the process control industry. The feedback path which encourages iteration towards an optimum solution, in particular, has been made explicit. The approach shown also attempts to mimic in a macrocosmic sense the microcosmic pattern of individuals engaged in inventive design, although the process in an individual may occur more as a parallel activity than as the serial process outlined here. This evolutionary process is purported to be realistic but not necessarily an optimum one for all systems. Experts disagree on what should be the ideal pattern for the system design process. Figure 2.1 presents the following logical steps in design hypothesis:

1. Mission Requirement. The specification of the systems and the statement of overall objectives in function-oriented language (as contrasted with hardware language) must already exist in a documented form prior to this step. In this step, then, these objectives become embodied in a requirement to perform the functions necessary to accomplish the plant's mission. The authors, however, agree that a purely functional statement cannot exist without some implied hardware hypothesis.

2. Hardware Hypothesis. The systems engineers and design team hypothesize that a certain engineering solution can perform the functions under consideration. This solution is selected from analogous past technology modified as necessary. To allow maximum latitude for design innovation, the hypothesis is stated in general rather than component-specific terms. The lower limit to the specificity of the hypothesis is difficult to state explicitly and must be left as a judgment to be made by the team.

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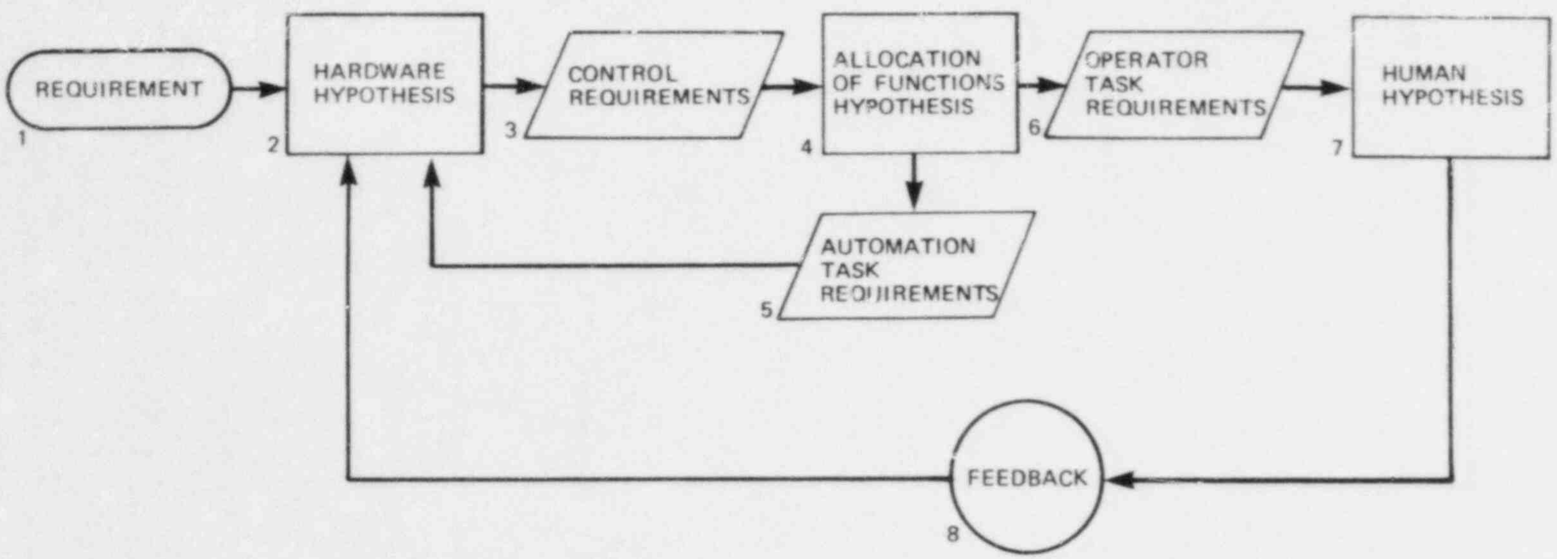

Fig. 2.1. Logical steps in design hypothesis.

3. Control Requirements. The mission and the hypothetically selected hardware impose certain control requirements, which are estimated.

4. Allocation of Functions Hypothesis. The designers hypothesize that certain control interventions will be made by a human operator and others will be made by automation.

5. Automation Task Requirements. Control interventions allocated to automation become automation requirements, and must be added to the hardware hypothesis.

6. Operator Task Requirements. Control interventions allocated to man become operator task requirements.

7. Human Organization Hypothesis. A human organization is hypothesized to meet support requirements of the operating crew. This includes supervision, control room crew structure, training, etc.

8. Feedback. If an acceptable human organization cannot be hypothesized, the hardware hypothesis must be modified. This iteration is not optional but is a necessary part of the process.

These eight steps are logically sequential. In fact, the steps are closely interlinked and may seem to occur as an effectively simultaneous decision. This does not alter the fact that the hardware hypothesis affects the content of all subsequent steps, as is the case when the designers adapt a well-tested existing (analogous) technology. They call on historic experience, which includes not only information about the capabilities of the hardware, but also precedents for the allocation of control functions and experience with the human organization.

2.1.6 Allocation is Implicit in Hardware

The engineering subsystem (the plant) is defined by the sum of the hardware hypotheses which survive design review and are incorporated in the final system design. Similarly, the human subsystem (the organization) is defined by the sum of the human hypotheses which survive and are incorporated in the final human factors plan. At that point, the three elements of a system design are present: an engineering subsystem, a human factors subsystem, and an allocation of functions between them. Embodied in them are the control allocations chosen. In the human subsystem, allocation of functions determines the operator task requirements which the human subsystem satisfies; in the engineering subsystem it generates the control requirements and automation capabilities.

The human subsystem design may or may not fully reflect the allocation of functions, at least as observed from outside that system. But once the design is conceptualized, the allocation of functions is completely implicit in the engineering subsystem. That system (which includes instrumentation and controls) determines whether a control function will be performed automatically or by man. This becomes a limitation on the system more difficult to change than if it would leave arisen from the human subsystem.

2.1.7 Allocation Drives Human Factors Requirements

A decision to allocate a function must also be accompanied by an analysis of the secondary consequences of that allocation. If a function is allocated to man, that allocation will drive requirements for operator selection, operator training, and procedural documents. The later development of selection, training, and procedural documents is an assumed condition for the decision. The allocation will not work unless those conditions are fulfilled, and their cost and feasibility are considered in making the allocation.

2.1.8 Allocation Documentation

In conventional practice, the engineering subsystem is usually documented in its final form by drawings and specifications. In contrast, the human subsystem is often less well documented, which may reflect a lack of attention to human factors design. The allocation of functions usually is not documented at all, either because allocation decisions are not now made in a deliberate way or because the designers do not recognize allocation as an important question.

To provide for analysis of allocation decisions and develop a base for future decisions, it is essential to fully document the allocation process, including alternatives, criteria, and final decisions. Although allocation is completely implicit in the engineering design, the reasoning behind each decision and the options which were rejected are not discoverable from that design. Allocation data will be valuable later, each time the engineering team detects a problem in design hypotheses and thus must reconsider the earlier design steps; this necessity recurs constantly. For the same reason it is also desirable to preserve selected historic records of the engineering and human designs, records which in the nuclear power industry are usually discarded too soon. Documentation will be discussed in more detail in Sect. 2.8.

2.1.9 What Allocation is Not

The allocation of functions is only one of many steps in the design sequence. It does not include some other issues with which it may be confused. These include:

1. Interface Design: The design of controls and displays depends on clearly specified operator task requirements (Fig. 2.1, Block 6). These requirements follow from the allocation decision and are greatly assisted by a clearly documented allocation, but the actual interface design is a separate set of decisions.

2. Automatic Control System Design: This separate step also uses the automation task requirements which result from allocation.

3. Human Factors Engineering: Allocation of functions supplements human factors engineering and uses the same professional skills but does not replace it. Human factors support is a separate and continuing requirement during design.

4. Job Design: Job design is the separate step by which human tasks are allocated to particular job positions. It is part of the human subsystem design.

5. Component Selection: According to some of the design literature, allocation of functions is considered to consist only of selecting system components in reference to human capabilities and limitations. This is an insufficient view of the problem. This view may result from too specific statements during the allocation decisions.

6. Maintenance: A system in operation requires two kinds of intervention by man: control and maintenance. Although this report is restricted to the allocation of contiol functions, allocation of maintenance is no less important. Treatment of maintenance allocation requires a separate and substantially different approach.

2.1.10 Summary

Allocation of functions should be a logical step in the process of system design, a step in which an interface is created between the control responsibilities of the engineering subsystem and those of the human subsystem. This step should define requirements for automatic control equipment and human operators. Once a system is complete, the allocation of functions is implicit in and bounded by the hardware design.

Allocation is invented along with the design (subsystem) engineering and human subsystem designs. Preservation of records tracing the logic behind allocation decisions is a necessity because those decisions must be reconsidered frequently during the design process.

2.2 THE DESIGN PROCESS

Economic requirements are generally the driving force in system design, although in some systems (such as aerospace) a social requirement may supersede the economic one. Designers must invent a new system to meet that requirement by adopting elements of existing technology, and then proceed by repeated cycles of hypothesis and test. First the gross elements of the system are hypothesized; those elements are then decomposed into subsystems, developing and elaborating detail with each cycle of hypothesis and test. Hypotheses are rejected when they prove infeasible or in conflict. Once the system has been hypothesized and tested at the component level, the design is complete.

2.2.1 Invention

Design is a process of invention even when, as is frequently the case, a new design is nearly identical to a prior design. It appears that no matter how originial a new deign may seem, the invention of it proceeds by a process of resynthesis and adaptation from existing technologies.

Invention is the process by which hypotheses are formed that postulate a possible system solution to the requirement and to each of its supporting functions. Invention provides hypothetical solutions for each of the three elements of a system design: (1) a hardware solution, (2) an allocation of functions, and (3) a human solution.

2.2.2 Process Sequences, Subsystems, and Plant States

A plant achieves its objectives and thus meets the mission's requirements by a process of functional sequences. To perform those sequences, the subsystems of the plant are configured through a series of distinct operational states that correspond to the required functional sequences. For instance, an NPP must be able to assume (among others) a refueling state, several power generation states, and several shut-down states. It must also be able to assume emergency, maintenance, and test states which may actually be substates.

The state analysis begins by hypothesizing (1) the major process sequences, (2) a sufficient set of subsystems to perform those sequences, and (3) the states (including transitional states) that the plant is required to assume. These are the elements of the requirement. Additional control requirements will be discovered by further hypothesizing the control interventions needed to maintain stable states, and to achieve transitions from plant state to plant state, including emergency, test, and maintenance states.

2.2.3 Hypothesis and Test

Design decision proceeds by a repeated cycle of hypothesis and test, as has been noted earlier. For each element of the requirement, the designers formulate a hypothesis concerning the engineering solution, the allocation of functions, and the human solution. They then test these hypotheses in a number of ways. They test for completeness and consistency of the match between engineering and human solutions, for engineering and human factors feasibility, for consistency between subsystems, for cost, and by system simulation or other empirical tests. More often than not, these tests reveal weakness or error in the initial hypothesis. Cycles of hypothesis and test continue until a sufficient system-wide set of hypotheses is achieved.

2.2.4 Iteration

Engineering design is recognized to be an iterative process, during which an optimum design is achieved only after many cycles of preliminary design, test, and modification. Design of the human component in a man-machine system likewise should be an iterative process. We actually know less about human performance and human materials (which are more variable) than about engineering performance and materials. It follows that an optimal allocation of functions during design does not result from a one-time decision. Instead, the allocation of functions requires repeated effort, concurrent with each cycle of engineering and manpower subsystem re-design, throughout engineering development and continuing during the life of a system. Each cycle of iteration should result in a reduction of errors and an elaboration of detail.

2.2.5 Elaboration of Detail

As suitable hypotheses are developed for the gross elements of design (major subsystems and processes), those elements are decomposed into their subelements, which are in turn developed in detail by hypothesis and test. Each iteration of hypothesis and test provides a further elaboration of detail until the plant has been defined to the component level. This report, however, does not address allocation of control functions at the component level but rather with "functional design," an early phase of design (see the discussion of levels of design in Sect. 2.3.6).

2.2.6 Expert Judgment

As the design process continues, detail and specificity increase. The performance of humans and of components is stated specificially in terms of their characteristics--what they require as inputs, and what they produce as outputs. But in actuality, practically all design hypotheses depend not so much on quantified data as on expert judgment, which in turn may be highly subjective. This is true because there are too many variables interacting, because time constraints do not permit in-depth analysis of options, and because many of the variables are in fact not quantifiable. For instance, there is always a distinct uncertainty about when, how, and why even a proven component will fail. A great uncertainty remains about the system-wide consequences of a component failure. And each time a previously undemonstrated technology is introduced, these uncertainties increase. Therefore, to an extent that designers may be reluctant to admit, all design depends on the continuous exercise of expert judgment and on experience, if not intuition. This is true particularly during the early stages of system development.

2.2.7 Analogous Technology

As was suggested earlier (Sect. 2.2.2), all invention or system design proceeds by the adaptation or resynthesis of previous technologies. This is true at both high and low levels of innovation, where innovation may be represented on a one-dimensional continuum.

At the lowest level of innovation the designers simply reproduce portions of a previous design, adapting it only enough to fit into the scheme of the new system. In such cases there is probably ample data on the empirical performance of the equipment, and perhaps even anecdotal data on its human factors suitability. But even with a proven design there are some uncertainties. There are likely to be unexpected mechanical interactions between portions of the new system, and there may be unexpected human problems, due (for instance) to perceived control inconsistencies between subsystems of the overall design. Some of these problems can be predicted by mathematical analysis and simulation. But in general it is the designers' experience with prior designs--with analogous technology--that tells them where to expect problems in adapting proven technology to its new system setting.

At the highest level of innovation, designers occasionally develop completely new applied technologies, previously known theoretically or as a laboratory phenomenon. During the 1950s, for instance, most of the modern reactor types went through this process. In such cases the number of unknowns is enormous, and the designers must certainly depend on their general experience with analogous technologies in order to predict the performance of a uniquely new design. They must do this at the component level, at the level of system interactions, and at the level of interaction between the equipment and humans.

Analogous technology makes expert judgment (Sect. 2.2.6) an effective basis for decision. Expert judgment is based almost wholly on, and is calibrated by, expert experience with analogous technology, human and machine.

2.2.8 Elements of System Design

The design process outlined in Sects. 2.2.1 through 2.2.7 defines the functions of a new system, and for each function develops the elements of design: (1) a hardware solution, (2) an allocation of functions, and (3) a human solution. At the whole-system level, these elements are summed to form the elements of a system: (1) an engineering subsystem, (2) an allocation of functions, and (3) a human factors subsystem.

2.3 THE SYSTEM APPROACH

Previous paragraphs have suggested a distinction between "design" and "system design." As used here, system design refers to a modern industrial design concept most widely known for its use in government procurement procedures. System design refers to the formalized use of a set of rather ordinary logical practices in design. These include precisely stated objectives; integrated plans for all engineering and human subsystems; timed delivery schedules; central management; and planning to optimize costs, risks, and benefits for the full life cycle of the system. These practices have always been features of good management. They were formalized in the 1950s for defense systems development, with the objective of controlling costs and assuring that the required elements of a new system would come together at the proper time for operational use.*

This doctrine is now documented in DOD Directive 5000.1 (ref. 15) and in numerous supporting regulations.

Features of the system concept which should be (but sometimes are not) recognized in NPP design include the following:

2.3.1 Stated Objectives

Clearly stated objectives are derived from the system-level specification. Such objectives should be relatable to system functions. Further analysis and design will respond to them.

2.3.2 Defined Subsystems

The system is described in terms of its subsystems. The major subsystems can be grouped as the engineering subsystem (plant) or the human subsystem (organization). These, in turn, include subsystems such as the training program, procedures, simulators and training facilities, fuel supply, and spent fuel disposal, plus the conventionally recognized engineering subsystems (reactor, steam generator, etc.).

2.3.3 Target Dates

In the nuclear power industry target dates are often perturbed by regulatory and other delays. Nonetheless, it is essential to plan so that trained staff and developed subsystems can come together at dates required by a development plan. System planning normally uses a formal procedure (PERT, Critical-Path Method) to coordinate the interdependent subtasks of design and development.

2.3.4 Interdisciplinary Teams

Large systems are designed by teams of specialists, and their coordination becomes vital in order to avoid wasted effort and to ensure that all subsystems are able to interact consistently. This coordination is provided, first by active central management, second by formal cross-consultation between teams, and third by requiring interdisciplinary team

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*Elements of a military system include the timely availability of prime mission equipment, munitions and supplies, logistics, operating crews, maintenance personnel, a training support system, communications, spare parts, and all other support equipment needed from initial development to retirement of the system.

membership (and here human factors consultants should be present when control design is being considered). Finally, good design documentation records the process and products of the team efforts.

2.3.5 Design Documentation

The value of a documentation system will be treated in detail in Sect. 2.8. Suffice it to say here that, to be effective, the documentation system must be formal, must use common terms and conventions, and must be available for access by all designers at all times. Use of the documentation system should be enforced to ensure that its data is always timely regarding each subsystem under development. Selected historic design data should be preserved. Such a data base can be effected by computer technology and integrated into design by computer-aided engineering (CAE) and computer-aided design (CAD) systems.

2.3.6 Functional Design and Developmental Design

Design theory recognizes that a new design evolves through several phases of progressively greater completeness and detail. These phases are usually described by terms such as "concept investigation," "system analysis," "experimental development," "breadboard design," "advanced design," "full-scale design," "final design," and so forth. Here the authors distinguish only two levels: functional design and developmental design. This report deals only with functional design, which is that phase of the design sequence during which the major functions of a plant are identified and are assigned generalized design solutions, including a generalized allocation of control functions. Similar procedures and principles will apply during developmental (component-level) design, but the terminology is somewhat different and new issues will arise during that later phase.

2.4 DEFINING A FUNCTION

For the allocation process to work, an operational definition of a function is necessary. This has already been suggested in Sects. 2.1 through 2.3. Functions then are what the plant does to achieve its mission, and they are defined operationally during the process of designing the plant.

2.4.1 A Function Provides an Interim Product

A function, as used here, is the capability of specified subsystems to produce a specifiable final or interim product, a capability which is useful to consider as a unit during early design. All functions of the plant taken together should be sufficient to carry out the plant's normal and emergency missions.

Function products can be either material or informational. For instance, we can define the functions "produce steam" and "achieve criticality;"

these are material products. We can also define the functions "display reactivity data" and "keep the grid dispatcher informed;" these are information products.

2.4.2 A Function Exercises Subsystems

Each function is performed by exercising one or more subsystems or components of the plant in specific configurations. For instance, "produce steam" exercises the reactor, the steam generator, the pressurizer, the feedwater system, and the control system, each in one or more operating configurations. However, for two reasons a function cannot be defined solely by the subsystems it uses: First, many subsystems serve more than one function, just as the feedwater system supports both the functions "generate steam" and (indirectly) "cool the core." Second, functions are defined in part by the plant states they employ or support.

2.4.3 A Function is Performed Under Specific Plant States

A function is further defined by the set of plant states under which it is performed. A plant state is a specific configuration of the plant and its process parameters. Thus "produce steam" may be performed under several normal and partially degraded operating states, as well as some non-operating test states.

2.4.4 Function Products Can Be Necessary or Accessory

The interim products which a function produces are necessary if they are part of the minimum set essential to operate the plant accessory or if they are useful but not essential. In fact, it may be useful to distinguish three principal categories of function as defined by Price, Smith, and Behan (ref. 16). These functions are multiplicative, additive, and control. This classification is based on an assumption of two serial requirements in system development: The first is to specify the tolerance limits within which the system must remain, and the second is to maximize the reliability of the system within those limits.

1. Multiplicative Functions. Multiplicative functions are required for normally stable system performance. Reliability is an additional and different consideration. Thus in an extant system one can identify multiplicative units by considering each unit in the system individually and asking whether it would be possible to obtain the system output if the unit were deleted. For most complex systems, it will be possible to delete many units without making the system output impossible. Those units which prove necessary to the output of the system are called multiplicative.

2. Additive Functions. Additive functions are included to improve system reliability or product quality. Reliability of complex systems is obtained by two general methods. The first of these is the use of

inherently reliable components within the multiplicative or prime system, and the second is the inclusion of additive functions which can return performance to normal limits whenever performance of the multiplicative system goes out of tolerance. For example, emergency power supplies provide additive functions. Additive functions may also include other features not directly related to performance, such as safety, confidence, information, and data filtering. It may be said of additive functions that the final system output may occur even if the output of any such function does not occur.

3. Control Functions.

   a. Essential control functions. Essential control functions are multiplicative functions as defined above, including those control and display functions which are exercised in the principal or most usual modes of control.

   b. Accessory control functions. Accessory control functions are additive functions as defined above, including those display and control functions which are themselves additive--controls and displays which are redundant or provide alternative modes for control.

2.4.5 Functions are Defined by Progressive Partition and Invention

Functions are defined by partitioning the system into sets of hypothetical functions (see Sect. 2.2) and then attempting to invent the elements of design for each function. The functions of a system have been operationally defined and the functional design phase (Sect. 2.3.6) is completed when the plant has been partitioned into elements for which it proves possible to provide a satisfactory hardware solution, an allocation, and a human solution, and when the functions are defined at a satisfactory level of detail.

"Satisfactory" levels of definition and detail (which the design team must decide) are levels which provide sufficient information to begin developmental design and component selection. Ordinarily, the functional design phase continues until it is no longer practical to further partition the functions. This is desirable because better designs can be achieved if options are kept open by not selecting particular components until a highly detailed functional design is complete.

2.4.6 Functional Decomposition May Not Be Unique

Obviously, most systems can be partitioned into functions in more than one way. Usually more than one set of definable functions could meet the mission requirement. Some of these may be better than others, but none are wrong if they produce a system that meets the objective. Thus the best set of defined functions is the one which is most useful in the design decision process.

2.4.7 A Function as an Artificial Construct

Each function represents some hypothetical capability (an included interim product) of a future plant, a capability which may some day be made concrete in working processes and components. Those detailed processes and exact components are not known early in the design process. Defined functions provide an artificial construct by which the designers can deal with the processes of the plant while the plant's exact structure is still being determined.

2.4.8 Keeping the Solutions Out

Restating: (1) a function is defined by partitioning the processes of a future plant into subprocesses, each of which produces an interim product; (2) a function is defined operationally by an interaction between two hypotheses--a hypothesis about the mechanical subsystem (the hardware hypothesis) and one about the human subsystem (the human hypothesis). This reference to a hardware hypothesis implies that the designers will form an early hypothesis about the design of equipment. In fact, Sect. 3 will expand this logic by describing how the designers begin by hypothesizing an engineering solution to which later steps react.

This appears to contradict some experts in the field of system theory who emphasize that designers should keep their options open by not selecting the particular means by which a function will be accomplished. It is said that designers should "keep the solutions out" until the functional design is complete. Functions, it is said, should be specified only in abstract terms or in terms of inputs and outputs.

This guidance is considered somewhat unrealistic. It seems neither practical nor desirable to consider functions as totally abstract subprocesses. In fact, humans cannot think about future capabilities except in terms of past technological experience. Real-world design occurs by adaptation from the past. It rarely makes great leaps of invention, but creates by adaptation, exception, and improvement to the capabilities of prior technology. So it is permissable, potentially useful, and even inevitable that, having defined a function, the designers will immediately begin to hypothesize its engineering solutions. To retain flexibility of choice, however, engineering solutions should be described in general (not specific equipment) terms.

2.5 THE MULTIVARIATE SETTING

Men and machines working together in systems represent an activity too complex to be completely described, even by expert analysis. In each man-machine transaction a great number of mechanical, perceptual, cognitive, and other variables are at work, with no two transactions being the same. As a result, no simple algorithm or decision rule is currently achievable by which the categories of control transactions can be classified or the allocation of functions decided. In other words, "there is no cookie cutter."

Instead, the decision to allocate functions is characterized by the following features:

1. Not all variables can be identified.

2. Of the variables identifiable, many cannot be measured practically.

3. Most decisions are perturbed by value judgments: cost versus safety, safety versus power production.

4. Most decisions require statistical assessment of probability in reference to risk, future equipment performance, and future human performance.

5. Engineering predictions can be based to some extent on mathematical analysis. By contrast, there are few reliable equations or quantified data to predict human performance (see also Sect. 2.6).

6. Even engineering predictions must finally depend on expert judgment (Sect. 2.2.7).

As a result, decisions to allocate functions can often be made only by an exploratory process in which the final basis of choice is expert judgment. From this perspective, the allocation of functions resembles other decisions in engineering design.

2.5.1 Professional Judgment

Under these conditions, the system designers are ultimately forced to rely on the judgment of informed professionals. At each step in the allocation process some limited quantitative information can be provided which may include information about expected engineering performance and the control demands which engineering imposes, but even this is speculative because the system does not yet exist. Human performance can be predicted by analogy to past experience, as was mentioned earlier, but the available data must be evaluated against the other variables and unknowns, using expert judgment.

Professional judgment will be most effective if it is a consensus representing several disciplines. It is therefore suggested that these decisions be made by a panel, which should include at least the following features:

1. Documents and resources should be assembled beforehand.

2. Minimum qualifications of members should be specified and enforced. The panel should include a senior member who has broad system experience; participation by human factors, engineering psychology, or equivalent members; and participation by design engineering experts from the specialized areas concerned.

3. Meetings should be formal and controlled by an agenda. The agenda should assure that all decision steps (Sects. 3 and 4) are taken.

4. Formal records should be kept of alternatives considered, of decisions made, and of the basis for decision.

5. A forced decision strategy should be employed when necessary to speed functional design. Experts on group interaction encourage consensus on decisions to preclude the alienation of individual participants.

2.5.2 Analogy to Known Systems

A useful source of information for these tasks will be experience with analogous systems. This, after all, is the source of all design data, predictive or speculative. Analogous systems will be particularly useful when records or anecdotal data concerning human performance in those systems are available. Unfortunately, such data have usually not been recorded, and the design team may have to rely on the personal experience of its human factors members (see Sect. 2.2.8).

2.5.3 Operator Experience

Potentially the single most useful source of information is the past experience of operators. Experienced operators should be present on the design team, as well as available for consultation as subject matter experts (SMEs). The value of operator experience will vary, depending on the quality of the people available and the degree to which their experience has been with systems analogous to the one being designed. However, operator experience will be observational only, with little theoretical speculation.

2.5.4 Forced Decisions

In dealing with many variables, the consensus of a team is more reliable than any single judgment. Therefore, allocation of functions should be performed by a multidisciplinary team (Sect. 2.5.2).

A team, however, can be cumbersome if required to actually agree on every point. Several hundred separate decisions must be made during each of several iterations of the hypothesis-test cycle, and it is more useful to make decisions rapidly and test them repeatedly than to seek perfection in each decision. Thus it may be more expeditious to use an authoritarian procedure in which a group discussion is followed by a brief effort to reach a consensus, but concluded, if necessary, by the team leader prescribing a decision. Care must be exercised to prevent this procedure from alienating individual team members.

2.5.5 The Methodology

Section 4 describes a methodology for the allocation of control functions to man or automation. Present practice permits the allocation judgment to be overlooked altogether or to be made by unqualified persons without using available information, without considering all aspects of the question, and without reference to the rest of the ongoing design process. The methodology of Sect. 4 is designed to ensure that

1. All available information is gathered and made available.
2. The allocation decision is broken into its logical elements.
3. The allocation decision is the sum of several judgments, made in a rational sequence.
4. Judgment is made by qualified personnel, by consensus when possible.
5. Each judgment is informed by an expanding body of analysis and design data.
6. All aspects are considered.
7. Each judgment goes through several cycles of hypothesis and test.
8. Allocation is closely responsive to other design decisions, and it changes when those decisions change.
9. A record is preserved for use during later cycles of redesign or retrofit.

2.6 INFORMATION PROCESSING AND INFORMATION PROCESSING BEHAVIOR

In preliminary research for this project the authors found that several methodologies for allocation of functions have been reported in the literature or demonstrated in industry, but that none of these was directly applicable in the nuclear power industry. In general, this was for two reasons: (1) the method assumed that extensive standardized data on human performance would be available, data that actually do not exist, or (2) the method was useful only in allocating functions for overtly observable psychomotor behaviors. No existing methodology could handle the cognitive tasks which are the principal activity in process control such as found in an NPP.

2.6.1 Process Control

Control requirements in process control are different from those in other industries, as well as from those of the industrial settings where applied psychology has had its greatest success. To examine the differences, it seems useful to classify human tasks into two major categories:

1. Ergonomic Tasks. There are tasks which are primarily ergonomic. In such tasks, the operator reacts to situational stimuli, using overtly visible psychomotor responses which can be described and measured. Included are tasks such as shoveling coal, piloting a vehicle, typing, and using tools to repair equipment. While these psychomotor tasks require the mental processing of information, they can be adequately measured from overt behaviors and immediate work products.

2. Information Tasks. These are tasks which take place primarily in the mind of the operator. In such tasks, the operator observes equipment, monitors instruments, compares, evaluates, predicts, remembers conditions, and plans actions. When he acts, typically it is by a verbal command or by momentarily touching a control. That action does not reveal to the observer what the operator did in making the decision, nor what he expects his action to do to the plant. Such cognitive/information-processing tasks occur in process control, management planning, computer operation, labor supervision, military intelligence analysis, and research. Cognitive tasks are an increasingly large proportion of all tasks in modern industry, but neither industrial psychology nor industrial management are equipped to deal with them.

   The methodology reported in Sect. 4 is specifically adapted to the consideration of cognitive informational tasks. Specific analysis tools are identified for dealing with such tasks, and, in particular, the use of a formal cognitive model is suggested (see Sect. 2.6.2). In contrast to some earlier methodologies, the method recommended is heavily dependent on expert judgment rather than quantified analysis. This is perhaps undesirable, but it is made necessary by at least two considerations:

   - As was noted above, past methodologies failed because the quantified standard performance data on which they depended do not exist and probably will not exist for many years. Those data that do exist are for psychomotor tasks only; quantified data for cognitive tasks are almost wholly nonexistent.

   - Even if data existed, the number of operating variables and the complexity of their interaction is so great that no algorithim for their analysis would be feasible, as was noted in Sect. 2.5.

2.6.2 Use of Information-Process Models

Plant functions which require cognitive tasks in control can be evaluated using formal models of the information processing sequence. Three categories of possible models are shown in Fig. 2.2.

1. Models of the control requirement. Block 1 of Fig. 2.2 represents possible models of the control requirement for a task or function. Given a general future engineering design, one might ask what control actions will be required to configure and control the plant in all

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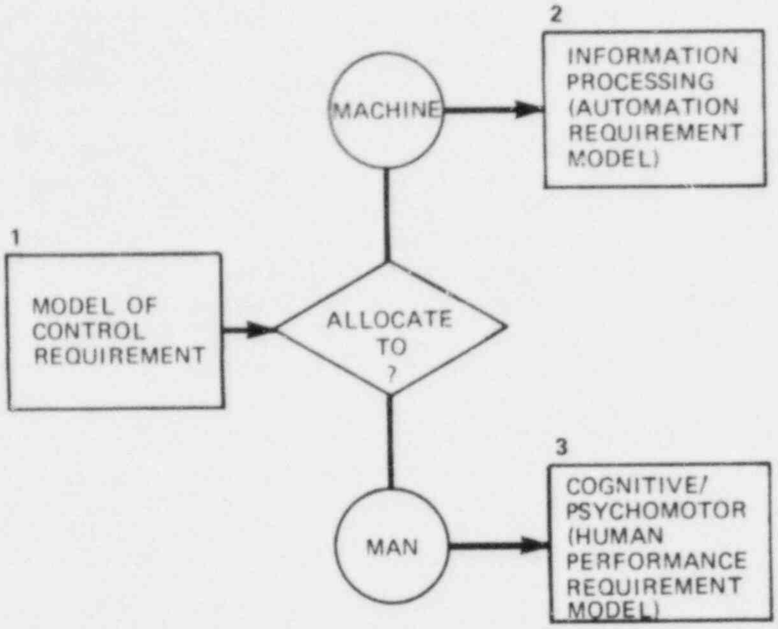

Fig. 2.2. Models involved in analysis of functions.

its normal and failure conditions. Given those requirements, it is possible to model the actions which must be taken to acquire information, formulate control decisions, and actuate controls. There is no developed science for specifying such information, although it is known that for each feasible control task there is an underlying sequence of information processing steps which can convert sensor data into control signals. Later provisional methods will be discussed for describing the control requirements of a future plant function during early systems design.

2. Models of the automation requirement. For any control requirement that is to be met by automation, there must be a sequence of automation steps which lead from input data to control signals. Block 2 of Fig. 2.2 represents possible models of this requirement. It is possible to specify these in block diagrams, although it is difficult to match the language of computer automation and that of system control requirements (Block 1).

3. Models of the human performance requirement. Block 3 represents possible models of human psychomotor and cognitive performance which man must exercise to perform the control requirement (Block 1), or in other words, actions paralleling the automated control process (Block 2). It is important that these three models be mutually consistent and valid as representations of the control requirements.

The emerging science of artificial intelligence shows promise of being able to map these three models in a common language. Meanwhile, a method of analysis will be proposed which begins with the model of man (Block 3) and uses the same language to describe the control and automation requirements (Blocks 1 and 2).

2.6.3 Recommended Model

To summarize Sects. 2.6.1 and 2.6.2, the use of cognitive/psychomotor models has been suggested as the means of analyzing control requirements and providing a standard language to describe the steps in information processing. The model of system performance reflected by Fig. 2.3 is recommended by the authors. The diagram shown contains three control loops, a closed control loop between man and machine and open loops from and to the external system or environment. "Man" must be recognized to include the control room crew, and "machine" to represent the NPP and its links to the electrical grid.

2.6.3.1 Core Performance Areas

This model can be re-expressed by the model of Fig. 4.3 in Sect. 3 of this report. This model identifies eight core performance areas (ref. 14). These core performance areas are recommended as a working taxonomy to describe the steps which must be taken in order to process data from sensors to control signals, whether these steps are taken by man or machine.

2.6.3.2 Alternate Models

Future users of the methodology in Sect. 4 may wish to use other models or taxonomies. Those reported by Mertes and Jenney (ref. 6) and Rasmussen (ref. 17) are possible alternatives. In addition, a summary of cognitive models by Pulliam and Maisano (in press, ref. 18) will offer a range of alternate models. An earlier report by Pulliam (ref. 19) illustrates a detailed method for dealing with information processing tasks at the developmental design level.

2.6.4 Mental Models

An important related concept is that of the operator's mental models of the plant. Such mental models must not be confused with the "information process models" just described. The mental models are in fact maintained in the cell labeled "memory," within the "man" block of Fig. 2.3.

The operator performing his control tasks develops a mental representation of the plant. Reading the instrumentation, he refines his model of the plant's current configuration, parameters, and dynamic state. He uses his mental model to interpret the progress of the plant and to predict the plant status at times in the near future. He also uses his mental model to predict the outcome of a control action should it be

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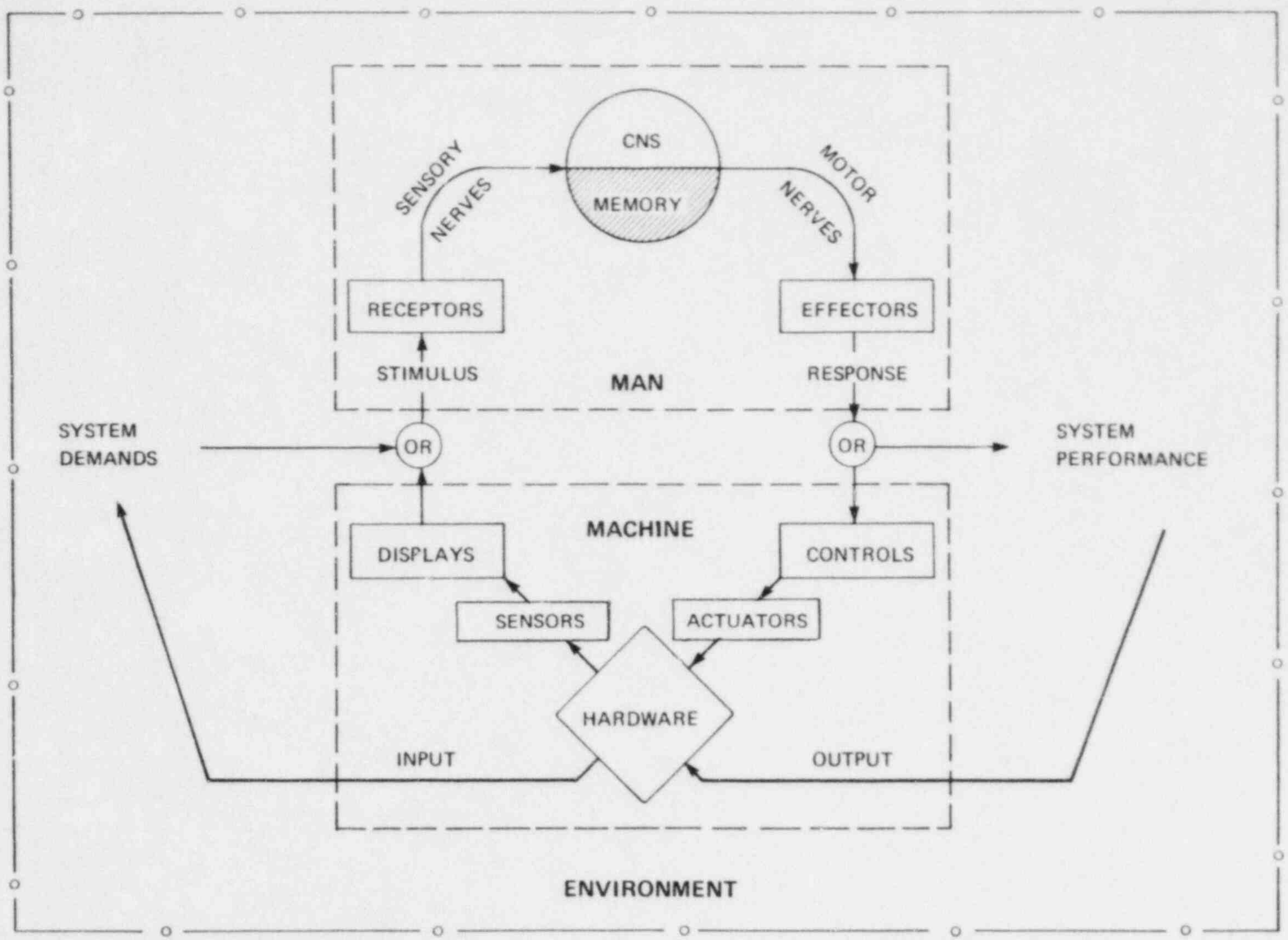

Fig. 2.3. A simple model of man-machine system performance.

taken, and he plans control interventions accordingly. The more complete and reliable the operator's model, the better he will be able to recognize abnormalities, anticipate emergencies, and diagnose failure conditions.

It is therefore a major objective of the system designer to ensure that each operator can maintain a mental model which is at least adequate to the decisions he must make. This means not only providing adequate instruments and data displays; it also means ensuring that the operator engages in activities which cause learning and enforce his attention to the plant's operating states.

2.6.5. Cognitive Support

Should a function be automated (allocated to machine), a likelihood exists that the operator or crew will be deprived of information concerning the automated events. There should be, then, a requirement for specific means (a) to provide that information, and (b) to ensure that the operator will assimilate that information. This is a critical issue in the allocation of functions.

In manual operations, the NPP operator maintains his mental model of the system, which he uses to interpret instrument readings, decide control manipulations, and continuously predict system behavior by mentally "running" the model. In an emergency, he uses his model to diagnose the problem and predict an appropriate control intervention, or even to reconfigure the NPP.

As he works he continuously updates his mental model, keeping it current as to system configuration and state. If he must personally decide on control actions, he is automatically forced to update his mental model. Across time and with experience this model will become progressively more detailed and more finely calibrated.

When any segment of the control sequence is automated, the operator is taken out of the loop. Even if good data displays are provided to inform him, he will no longer be active and will revert to a monitoring role. Man is not a good monitor; in that role he invariably learns more slowly and maintains a less effective mental model, his attention may lag, and he is less satisfied with the work and less effective in an emergency.

It is therefore an urgent condition of automation that we provide systems for cognitive support to the operator. These systems must both (a) provide the right data efficiently, and (b) actually require the operator to interact with that data so as to maintain a well-calibrated mental model of the system state.

2.6.6 Man-Machine Communication

A major need in automated systems is man-computer communications--that is, a means by which (a) the operator can be kept aware of the system states even when computers exercise control, and (b) the computer logic can be kept informed of human interventions and the purposes of those interventions.

If these conditions are not met, the automated devices and the control room crew may be working on the basis of different information, and they will try to drive the plant in conflicting directions.

A common example of this failure is when a set-point device controls a parameter such as pressurizer level. If a minor loss of coolant begins, the control device may begin to draw coolant from reserves. The operator may remain unaware of the problem until it reaches an alarm level. He may fail to take defensive actions. Finally, when the alarms occur, his first response will be to manually initiate an increased flow from reserves, not realizing that the reserves are already exhausted.

2.7 THE TWO-VARIABLE DECISION MODEL

The question of whether a designated function will be better performed by man or by machine is sometimes viewed as a single-dimensional question. it is assumed that if man performs a task poorly, a machine will necessarily perform it well. This is obviously not the case; there are tasks, such as low-speed sorting of objects by size, that both men and machines perform very well. There are other tasks, such as multivariate value weighing, for which neither men nor machines are well suited. In fact each allocation decision requires two separate assessments, the effectiveness of man and that of a machine.

The relationship between these two assessments can be illustrated by a two-dimensional decision space in which any task or function is represented by a point. The following text examines first the general characteristics of the decision space (Fig. 2.4) and then a specific decision matrix (Fig. 2.5) which can be drawn within the decision space.

2.7.1 Multivariate Dimensions

Allocation decisions are always complicated by multivariate judgments. As a result, the two major dimensions described are themselves multivariate: (1) the effectiveness or suitability of man and (2) the effectiveness or suitability of automation, in reference to a function or a set of tasks. Each of these dimensions will sum many human or machine variables. Furthermore, each will be an estimate--an attempt to realistically predict the performance of man or machine in controlling a future system, one which does not yet exist except in concept.

2.7.2 The Allocation Decision Space

Figure 2.4 represents the decision space concerned, which is defined by two dimensions. The horizontal (X) dimension (abscissa) represents the

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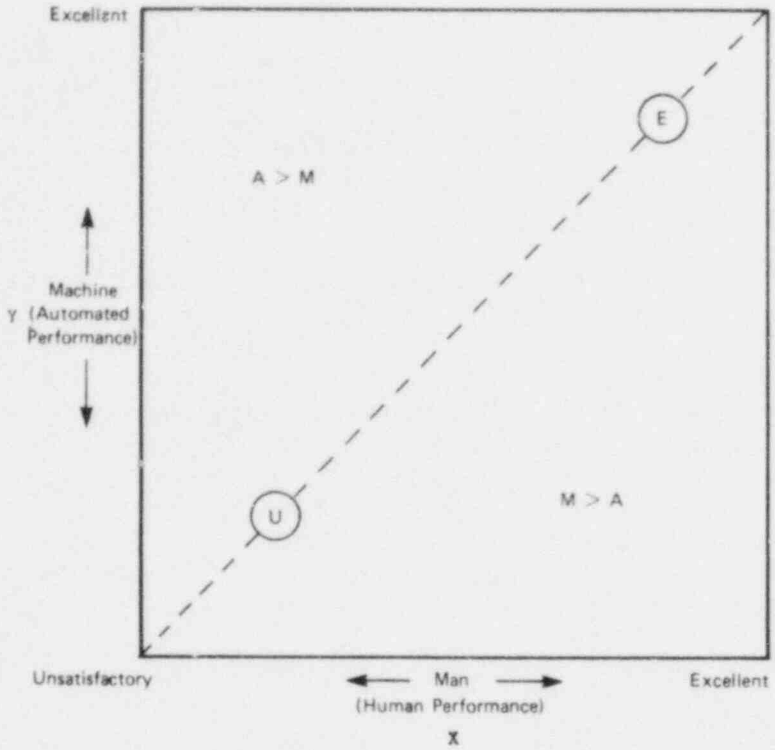

Fig. 2.4. Decision space for relative control performance of man and machine.

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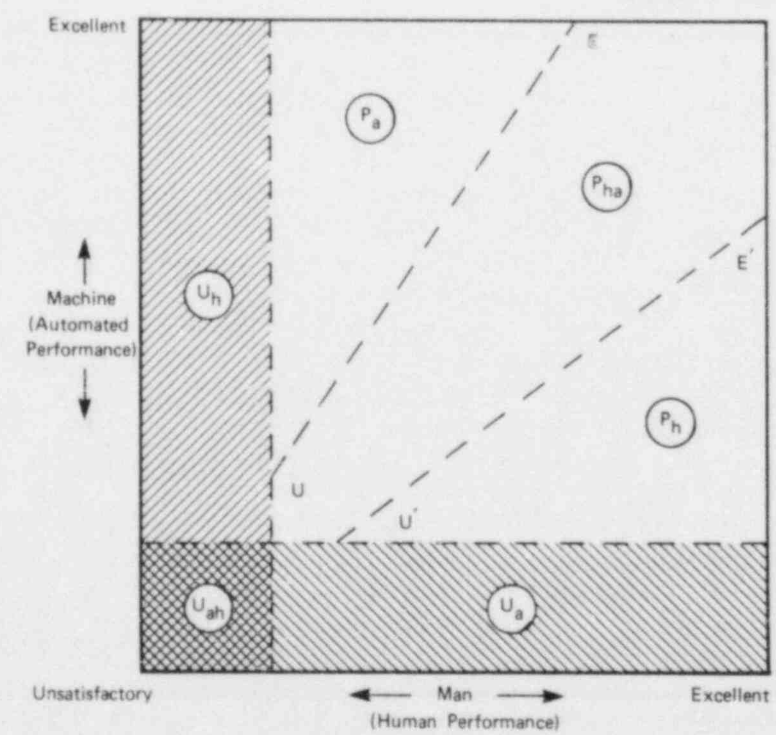

Fig. 2.5. Decision matrix for allocation of functions.

relative effectiveness of man, scaled from "unsatisfactory" at the left to "excellent" at the right, and the vertical (Y) dimension (ordinate) scaled bottom to top represents the corresponding effectiveness of a machine. The X and Y values of a point in that space will represent the estimated probable effectiveness with which men or machines, respectively, can perform a specified function or set of tasks, and the position of that point will prove useful as a means of deciding how the function should be allocated.

At a gross level, this decision space can be divided into two areas by the diagonal line U-E, representing the values of $X/Y = 1$. Any point in the upper left area now represents a function best suited to a machine, and any point in the lower right area represents a function best suited to man. This distinction alone is not a basis for an allocation decision, since special conditions exist at several points. At the lower left, for instance, in the area marked (U), are tasks which are not performed well by either man or machine. Such tasks may actually be infeasible or impossible to achieve safely. During the early days of flying, a point in this area would have described the function of piloting an aircraft. By contrast, at the upper right corner near (E) is an area in which all functions are performed so well by either man or machine that the allocation decision is largely a matter of choice. In fact, any function defined by a point close to the diagonal line U-E is one for which man and machine are equally well suited (or equally poorly suited). Allocation of such functions can be based principally on criteria other than the relative suitability of men and machines, viewed as engineering components.

2.7.3 The Decision Matrix

The decision space of Fig. 2.4 can be redrawn as a decision matrix (Fig. 2.5) containing five differentiated regions. The appropriate decision strategy for allocating functions is significantly different for each region.

The matrix includes two regions shown as shaded, (U_a) (unacceptable: automation), and (U_h) (unacceptable: human). Functions falling in region (U_a) are too low on the "machine performance" scale to be considered for automtion; they can presumably be allocated to man by default. Conversely, in region (U_h), any allocation will presumably be to machine. However, at the intersection of (U_a) and (U_h) is the region (U_{ah}), where both men and machines perform unacceptably. This corresponds to the area (U) in Fig. 2.4. Any function which falls in this region should be considered for redesign or included in a system only as a final resort.

The regions not shaded in the matrix represent functions which might be acceptably performed by either man or machine, with varying degrees of advantage. In the region (P_h) (preferred: human), man is expected to be substantially superior as a control component. Functions in this region will be allocated to man in the absence of other overriding considerations. Conversely, in the region (P_a) (preferred: automation), allocation will ordinarily be to machine.

Finally, there is the region (P_{ha}), bounded by regions (P_a), (P_h), (U_a), and (U_h), and by the lines of constant proportional difference U-E and U'-E'. At all points in this region the difference between the expected performance of man and machine is not great. This is a region of less certain choice so far as the relative control performance of man and machine is concerned. In this region the allocation decision can be based on considerations other than the engineering performance of man and machine as control components. The considerations include costs, worker preferences, and the availability of proven design experience.

The matrix of Fig. 2.5 will be used during allocation of functions to evaluate the merits of man or machine as control components. Any function planned for a new system will be evaluated for its estimated values of expected man-machine suitability, and will be recognized as belonging to the decision class which the matrix indicates. Note that no numerical values are suggested for the dimensions of the matrix. Both the man and machine performance variables (X and Y dimensions) are themselves multivariate parameters which resist quantification. In the absence of an ability to scale X and Y, no reasonable values can be assigned to the internal boundaries of the matrix. Furthermore, it must be recognized that the matrix concerns only the question of which allocation is preferred from the engineering component point of view. The decision rules suggested by the matrix may be overruled by considerations other than the relative effectivenss of man or machine, viewed as control system components only. This may happen, for instance, for reasons of cost, legal restrictions, worker preferences, or because of a technologic inability to construct a system using the ideal allocation.

This matrix will be encountered in a slightly altered form in Sect. 4, where the regions of the matrix will correspond to procedural steps taken during the allocation of functions.

2.8 THE ROLE OF DOCUMENTATION

The design process requires communication between differing disciplines, as well as an ability to preserve information. Essential to that communication is formal documentation, through which the designers refine their conceptions and communicate across time and specialty boundaries. In the nuclear power industry, documentation has often been underused, with the result perhaps that the disciplines were poorly coordinated and that the same lessons have had to be relearned from project to project. The use of a formal design data base is recommended as a requirement for the allocation of functions to man or automation.

2.8.1 The Requirements for Documentation

Design in the nuclear power industry requires a substantial interaction among disciplines and specialists, including design engineers, computer specialists, and human factors designers. There are actually several different specialty teams which typically act more or less independently, or even as separate contractors. As a result, expensive misunderstandings are frequent. Simulator developers sometimes design details of the training simulator based on old data, long after control engineers have changed the real displays and controls. Procedure developers write and publish procedures using control assumptions and terminology different from those being used by training developers and control board designers. These failures are expensive in terms of retrofit costs, as well as in terms of the safety and effectiveness of the end system.

2.8.2 Over the Wall

The situation often encountered in the nuclear power industry resembles that represented by Fig. 2.6, with the absence of the "Design Documentation" box. Several design teams operate within their own respective walls, with an exceptionally high wall between the designers of the engineering and human factors subsystems. Too many people are involved to permit direct communication; only a documentation system can provide effective communication "over the wall."

In NPP design, the wall has been a more serious problem than in some other fields. This is true because in the nuclear power industry documentation is often relatively informal or it is not preserved as the design develops, a fact which hinders interdisciplinary planning. Good, relatively standardized documentation is necessary not only to an optimized allocation of functions but also to design as a whole, and it will be essential for recalling past successes and failures. Thus documentation should serve the following purposes:

- Mediate interdisciplinary communication. It should be written in a language and conform to a set of conventions that are reasonably standard and translatable among disciplines. This implies that there must be some central direction of the documentation effort.

- Permit access to data from the other specialities, and provide that data at a time and place of the user's choosing. Each disciplinary team should have continuous access to the current level of design as conceived by each of the other teams.

- Provide a durable historical record. It should make possible the ability to go back and fully recall past decisions within any discipline. This implies that not only the design but also the rationale for decisions should be recorded.

- Provide continuity of effort and direction as people and design teams change.

- Assist redesign and retrofit. It should provide both a detailed record of what is to be retrofitted and a record of the past alternatives which were considered but not selected.

- Permit a design to be tested by deductive analysis, even though there may as yet be no hardware to test empirically.

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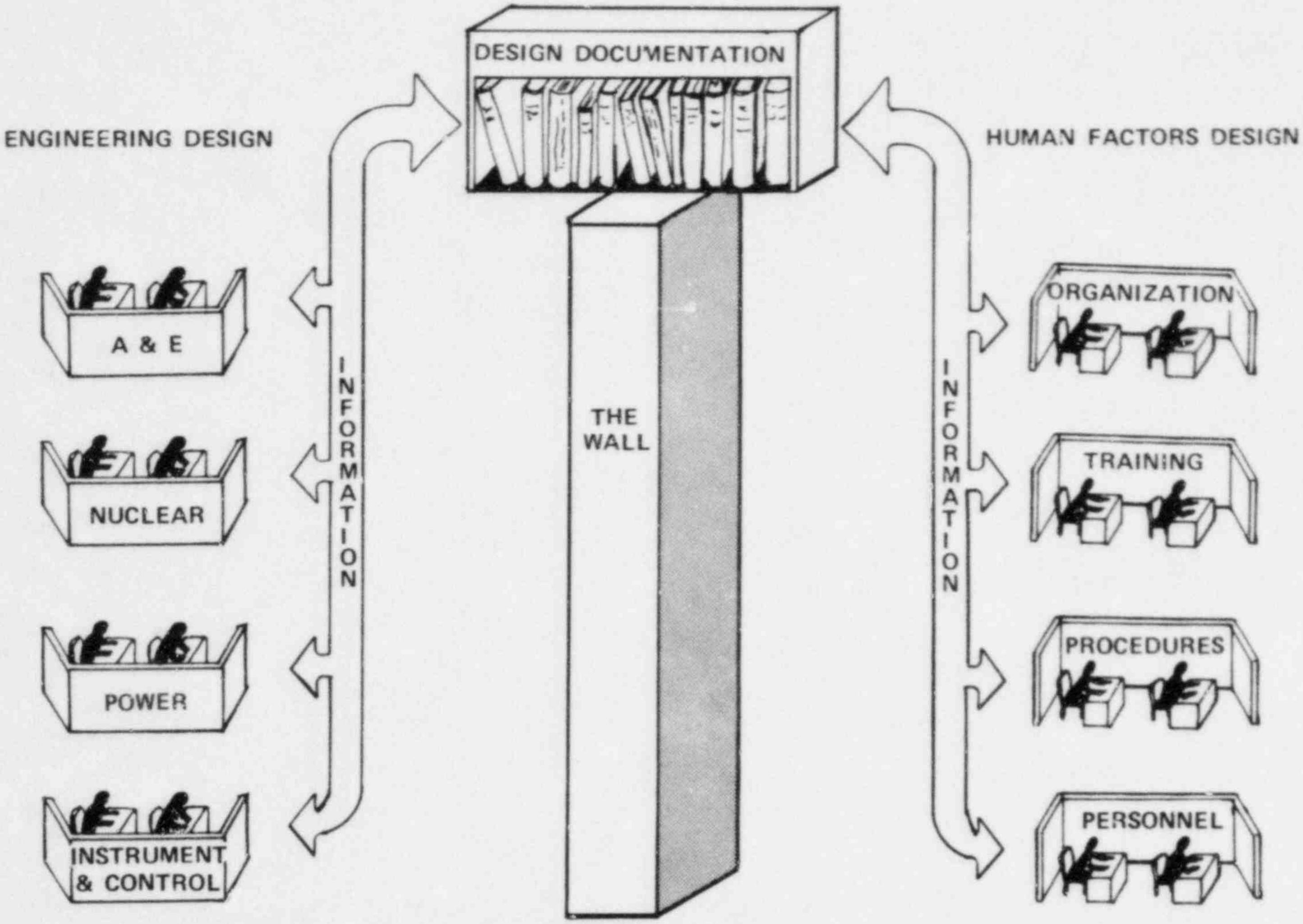

Fig. 2.6. Role of the design documentation base. (Adapted from Livingston "Over the Wall," ref. 16).

2.8.3 Complexity and Documentation

The design of relatively simple systems is feasible using relatively informal documentation. This is true because fewer people are involved, less time is required, and design leaders are able to understand the entire system in breadth and depth. But as systems increase in complexity people from more divergent specialities are needed, and the project time span may increase. At some degree of complexity design becomes infeasible without the support of a sophisticated documentation system.

Of course, maintaining a more sophisticated documentation system requires a larger portion of each person's time. This is a penalty of complexity, but the lost time should be repaid by the avoidance of costly errors.

2.8.4 Institutional Memory

Effectively allocated engineering designs result from institutional experience with many earlier designs. That experience is stored in (a) engineering documents, and (b) members of the engineering and human factors professions. Failure to achieve reliable man-machine allocations is attributable in part to the lack of institutional memory pertaining to allocation of control functions. The lessons learned during each system development are lost because they are not documented and they are not shared by a body of professionals who assume responsibility for and develop a special competency in making allocation decisions.

This suggests that the devlopment of criteria and method in this project will not by itself solve the allocation of control functions problem. It will not be possible to achieve optimum human factors designs (including judgments concerning the allocation of functions between human and automated control) until a corps of professionals and a body of historic documentation for human factors design in control systems comes into existence.

Sections 3 and 4 will describe the requirement for a formal design documentation base. A minimum set of inputs to that base will be specified, and all decision steps will be exercised using data from the design documentation base.

2.9 THE ROLE OF MAN

No matter how sophisticated or effective automated control may become, a minimum role for man will always be necessary because machines exist to perform man's work and must be controlled to that purpose. The designers of a new system must agree at the outset on a general philosophy and on their objectives regarding the role of man.

2.9.1 Theoretical Limit of Automatic Control

There is a theoretically imaginable level of automation at which a plant, once in place, is automatically brought into operation and produces power at its design capacity throughout its entire lifetime without supervision. This level is illustrated in Fig. 2.7.

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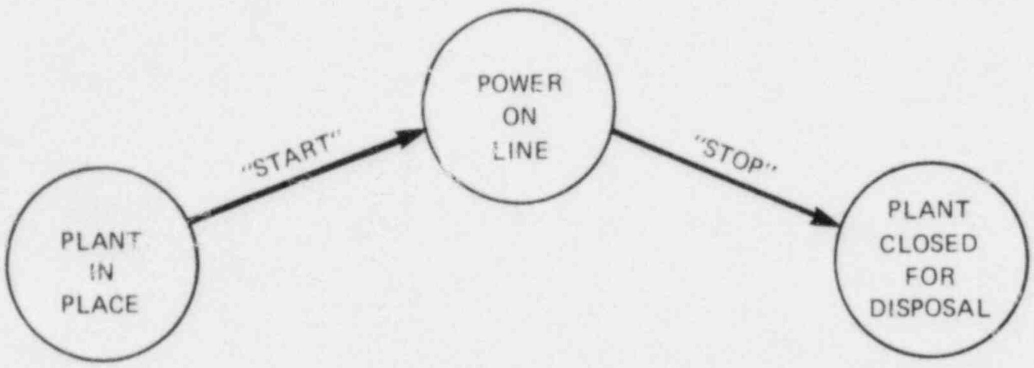

Fig. 2.7. States of a theoretical fully automatic power plant.

In this theoretical case, the plant goes through only three states: "in place," "running," and "closed." Human intervention is required for only two transitions: start and stop. The running state, "power on line," may include alternating states of production and refueling, but these do not require human intervention. The power levels and schedule for operation may be dictated by an automated dispatch center so that the plant may become a lower element in the hierarchy of a large-scale power distribution system.

Although social and technological boundaries may prevent the total automation of a power plant as described, the state approach used will be expanded from this lower theoretical limit to a useful tool which will be used in later sections.

2.9.2 State-to-State Diagrams

To develop a state-to-state diagram more useful than that in Fig. 2.7, one which defines those states and transitions that are actually desirable, requires expansion to show the minimum set of definable states that the plant should be able to assume, as well as the minimum set of controllable transitions that will be necessary at a desired level of achievable automation (the role-of-man objective). The following questions may aid in the development of such a state diagram:

- What must be controllable to meet human, economic, social, regulatory, and management objectives?
- What operating states are required to meet the plant's requirements during its life cycle?
- What test, maintenance, and refueling states should occur?
- What degraded and failed states may occur?
- What transitional states lie between the operating and degraded states (including emergency transitions)?
- What is the maximum (theoretically) achievable set of automatically controlled transactions?
- What automatically controlled transitions are reasonable design targets, considering the role-of-man objectives, the cost, and the current state of automation technology?

This analysis should lead to the development of a state-transition diagram resembling Fig. 3.5 in Sect. 3.

2.9.3 Asymmetry of Roles

To assume that the roles of man and automation are potentially equivalent is misleading and potentially erroneous, even though there appears to be superficial symmetry (i.e., most control and decision tasks can potentially be performed either by a human operator or by an automated control system). There may be differences between the relative suitability of man and machine for a given task, depending on such variables as speed, reliability, precision, complexibility, and cost, but those differences may be quantitative rather than qualitative. Up to a limit, allocation to human or machine components can be selected much as selecting engineering components: by comparing their relative performance characteristics to the requirements of the control tasks. In many cases, either can be made to perform to specification.

However, there are basic differences between the ultimate roles of man and machine as controllers. In fact, man and machine cannot undertake fully equivalent roles even if, when viewed only as engineering components, they are equally capable of performing the task concerned. This is true for two basic reasons: First, man must retain ultimate control of what he builds, and second, man must be kept informed whenever the machine assumes control. These reasons will be elaborated.

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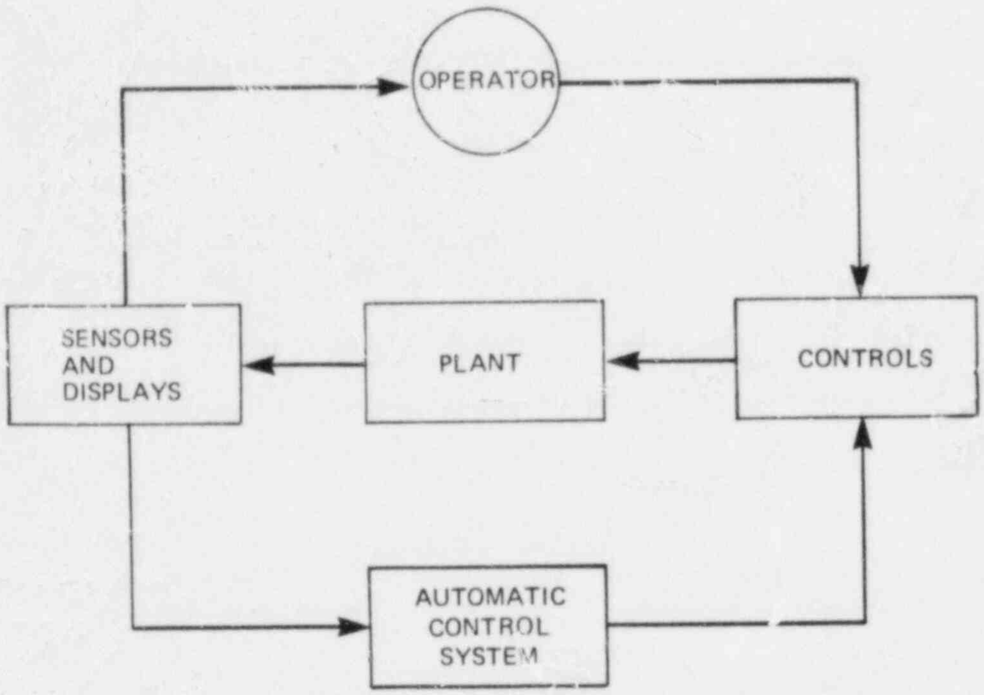

Fig. 2.8. A symmetrical man/machine model.

2.9.3.1 A Symmetrical Control Model

Figure 2.8 represents a hypothetical industrial process (a plant) and its control system in which man and machine are assigned symmetrical roles. The plant (center) is governed by controls (right), and its state is observable through sensors and displays (left). The operator (top) receives information from the displays and responds with control actions. The consequences of control actions are detected through the displays, by continuous feedback. Symmetrically an automatic control system (ACS) (bottom) senses plant status and affects control.

This is a potentially unacceptable relationship because the operator and the ACS are in competition for control of the plant. They are likely to undertake competing control strategies, and neither the operator nor the ACS can act on the basis of complete information because actions by either party may change the system configuration. Neither party can plan a dependable control strategy without knowing what the other is planning.

2.9.3.2 An Allocating Control Model

A possible correction to this condition may be provided by a symmetrical division of tasks. Figure 2.9 illustrates a plant with an "allocator,"

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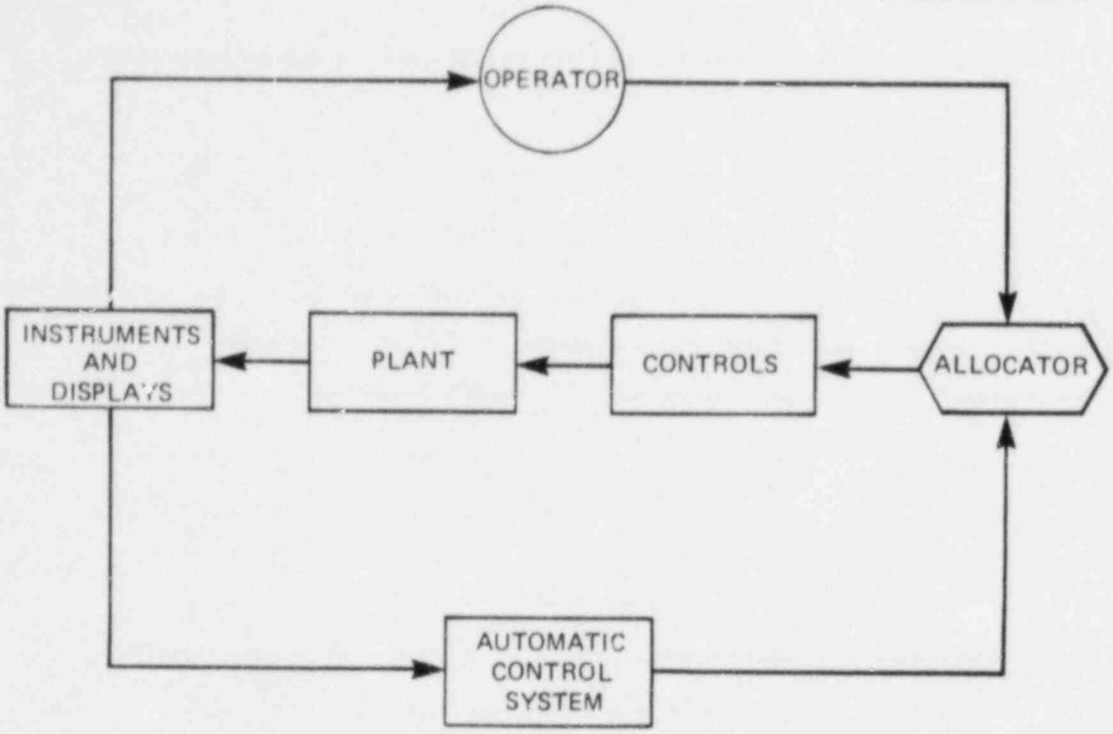

Fig. 2.9. An "allocated" man/machine model.

which exercises a predetermined rule or program to apportion tasks between man and machine. Allocation may be by function (man controls rod positioning and machine controls feedwater flow), or it may be apportioned item by item (man operates valve MOV-12 and machine operates valve (MOV-13). In any case, man and machine no longer oppose each others' actions. However, this configuration if strictly adhered to still is not fully satisfactory for complex, large-scale process control because:

1. Man (the operator) needs to intervene so as to supersede the automated control system in deciding the level of production or when to turn off the system.

2. Man needs to intervene should the ACS or the allocator become defective.

3. No means exist to ensure that man and machine are using a coherent control strategy. This would imply that man should know what the ACS is *going to do*, and that ACS program actions will support the man's control strategy (that the machine "knows" what the man is going to do).

4. Specific means are required to make the human operator aware of the total plant status. This includes the status of the ACS and the allocator, as well as any changes in plant configuration caused by the ACS.

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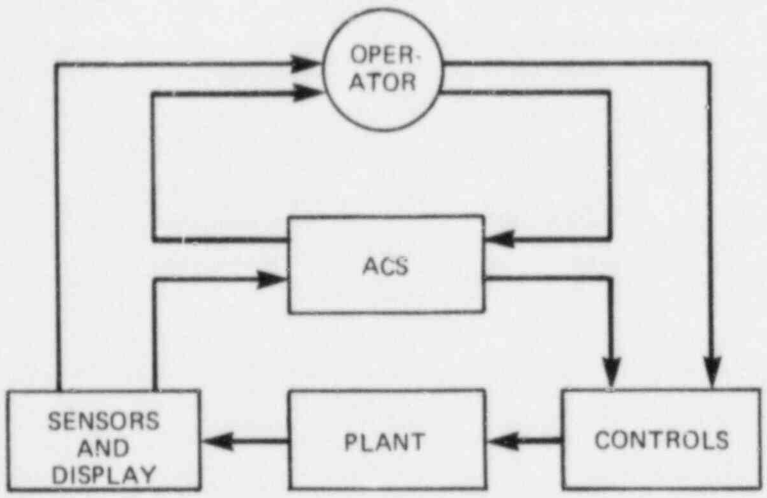

Fig. 2.10. A hierarchical control system.

2.9.3.3 A Hierarchical Control Configuration

This is a control system in which the automation loop always lies within an outer man-driven loop, where it can be observed and overridden by the human operator. Fig. 2.10 illustrates such a system.

This model provides an inner loop in which the automatic system controls either (a) specifically allocated functions, or (b) the whole plant under standard conditions. An outer loop is available to the operator, through which he can control the plant directly. Finally, an operator-to-ACS loop permits the operator to decide selectively whether the ACS will assume control of any particular function.

2.9.3.4 Exception: Safety Features

There are a few notable exceptions to the rule of ultimate human control, notably in the case of engineered safety features (ESF). Note, however, that any safety feature which is designed to be automated and observable but partially uncontrollable by the control room (CR) operators, is, in effect, an allocation to man at the design, policy, or regulatory level. Control is vested in those who designed and built that system, because the CR operator is excluded from having *immediate* control of a safety response.

2.9.4 Basic Rules for the Role of Man

At least six working rules for the role of man in an automated system can be extracted from the preceding development:

1. Ultimate control should remain with man, in that he can set objectives for and start or stop the process.

2. Override capability should be given to man to correct automatic control if necessary.

3. Information should be provided to man concerning the actions of automatic control and its objectives (i.e., what the control logic is trying to achieve).

4. Program logic should be provided for assuring that the control logic is informed when man takes an action and it can plan for man's intentions.

5. The system for informing man (plant displays and ACS displays) should be behaviorally suitable.

6. Adequate cognitive support should be available to the operator, so that he will have an adequate mental model if required to assume control.

2.10 THE PROGRESSION OF ALLOCATION OF FUNCTIONS

The specificity and detail of the allocation changes progressively during the development of a design. As functions are partitioned to increasing levels of detail, the number of functions increases, and each function describes an increasingly small portion of the plant process. Also, the allocation to man or machine progresses from a set of highly generalized statements to more specific statements until it finally reaches the component (i.e., button and knob) level.

2.10.1 Content of Allocation

Figure 2.11 illustrates the possible content of an allocation of functions document after about four levels (or cycles) of partitioning. This must necessarily include the following six pieces of information:

Field 1--Identity of the Function: Field No 1 identifies a function. The function code number (1.5.2.3) identifies the address of this function in design documentation, and suggests that it is number 3 among the subfunctions of a larger function coded 1.5.2. The descriptive name of the function follows the code number.

Field 2--Identity of Equipment Subsystems: This field identifies the principle subsystems concerned for this example (heating, ventilating,

1. Function	Code 1.5.2.3: Heat, cool, vent areas of RAB with filtered air at specified temperatures. Maintain human habitability. Cool RAB equipment. Control radiation leakage.
2. Subsystems	HVAC RAB subsystem. RAB equipment. On/off site power. Pumped river cooling water system. Ambient air. Heating steam supply system.
3. Plant States	(1) Normal operation. (2) Equipment fire. (3) Equipment radiation leak. (4) Radiation leak external to RAB. (6) HVAC component failure/maintenance. (7) Transition to/from (2) (3) (4) (5) (6).

4. Control Requirements	5. Equipment Function	6. Operator Function
Maintain normal cooling level. Maintain normal heat level. Maintain required rate of air flow. • • Etc. • • Start backup fans. Filter radiation from exhaust air. Reconfigure dampers for radiation containment. • • • Etc.	Activate fans, refrigeration, heating coils, using setpoint thermostats. Display temperature and flow data. Display predicted data from trend forecasts. Provide abnormal parameter alarms. Provide equipment failure alarms. Control dampers (normal) using program logic. • • • • • • • • Etc.	Recognize abnormality. Set thermostats seasonally by phone to Plant Equipment operator. Make periodic log entries per procedure. Start emergency fans. • • • • • Reconfigure dampers to contain radiation. Reconfigure dampers to control fire. • • • Etc.

Fig. 2.11. Contents of an allocation of functions document.

air conditioning system was chosen) and those systems with which it directly interacts, including in this example equipment within the reactor auxiliary building (RAB), and equipment which depends on its product (e.g., air cooling or heating, which can be a source of radiation leakage). Other indirect interactions are with on- and off-site power, cooling water, heating steam, and ambient air.

Field 3--Plant States: To the extent possible, the plant states that must be controlled are listed. These include normal operation, maintenance, several failure/emergency states, and state-to-state transitions.

Field 4--Control Requirements: The need to maintain stable plant states and to perform state-to-state transitions leads to control requirements. These are listed and described at a level of detail which increases as the design becomes more concrete and itemized.

Fields 5 and 6--Equipment Function/Operator Function: It is now possible to describe the allocation of functions in detail. All functions which need to be performed to support the control requirements of Field 4 are listed, each in its appropriate field.

Should a control action be allocated wholly to automation, an entry is required only in Field 5. Should an action be allocated wholly to man, an entry is required only in Field 6. For example, "Reconfigure dampers for radiation containment" is allocated wholly to man and is reflected by the entry in Field 6.

However, so long as the functions are still defined at a fairly general level as they are in this example (the 4th level), the control requirements are stated broadly and will usually be performed by mixed actions of man and automation. Should mixed allocation be the case, an entry is required both in Field 5 (to describe in general terms what the equipment does), and in Field 6 (to describe in general terms what the operator does).

2.10.2 Increasing Specificity

As the design develops, the control requirement statements will become more exact and detailed. As this happens, more functions can be allocated wholly to man or wholly to machine. Eventually, during the final phases of design, the requirements may be stated in terms of single control actions: "adjust No. 16 fan speed," "stop cooling-water pump P-171." As this happens, actions may be classified as either single discrete decisions or single analog adjustments, and may be allocated either wholly to man or wholly to machine.

2.11 COMMENTS ON APPLICATION

The method reported here was developed with the special requirements of NPP control in mind. However this method will apply without significant modification to control rooms and control systems for process-control industries in general. In particular, it should apply well in the control of fossil-fuel power plants and in chemical industry production control.

Furthermore, this method is based on general principles of human and machine interaction, which makes it applicable to other settings as well. With minor additions the method would apply to the allocation of functions in complex control settings such as traffic routing, intelligence analysis, or vehicle operator control.

2.11.1 Cost

Sections 3 and 4 of this report describe a generic design process and specify an allocation method. They also imply some additional formalization of the design process and a requirement for additional participation by human factors specialists. All of this will require professional effort; it will "interfere" with engineering decisions and will require additional paperwork for the design documentation system. Is it worth the cost?

The answer seems clear: Human error now causes about half of the accidents leading to a release of radiation; 20 to 50% of reported plant failures are also due to human error (ref. 20). In those cases where equipment fails, human action should minimize the consequences and bring the plant under control. The human element is the more complex part of the man-machine system, yet less than 10% of the design effort is invested in consideration of the human role. Not only do greater efforts seem justified, but allocation of functions is only one key step in what should be a more general investment in human factors consideration during control system design.

If systems are relatively simple, intuitive judgments about the human role are more likely to be right, and the general adaptability of human beings can be expected to suboptimally correct for some inadequacies of human engineering design. With systems of greater complexity, such suboptimality is seriously degrading to safety and performance, and it becomes increasingly necessary to invest effort in human factors analyses as an integral part of the design process.

2.11.2 Not a Final Solution

This report is believed to add to the technology of system design, in that it provides a practical method for allocating those functions which are performed in the machine largely by program logic and in man largely by cognitive processing. This will by no means totally solve the problem of allocating functions. There is still much to be done. Some recommended next steps are presented in Sect. 7, Conclusions.

However, the problem of allocating control functions to man and machine has been and continues to be a very intractable one. It is even probable that the increasing complexity of systems, with the advent of computer control, will continue to outdistance the science of system design. In spite of research, and in spite of developments in system theory and practice, it is probably more difficult to achieve a good design today (in the 1980s), than it was in the 1960s with a simplier control technology.

The methodology described in the following sections is offered as a contribution to the science of system design, with the expectation that other researchers will now take up the challenge of application and will further advance our ability to design good man-machine systems.

3. THE DESIGN PROCESS

3.1 GENERAL

The allocation of control functions to man and machine takes place as part of the creative process in system design. This section describes how allocation is embedded in the functional design process, and outlines a general procedure for ensuring an appropriate allocation. Since these allocation decisions are deeply embedded in other decisions required to produce an engineering and human system design, this section must necessarily treat the major steps which occur in designing functional-level engineering and human subsystems.

This section will

- Identify the major steps necessary during the initial, or "functional design," phase of system development. (Refer to the discussion of developmental versus functional design in Sect. 2.3.6.)
- Explain how those major steps affect the allocation of control functions.
- Identify the steps which produce information necessary to the allocation decision.
- Describe the two major steps at which allocation of control functions is (1) decided hypothetically, and (2) tested deductively.
- Identify the points at which allocation of control functions data are applied or will affect other engineering or human system decisions.

3.1.1 The Engineering and Human Subsystems

The successful allocation of functions can take place only in the context of a design effort in which the human component is given adequate treatment. Design practice in the nuclear power industry has occasionally neglected the human component, or has considered it only after an engineering design was well advanced. This description of the design process emphasizes those steps which ensure planning for the human component, and refers to the "engineering subsystem" and "human subsystem" as co-equal parts of a system design. (Refer to discussion of system design in Sect. 2.3.)

3.1.2 Limits of the Description

No effort is made to provide a complete procedure for NPP system design, but Fig. 3.1 is a diagram of a possible design sequence, showing normal real-world practice as it applies to the allocation of control functions. The diagram omits certain steps, especially engineering decisions, which are not directly involved in the allocation.

The system functional design sequence is d
essential to allocation decisions.

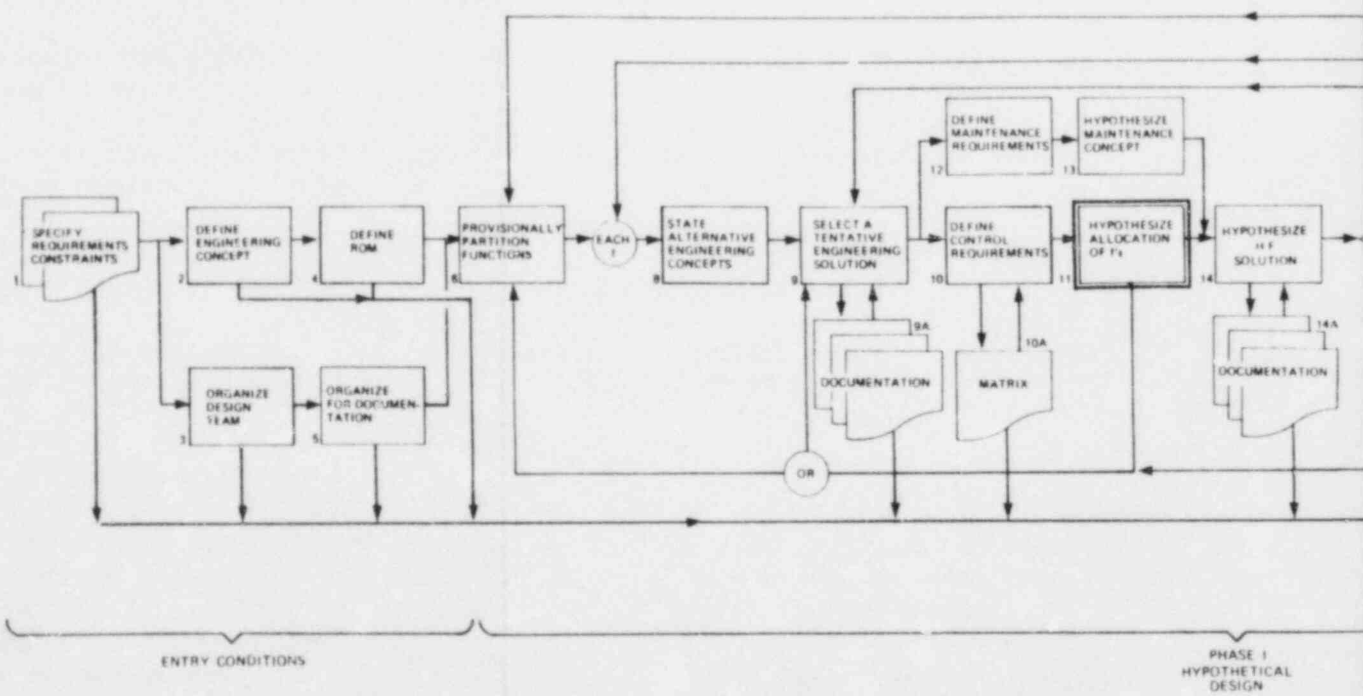

Fig. 3.1. How allocation o
process. (The system functional
allocation of functions and othe

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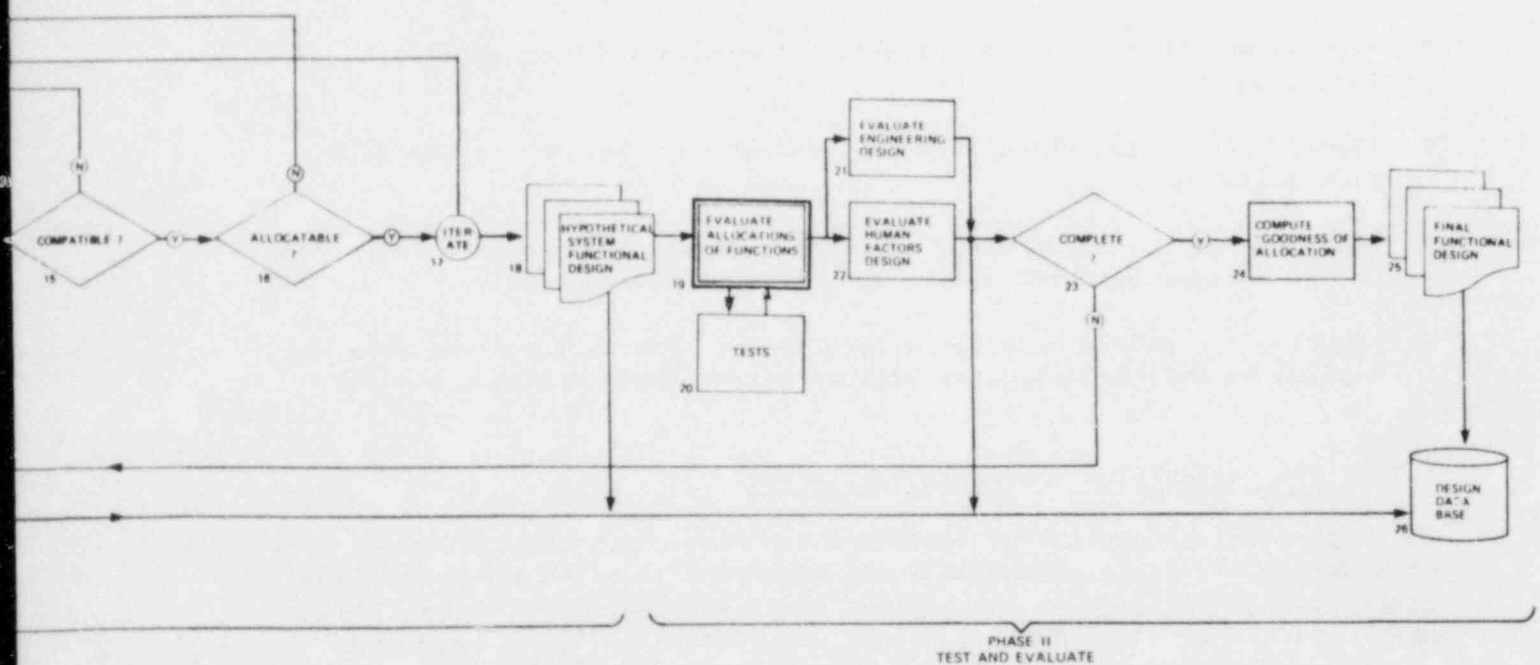
iagrammed, showing the allocation of functions and other steps



control functions is embedded in the design design sequence is diagrammed, showing the steps essential to allocation decisions.)

The steps shown are not intended to be prescriptive, nor to prescribe an "improved" practice in design, except as enumerated below. Shown are the steps which do occur (and necessarily must occur) during functional design, although they may not always be formally recognized or described in the terms used here.

1. Data sources specified. Formal steps are called out for those design decision points which provide information that must be available to support assignment decisions.

2. Allocation procedures prescribed. A specific procedure for allocation of control functions is described and recommended to users.

3. Allocation effects identified. Formal steps are described for those points at which allocation of functions decisions impact upon other decisions in engineering or in human factors design.

4. Human factors steps. In particular, certain human factors decision steps are described which are important to allocation of function, but which have sometimes been inadequately considered during NPP functional design.

5. Documentation. Because successful allocation of functions depends on good project documentation, a minimum necessary set of design documentation points are suggested.

3.1.3 Source and Application of the Methodology

The functional design methodology described in this section reflects underlying decision steps which have been exercised in the past in NPP design, although those steps frequently have not been named or documented. The methodology also reflects recognized good practice as it is reported in the professional literature, and uses the language of that literature. (Refer to discussion of the systems design process in Sect. 2.3.) The methodology for the allocation of functions is adapted from the Price-Tabachnick allocation model described earlier in this report and in prior reports (see refs. 1 and 14).

The design methodology described here applies generally to any conceptual systems design, especially for a moderately large or complex system. However, it has been particularly adapted to the design requirements of process control industries, including the nuclear power industry. This methodology goes only as far as the completion of a functional system design. (See Sect. 2.3.6 for a discussion of developmental versus functional design.)

3.1.4 Hypothesis and Test

In Sect. 2.2 it was emphasized that design is an inventive process which proceeds by repeated iterations of hypothesis and test. This applies to both engineering subsystem design and human subsystem design, and to the allocation of functions between those two subsystems. Most methodologies for system design recognize this fact by prescribing alternating steps of hypothesis and test. Thus the methodology described here is divided into two principal phases in which initial solutions are first hypothesized and then followed by a deductive test.

3.1.4.1 Entry Conditions

Figure 3.2 is a simplified representation of the design process.* Block 1 represents the initial conditions for design: A design team is presented with the general requirement to develop a system, along with a set of limiting constraints and design resources. These data are the initial contents of the design data base (Block 7).

3.1.4.2 Hypothetical Design Phase

The design team proceeds by first identifying (at a gross level) the major functions which must be performed to meet the objectives of the system (Block 2). For each function they then develop a generalized engineering solution (Block 3), adapting prior designs or inventing new approaches as necessary. Based on that tentative engineering solution, a tentative allocation of functions to man and machine can be hypothesized (Block 4). (This step may show the engineering hypothesis to be defective or not achievable; if so, Block 3 must be repeated.) The tentative allocation of functions defines the requirement for human tasks from which a human factors solution (Block 5) can be hypothesized. At this point (Block 6) the team examines the hypothetical design to determine (a) whether there are contradictions between the engineering and human designs, and (b) whether the functions are adequately partitioned (i.e., into small enough functions). As necessary, the team returns to Block 2; partitions the functions into a larger number of smaller functions; and repeats Blocks 3, 4, and 5 to correct discrepancies, develop more detailed specifications, and improve the emerging design. This process of iteration, correction, and elaboration of detail may cycle rapidly within a small design group. Meanwhile, design decisions are recorded as design documentation in the design data base (Block 7).

3.1.4.3 Test and Evaluation Phase

At this point a more or less credible functional design has been documented (Block 7), and must now be subjected to systematic tests to detect the shortcomings which were not obvious during earlier steps. As a first test, the allocation of functions is evaluated to determine whether appropriate roles have been assigned to the engineering and human subsystems (Block 8). When this is done, the individual subsystem concepts are evaluted separately (Block 9). Normally, in this step the team will

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*This is the sequence shown in Fig. 3.1, except that it has been simplified by grouping several steps together.

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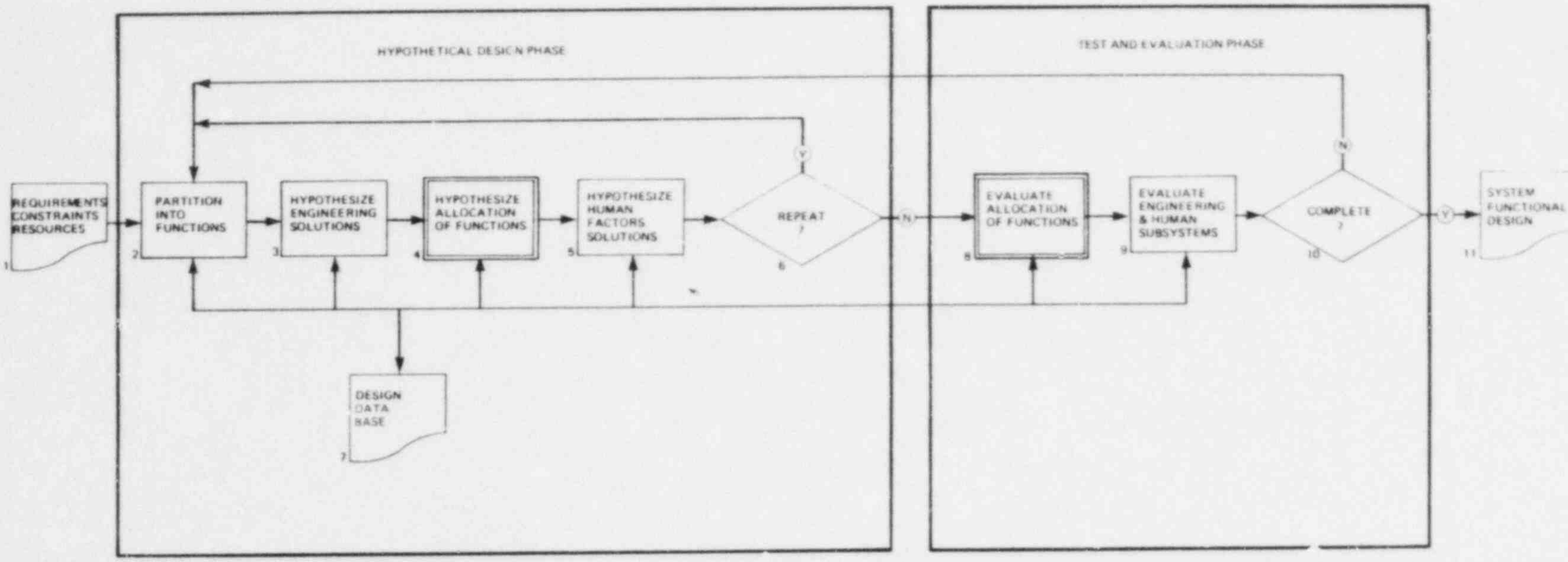

Fig. 3.2. The hypothesis and test phases in functional de^ign (simplified flowchart).

detect a number of design deficiencies and/or an inadequate partitioning of functions (Block 10), resulting in several cycles of feedback and redesign through the hypothesis phase. When the hypothetical design passes the evaluation tests, a system functional design is complete (Block 11).

3.1.4.4 Where Allocation Occurs

Allocation of control functions occurs principally in the Block Nos. 4 and 8, which are called the hypothesis and deductive steps respectively. The evaluation step is called "deductive" because, at this point in design, empirical tests usually are not possible. The evaluation method depends principally on deductive analysis, using the design documents. Section 4 will elaborate on the allocation of functions decision process shown in Blocks 4 and 8 of Fig. 3.2.

3.2 ENTRY CONDITIONS

This subsection describes the preliminary events which precede the actual design steps. Figure 3.3 illustrates the first five steps of Fig. 3.1, which are the first major steps leading to a functional design.

3.2.1 Specify the Requirement (Figure 3.3, Block 1)

A design sequence is normally initiated by establishing a design requirement. The requirement is a set of documents or verbal agreements which estabishes that a plant will be designed, and *specifies* the general requirements and constraints the plant must meet.

At the outset of a project this requirement may be very general. As a minimum it typically will specify

- That a design is required. Example: Grand County Power Company contracts for an NPP design.

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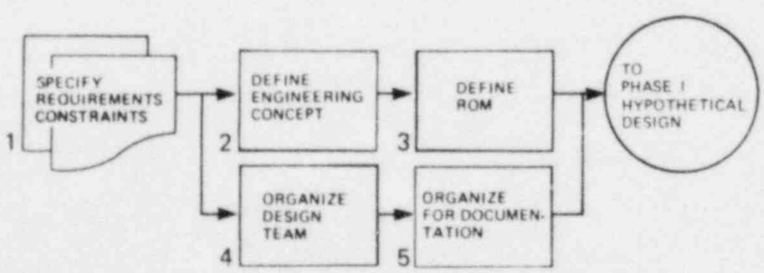

Fig. 3.3. The design process--entry conditions (extract of Fig. 3.1).

- A specific site or regional location. Example: Build on an existing site at Grand Tower, Nebraska.
- Approximate generating capacity and dates: Deliver 1,400 MWe by 1994.
- Cost limits. Example: Under an initial dollar limit during 1983-85; under a total dollar limit by completion.
- Environmental constraints. Example: Maximum hot discharge into the river of X MW thermal sustained, or Y MW thermal in any peak hour.
- Power distribution. Example: Deliver power into the regional grid at Ware, Nebraska.

3.2.2 Define Engineering Concept (Figure 3.3, Block 2)

Some basic engineering guidelines are normally formulated before design begins. These may be driven by business considerations (e.g., the company sells PWR technology) or by project-specific matters (e.g., the customer wants minimum automation or the company had problems with steam tubes in prior models).

A general engineering concept is formulated, defining a future plant in gross detail, as an initial hypothesis. This is only a point of departure and may be modified later. Typically, the concept might describe:

- Major components
- Number of reactor units
- Major departures from prior designs
- Rough plant layout (if a site is known).

3.2.3 Define Role of Man (Figure 3.3, Block 3)

A general expected role of man is specified, corresponding to the engineering concept just defined. This might include such matters as:

- The general level of automation desired
- General policy on emergency reconfiguration by operators
- General division of responsibility to management, shift supervisors, control room (CR) operators, plant crew, and maintenance.

Note that defining the role of man *follows* the definition of an engineering concept. This is because human subsystem design is in response to the particular engineering practice characteristic of the power and process control industry. (See also Sect. 2.1.5, "Allocation responds to an Engineering Hypothesis," and in Sect. 2.9, "The Role of Man.")

3.2.4 Organize Design Team (Figure 3.3, Block 4)

It is necessry to identify and organize a design team. This means designating team leaders and providing an interdisciplinary membership. It will require:

- Specifying minimum qualification, especially for the human factors participants. Suggested minimum full-time membership is (a) one team leader (a system engineer or equivalent); (b) one design-experienced engineering psychologist or equivalent (the "allocator" member); (c) one design engineer (the engineering design team leader); and (d) one organizational planning specialist or equivalent (the human factors team leader).

- Supporting staff should range across several disciplines and include experienced operators. Although these may not necessarily be full-time team members, there should be a nucleus of 5-6 people who are permanent assignees and who will actually be available for regular consultation.

- Subpanels should be identified. At the beginning these may include only engineering and human factors teams. More specialized panels will be useful later (e.g., control systems, training requirements).

- Supporting experts and consultants are identified.

- A general organization, schedule, and arrangement for meetings is agreed upon.

- The roles of any subcontractors are defined.

3.2.5 Organize for Documentation (Figure 3.3, Block 5)

The continued effective interaction of different disciplinary teams depends on documentation which can communicate between the disciplines and which is available for reference. Good documentation protects design integrity when team members change and facilitates the constant process of test, iteration, redesign, and elaboration (see Sect. 2.8, "Documentation"). The importance of project documentation cannot be overemphasized. NPP designs have frequently suffered from poor allocation documentation.

3.3 THE HYPOTHETICAL DESIGN PHASE

This phase begins the actual process of inventive design. The preliminary steps just described tell the designers what to design, and link the future system to its underlying economic requirements. Now the designers must produce a functional design.

A functional design is accomplished by a process of alternate hypothesis and test, progressively perfecting a design solution and elaborating detail. In this phase--hypothetical design--the designers develop hypotheses for solving the design problems, and in the next phase--test and evaluation--they will test those hypotheses. They will then return to the hypothesis phase to correct faults detected during test and evaluation and to develop further detail, cycling through these steps of hypothess and test until the design is complete at the functinal design level (refer to the discussion of iteration in design in Sect. 2.2.5). This phase includes steps 6 through 18 in Fig. 3.1. Figure 3.4 shows only those steps.

3.3.1 Provisionally Partition Functions

Step 6 results in a partition of the engineering subsystem (or plant) into its component functions, and in effect defines a "function" operationally. A function is a subprocess of the plant which is convenient to consider as a unit during early design. It describes a subprocess of the plant which produces a defined interim product. All functions, taken collectively, are sufficient to produce the required plant outputs and to execute all operating modes and states. Functions are developed by partitioning the plant in terms of its subsystems and its subprocess states until closely related elements have been defined, each of which produces a functional subproduct. These are subproducts which lend themselves to a design solution and which can be allocated to man or machine. (See also the more detailed definition of "function" in Sect. 2.4.) The number of functions and their boundaries is in part optional and depends on the design team (see the discussion of partition in Sect. 2.4.5).

3.3.1.1 The Physical Plant

The designers hypothesize a minimum breakdown of the plant into its essential subsystems (reactor, steam generation, power distribution, control system, etc.).

3.3.1.2 Plant Operating States

The designers define a minimum breakdown of the plant operating sequence into major states, and the transitions between states which are required during the life cycle of the plant. Figure 3.5 represents the kind of data which are required.

3.3.1.3 Transition States

The arrows in Fig. 3.5 represent the transition states of the plant. These states are the principal determinants of the control capabilities required.

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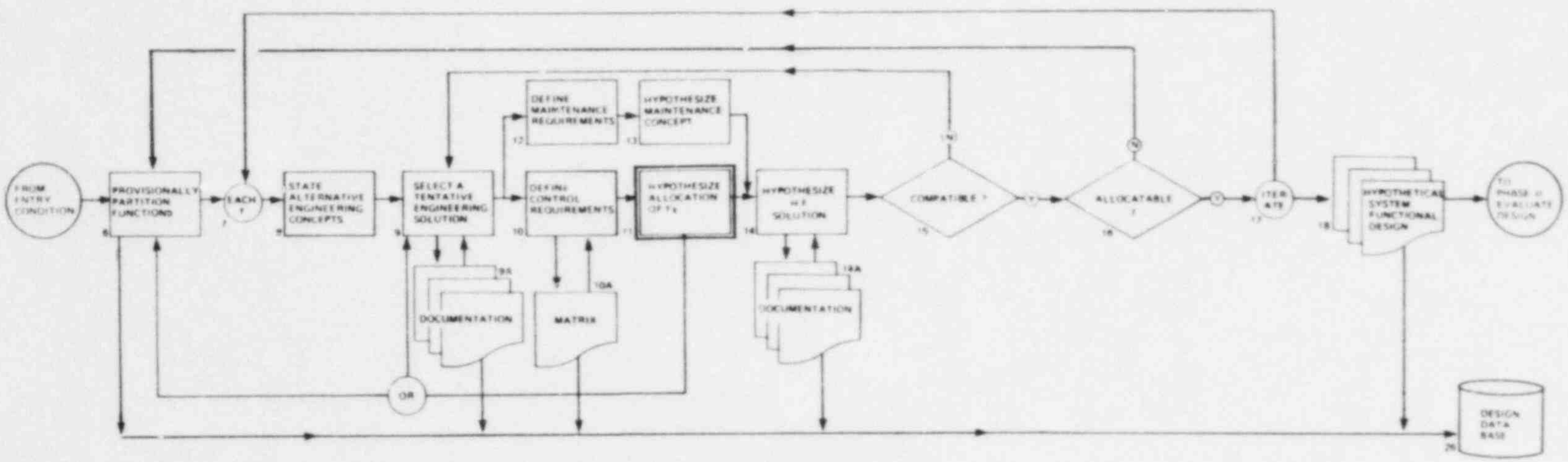

Fig. 3.4. The design process--phase I, Hypothetical Design (extracted from Fig. 3.1).

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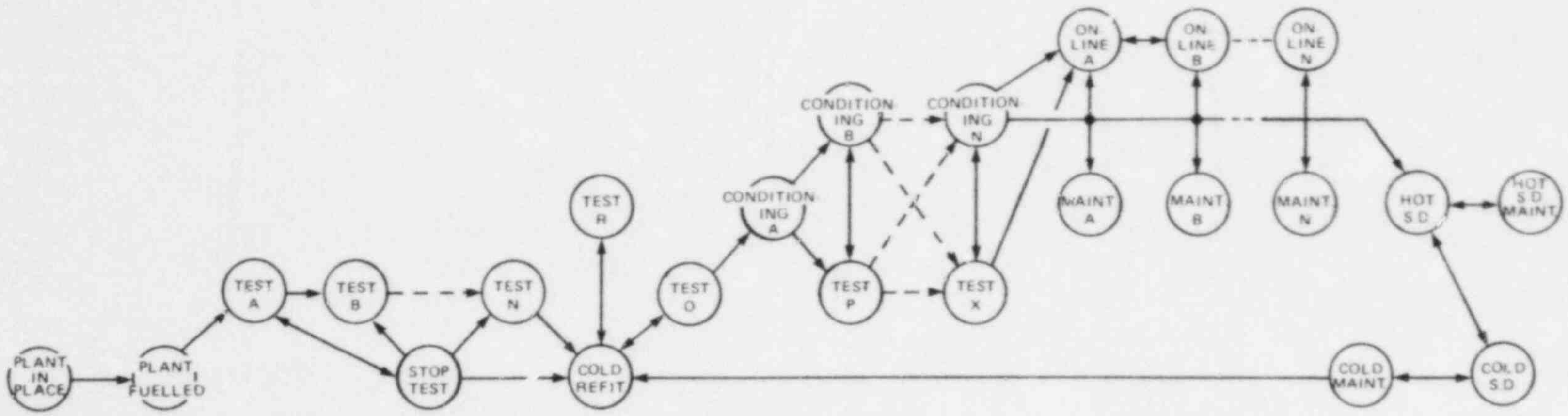

The major states are connected by arrows representing the expected normal and emergency transitions between states. States include:

1. "New plant in place"
2. "Plant fueld and provisioned"
3. an undefined number of of test states "A" through "N"
4. "Stop Test"
5. "Cold refit, modify, or recalibrate
6. conditioning/break-in states "A" through "N"
7. operational test states "A" through "N"
8. power production (on-line) states "A" through "N"
9. hot powered maintenance partially degraded configurations "A" through "N"
10. "Hot Shutdown"
11. "Hot S.D. Maintenance"
12. "Cold Shutdown"
13. "Cold Maintenance"

Fig. 3.5. Hypothetical gross state-transition diagram for NPP.

3.3.1.4 Failure States

Each operating state and transition state represents a plant status during which failure may occur. Failure may occur because parts fail, control errors occur, and, among other things, a change in plant conditions due to aging results in an out-of-parameter state. The failure state estimate is based on the histories of analogous systems and an engineering forecast. The designers describe, in general terms, what categories of failure may possibly occur, what specific failures will frequently or routinely occur, and what dangerous or high-cost failures may occur. It is important to anticipate these conditions, because they constitute an additional set of transition states for which control must be provided.

3.3.1.5 Analysis of Subsystems by States

Control requirements are derived from the need to maintain stable operating states, the need to implement transitions from state to state, and the need to minimize the consequences and propagation of failure. The subsystems partitioned in Sect. 3.3.1.1 can now be displayed as a matrix against the plant states (operating, transition, and failure) identified in Sects. 3.3.1.2 through 3.3.1.4. Each subsystem must be analyzed to determine its role during each defined operating and transition state of the plant. Figure 3.6 represents a portion of such a matrix.

Although it is not essential that a matrix be developed (but doing so will help in the partitioning of functions), it is necessary to identify the significant states that each subsystem needs to accommodate. These should be identified in terms of the general configuration to be assumed, the operating characteristics in that state, the inputs and outputs to other subsystems and states, and any stress or hazard that may occur. It is also necessary to identify the transitions between states, since these define control requirements.

In the example shown in Fig. 3.6, the analysts have crossed off the turbine system during shutdown states because it is not active and does not contribute to the plant process during those states. The turbine subsystem is in condition "A" (running loaded) during on-line operating states and transitions between states. It is in condition "B" (running down, not loaded), during transition to emergency condition 2, as the turbine is out of service.

Similarly, the HVAC subsystem assumes only two conditions during the states shown--normal running "A", and containment isolation "B".

3.3.1.6 Partition Into Functions

Based on these analyses, the designers select a tentative set of gross functions. An effort is made to minimize the number of functions by grouping closely related systems and states. For instance, the RHR & SG subsystems can presumably be treated together; they are therefore partitioned into only three functional states: (I) normal (full operation); (II) degraded normal (one SG isolated); and (III) emergency cooling

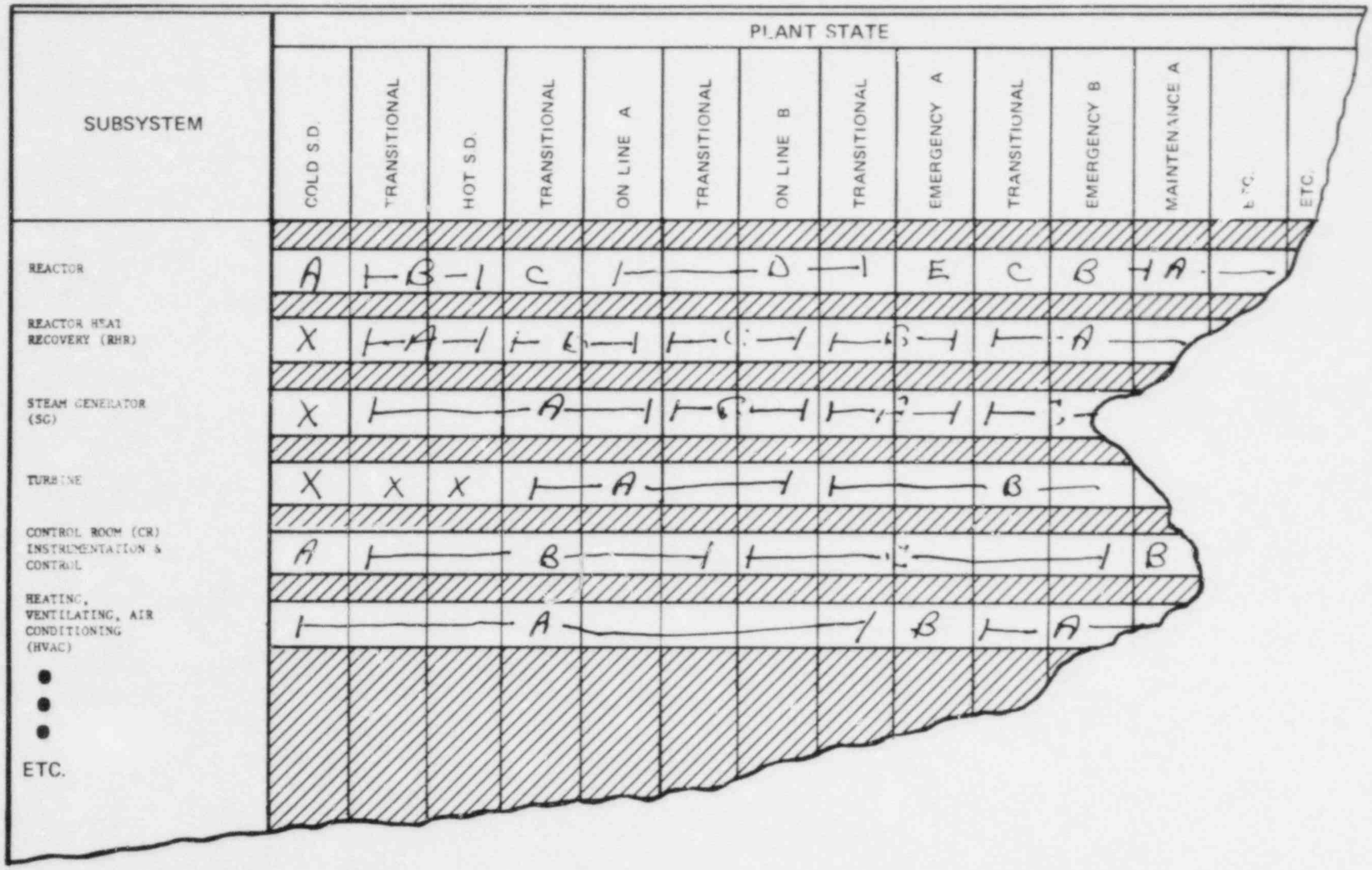

Fig. 3.6. Matrix analysis of subsystem states.

(Fig. 3.7). Each of these will include several intersections of subsystems and states, but the designers recognize these intersections as being closely related in terms of the engineering problems they will pose and the human control/maintenance requirements they will generate.

3.3.1.7 Attempt to Allocate Functions

Now the design team takes the provisionally defined functions and processes them through the succeeding steps (Fig. 3.7, steps 7 through 17). As will be explained later in detail, if the functions can be matched with an engineering solution, allocated, and matched with a human factors solution, they are considered to be provisionally defined as functins. Otherwise, they probably require redefinition, usually by repartitioning the function.

For example, in attempting to allocate function III of Sect. 3.3.1.6 (Fig. 3.7), the analysts may find that two distinctly different engineering subsystems are needed (see Fig. 3.4, step 9). Perhaps a special subsystem is required for emergency core cooling if elements of the RHR system are degraded. The provisionally defined function will be recycled to step 6 to be further partitioned. Similarly, they may find that at step 11 one portion of the function requires an allocation distinctly different from that required by the other; or at step 14 they may find that the function, as allocated, cannot be supported by a satisfactory human subsystem.

The single feedback path (arrow) in Fig 3.4 from step 16 to step 6 represents the fact that, if a function cannot be allocated, it must be returned for repartition. It should be understood, however, that the function might also be returned after blocks 9, 11, 14, or as soon as it is recognized that it cannot be allocated as defined.

3.3.1.8 Repartition

Functions are repartitioned and redefined until all functions can pass through steps 7-17, and until the level of definition of functions is sufficiently fine to support subsequent engineering design (see Sect. 2.4.5).

3.3.2 Treat Each Function

Step 7 of Fig. 3.4 represents a gate through which each function is passed, one at a time. When any one function has been allocated, it passes step 17 and becomes an element of step 18, the hypothetical system functional design. Then the next function enters the gate at step 7.

3.3.3 State Alternative Engineering Concepts

Step 8 of Fig. 3.4 is the step at which the engineering designers identify the possible alternative engineering treatments by which a defined function might be accomplished. Typically, these consist of familiar

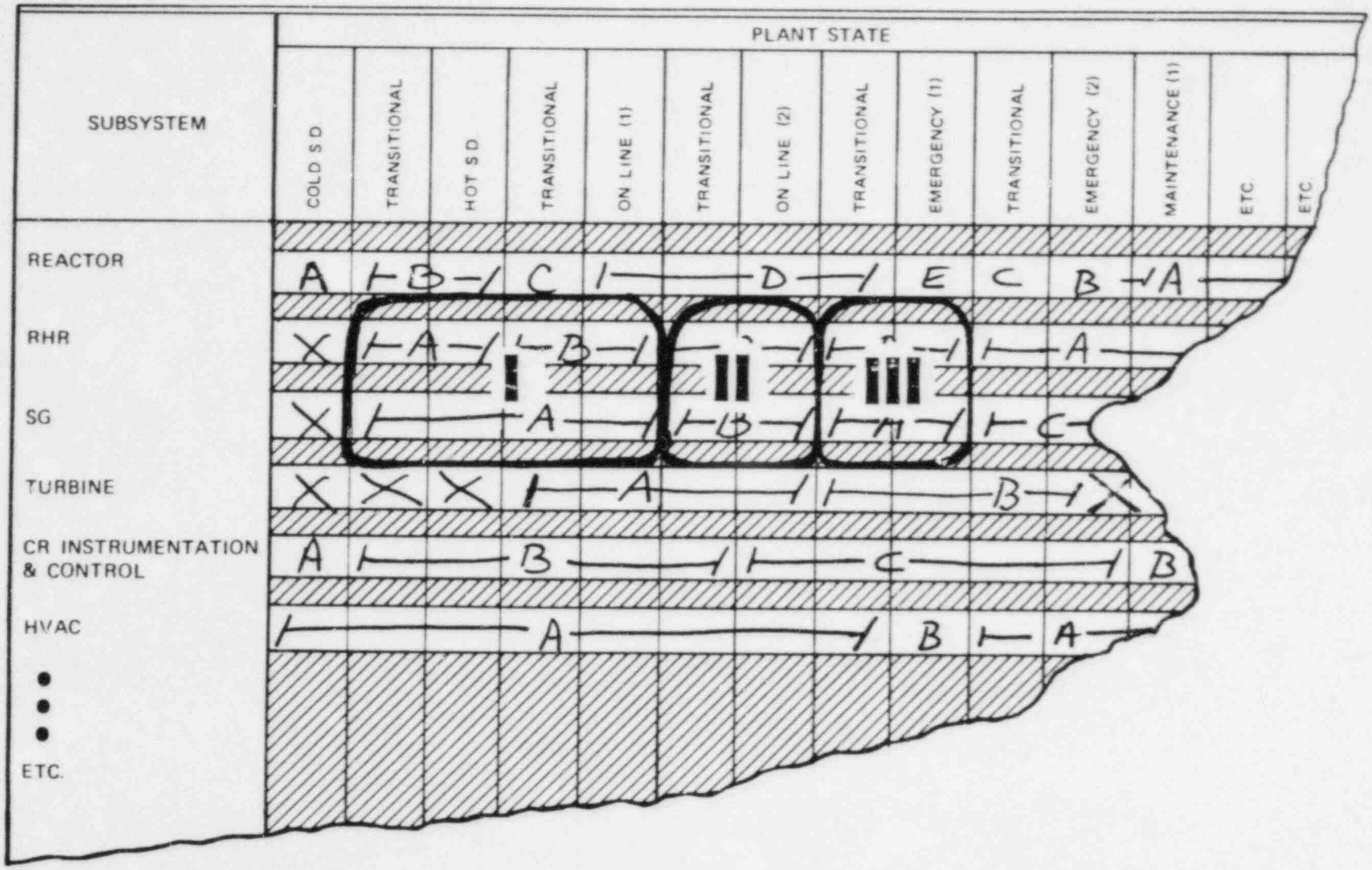

Fig. 3.7. Analysis of subsystem states.

technologies which may be applied as is, may be adapted for use, or may be proposed with technological improvements. Occasionally, new alternatives may be considered. See also Sect. 2.2.8, "Analogous Technology," and 2.4.8, "Keeping the Solutions Out."

3.3.4 Select a Tentative Engineering Solution

Step 9 of Fig. 3.4 is the step at which one of the engineering options, defined in step 8, is provisionally selected. The solution should be described in general, functional terms, not in terms of specific equipment.

3.3.4.1 Human Factors Staff Participation

This engineering decision should be made with all disciplines participating. Human factors staff may be able to speed up the process by promptly identifying options that are clearly not desirable from a human standpoint. More importantly, the human factors staff needs to be present in order to understand the rationale and engineering function for each technology selected.

3.3.4.2 Recycle Unsatisfactory Functions

At this point it may become clear that a function, as defined, cannot be fitted to an engineering solution. (The function may require two or more engineering solutions, or it may be technologically infeasible.) If a function must be repartitioned or redefined, it is fed back to step 6.

3.3.4.3 Documentation

Formal documentation (step 9A) becomes mandatory at this point, if it has not been initiated earlier. Documentation is required for the following reasons:

a. Team members can refer to what has been decided

b. There will be a record of the options and rationale of the decisions

c. The several disciplinary groups can continue to examine each other's decisions

d. Any required future redesign or repartition can be accomplished without duplicating earlier effort

e. The historic documentation can be used later in developing future improved designs

Documentation should consist of at least:

a. Drawings and flow charts

b. Records of the decision process, including alternatives considered and the basis for choice

c. The expected engineering-quantified parameters and input/output characteristics of subsystems for each function

d. Resource documents describing the characteristics of any prior technology to be applied or modified

Documentation is stored and accessed through the design data base, step 26. See also Sect. 2.8, "The Role of Documentation."

3.3.5 Define Instrumentation and Control Requirements

Step 10 of Fig. 3.4 provides for an analysis of instrumentation and control requirements. Control requirements are data which describe the points at which the prospective system will require control, and instrumentation requirements specify what data must be displayed to permit effective control. These data are of obvious importance in allocating control functions and designing a human factors solution (manpower, training, etc., step 14).

3.3.5.1 Specify at a General Level

Detailed definition of instrumentation and control requirements will occur later, during the engineering design phase. However, it is necessary at this point to make reasonable estimates or general descriptions of those requirements so that human factors design can keep pace with engineering design and critical control problems can be avoided.

3.3.5.2 Identify Control Requirements

It is a basic responsibility of the engineering staff to state where the plant will need to be controlled, although the human factors staff should assist. A useful point of entry is the matrix originally developed in Sect. 3.3.1.5 (Fig. 3.6). Each cell of the matrix can now be examined to estimate what controls must be exercised on the engineering subsystem concerned, at each of the plant states concerned.* Estimates should include the following:

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*This text by no means attempts to describe or elaborate on the tools and techniques of control engineering. However, it seems appropriate from an organizational perspective to employ a hierarchical control system design strategy, which can be described as having multiple layers and echelons of control functions having the following general characteristics:

a. higher levels of functioning exercise control over larger portions and broader aspects of the overall system behavior;

- Number of nodes to be controlled.

- Classes of control requirement: On/off (discrete), parameter adjustment (proportional), system reconfiguration, decision making, system coordination, etc.

- Frequency of required intervention.

- Control task complexity: Do several parameters interact? Are difficult judgments required? Are large memory stores required? Is the control of a stochastic nature? Is a multivariate optimizing scheme required?

- Speed of response: Are the required response times critical?

- The type and detail of information required.

3.3.5.3 Control Requirements Matrix

Some cells of Fig. 3.6 are not critical and can be disposed of by a descriptive comment. Certain critical cells or defined functions will deserve a more detailed analysis, which can be aided by a matrix in which the control groups are displayed against the plant evolutions to which they apply (step 10A).†

3.3.6 Hypothesize Allocation of Functions

Step 11 of Fig. 3.4 is the point at which allocation of functions is systematically considered. This step applies the first, or hypothesis, part of the general method for allocation of functions, which is the subject of this report. The second, or deductive, part of that method is

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b. the decision period of higher level functions is longer than that of lower functions;

c. higher level functions respond to the slower aspects of the overall systems behavior; and descriptions and problems of higher level functions are loosely structured, with more uncertainties, and are more difficult to formalize quantitatively.

At least three separate levels are distinguishable in a hierachical system: the lowest is performing continuous feedback control, the middle is executing algorithms (procedures), and the highest is making decisions and formulating goals.

†Several formats or methods of data analysis are possible. A format can be selected which is consistent with practices in the user's industry and company. As noted earlier, this report describes a general methodology, not a prescriptive procedure (see Sect. 3.1.2.1).

represented by step 19, Evaluate Allocation of Functions. These two steps, 11 and 19, are shown on Figs. 3.1 and 3.2 as highlighted blocks, and are described in expanded detail in Sect. 4 of this report. For the moment we will describe step 11 only briefly.

Steps 9 and 10 hypothesized an "engineering solution" and a set of control requirements for a specific function currently under design. Step 11 will now hypothesize an appropriate allocation of that function to man or machine. It is understood that more than one such allocation may be possible and appropriate: the problem is to divide responsibility for control of this function to man or to automation in one of several possible satisfactory ways. It is also understood that, in most cases, the allocation will be *shared* between man and automated control rather than allocated exclusively to one or the other.

3.3.6.1 Allocation Interacts with Other Steps

The allocation of functions responds to a hypothesized engineering design solution (step 9), using data describing control requirements (step 10). It anticipates the development of human subsystem functional design (human factors solution, step 14), and does two things: (1) It determines whether the engineering solution is acceptable from an allocation standpoint; if not, it may be necessary to reconsider earlier steps such as steps 6 and 9. (2) It develops a hypothetical allocation of control responsibilities between man and machine. Functions allocated to man will then drive the design of the human subsystem, and functions allocated to machine must be accommodated later by the instrumentation and control system functional design.

3.3.6.2 How Functions are Allocated

Functions are allocated to man, to machine, or (more frequently) to combinations of the two alternatives, by applying a series of tests to the engineering hypothesis. These tests ask, in an ordered sequence, the following questions:

1. Is automation mandatory?

2. If mandatory, is automation feasible?

3. Is human action mandatory?

4. If so, can man perform? (The cognitive steps involved are analyzed.)

5. Is the function too broadly defined to allocate (needs repartitioning)?

6. Is automation technically preferable (but not mandatory)?

7. Is human control technically preferable?

8. Should segments of the control behavior be allocated to automation (leaving others to man)?

9. Should control tasks be allocated to man to keep him occupied, interested, or informed?

10. Does the function need repartition (repeat step 5)?

11. Did the earlier criteria questions (1-10) force an allocation decision? If not, allocate by the residual criteria of cost or designer preference.

These steps and their supporting analysis are treated in detail in Sect. 4.1.

3.3.7 Define Maintenance Requirements

Step 12 of Fig. 3.4 provides for an estimate of maintenance requirements, which are implied by the engineering hypothesis (step 9). Steps 12 and 13 are taken concurrently with steps 10 and 11, and do not directly concern the allocation of functions for control room design. They are shown because they are essential to step 14, the human factors solution.

Step 12 consists of only a brief statement by the engineering staff concerning the probable levels and kinds of maintenance support which the engineering solution will require.

3.3.8 Hypothesize Maintenance Concept

Step 13 of Fig. 3.4 continues the analysis of maintenance requirements by hypothesizing *how* maintenance will be provided. This step is taken by human factors planners, working in concert with engineers. The product of this step is a brief statement of the kind of maintenance organization proposed to provide the maintenance support defined in step 12. This statement includes the kinds, numbers, levels of training, and organization of maintenance personnel, and will provide the basis for maintenance manpower planning.

3.3.9 Hypothesize Human Factors Solution

Step 14 of Fig. 3.4 is the step at which a human subsystem functional design is hypothesized to meet the requirements of steps 11 and 13. The system functions partitioned at step 6 are treated in sequence at this step. For each function a human factors solution is hypothesized. Collectively, those human factors solutions form the human factors subsystem functional design. This step is performed by a human factors team which includes several disciplines, such as training, job design, and procedures preparation.

Documentation is required by step 14A and will become part of the design data base (step 26). It should not be detailed, but rather should provide a preliminary statement of the human organization, with estimates of numbers and with quantitative requirements including life cycle costs. Documentation typically includes general statements regarding:

- Number of personnel
- Skill and training levels
- Job design, crew composition, and skill progression
- Procedures and job aids
- Training organization
- Selection and advancement
- Management structure

3.3.10 Compatibility Test

Step 15 of Fig. 3.4 represents a continuing test for internal compatibility which is applied to the emerging functional design. It concerns at least two areas:

1. Engineering/Human Solution Fit. Having gone through steps 9, 11, and 14 to hypothesize an engineering and a human factors solution for each function, the team again compares those two solutions: Do they really provide for all control requirements? Are they efficiently related?

2. Engineering/Human Subsystem Coherence. Are the individual engineering and human factors solutions merging into coherent engineering and human subsystem designs? Are the assumptions about levels of technology consistent? What about levels of skill and training? Do decisions made for different functions reflect divergent design philosophies?

If the emerging design is incomplete, fragmented, or inconsistent, it is normally necessary to reconsider some functional decisions from the "alternative concepts" point (step 8).

3.3.11 Allocatability Test

Step 16 of Fig. 3.4 represents a test that may, in fact, apply anywhere during the sequence from step 10 through 14. At any point it may be recognized that the function, as partitioned at step 6, is not allocatable because it represents too gross a segment of the system, and should actually be subdivided.

In this methodology, a function is a subset of the plant's necessary subsystems and processes, the parts of which are closely related, which produces a plant subproduct, *and which can be treated as a unit concept during early system design.* In other words, a function is defined operationally; the plant and its processes are initially broken into a minimum set of gross functions at step 6. Gross functions are tested at steps 8 through 15 to determine whether they can be matched with an engineering solution, allocated, and then matched with a human factors solution. If any one of these tests cannot be met, the function must be redefined, presumably by being further partitioned. If all tests are met, the function is passed through step 16 and becomes an element of the functional design at step 18. Once all functions have been partitioned (defined) at a level which permits them to be processed through steps 8 through 15, the definition of functions is complete, and Phase I, the Hypothetical Design Phase, is complete.

Step 16 is failed if at any point from step 8 through step 15 it becomes apparent that the function is too difficult to handle and should be redefined. When this occurs the function is normally returned to step 6 for repartition, although other steps may apply such as "basic concept change," steps 2 and 3, or "reselect engineering solution," steps 8 and 9.

3.3.12 Hypothetical System Functional Design

When all functions have been defined, given a satisfactory engineering solution, allocated, and given a satisfactory human factors solution, those data collectively constitute an engineering design, an allocation, and a human subsystem design--the three elements of a functional design (step 18). This design remains hypothetical until it has been tested deductively in Phase II, the Test and Evaluation Phase.

3.4 THE TEST AND EVALUATION PHASE

Phase I was a creative phase, during which engineering and human factors design solutions were invented as a set of hypotheses. Phase II provides a systematic deductive evaluation of the hypothesized design, an evaluation which normally leads to reconsideration of many initial design hypotheses. Major portions of the design are then recycled to Phase I for improvement and elaboration of detail. This iterative cycle of Phase I hypothesis and Phase II test is repeated until a satisfactory functional design is achieved.

3.4.1 Hypothetical System Functional Design

This step, which is step 18 of Fig. 3.8, represents the entry condition for Phase II, the existence (at some level of detail) of a hypothetical design. Figure 3.8 reflects only steps 18-26, the test and evaluation phase of functional design. (Refer to Fig. 3.1 for the entire design sequence.)

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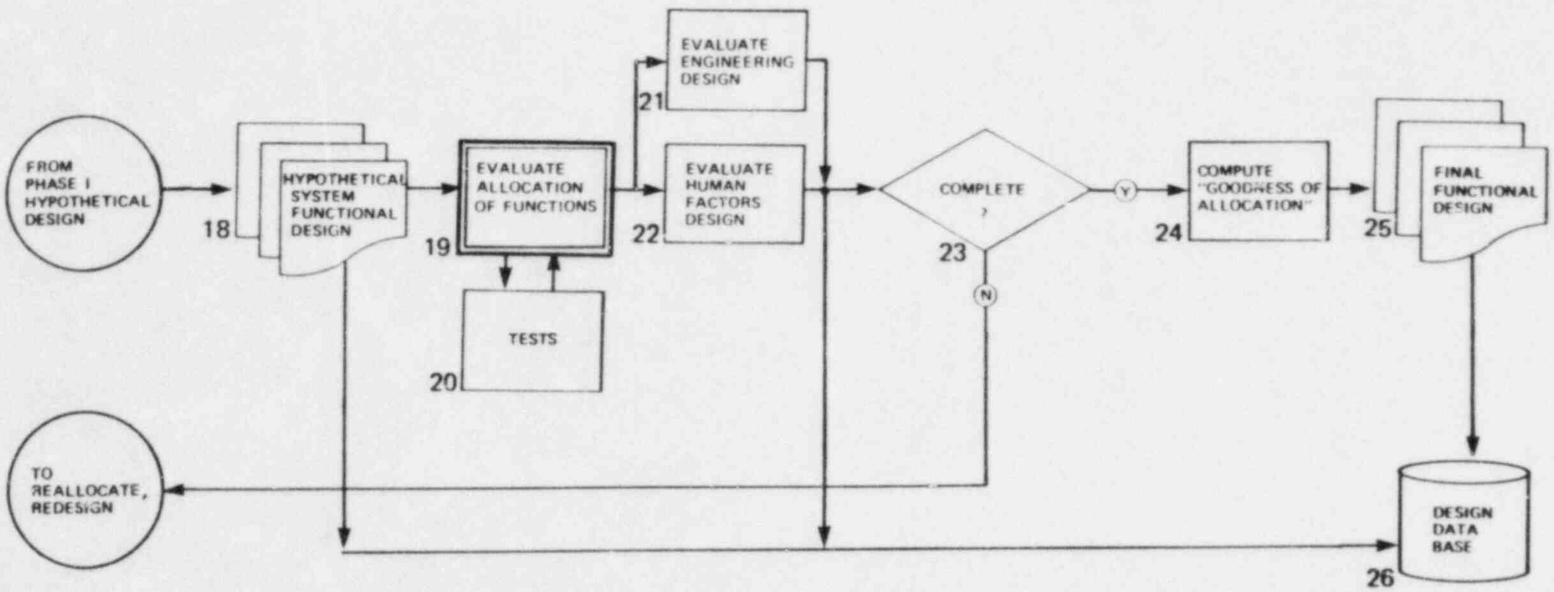

Fig. 3.8. The design process--Phase II, Test and Evaluation.

The level of detail may not be great during the initial cycles of hypothesis and test, but it will increase as a functional design is perfected. A minimum level of detail is assured because Phase I does not end until a tentative set of functions has been hypothesized. Detail must therefore be sufficient to:

- Identify the hypothesized functions and clearly state their boundaries
- Identify the engineering solutions
- Document the allocation of functions decisions
- Identify the human factors solutions

The design is documented in the design data base; therefore each of the participating disciplines can have access to all prior design decisions.

3.4.2 Evaluate Allocation of Functions

Step 19 of Fig. 3.8 is the essence of Phase II. It applies a deductive evaluation to the hypothesized design solution, including the allocation of functions. Data from empirical testing (step 20) may be entered as evidence. However, test data are rarely achievable during the early steps of design because there is so little to be tested.

Evaluation tests will be described in detail in Sect. 5 of this report. Briefly, this step consists of the following six tests which are applied to each function in sequence:

1. Does Man Meet Core Performance Requirements? A first test asks whether man, viewed as an engineering component, can meet the performance demands imposed by each function as hypothetically designed. A cognitive model is used to analyze performance in terms of eight core performance areas.

2. Does Man Meet Human Performance Requirements? This test considers man more broadly, as a complex organizm and as an element of the human factors design.

3. Are Cost Tradeoffs Acceptable? This test makes an initial judgment of the relative costs of the engineering and human factors solutions: Working together, do they result in optimum system cost?

4. Is Human Factors Structure Adequate? This test examines the proposed human subsystem design in order to estimate the adequacy of hypothesized training, procedures, personnel selection, and organizational structure. Are they reasonably adequate assumptions? Will they support the performance requirements identified by tests 1 and 2?

5. Is Cognitive Support Adequate? This step asks whether the operator will be provided sufficient information to continually be aware of the plant status.

6. Is Job Satisfaction Optimal? This step examines the factors which lead to human acceptance of the job.

Failure to qualify on any of the six tests in this step will return a hypothetical function to an appropriate step of Phase I for redesign. (This feedback is shown as step 23.)

3.4.3 Evaluate Engineering Design

If by step 19 of Fig. 3.4 a function is found to be properly allocated, then in step 21 of Fig. 3.8 the engineering design is evaluated for technical suitability and for compatibility with the whole plant design using recognized methods of engineering evaluation. This is the responsibility of the engineering staff.

3.4.4 Evaluate Human Factors Design

If by step 19 a function is found to be properly allocated, then in step 22 of Fig. 3.8 the human subsystem is evaluated for its technical suitability, for its compatibility with the plant engineering design, and for its compatibility with the human factors design of other functions (whole plant design). This is the responsibility of the human factors staff, who will use recognized methods in human factors evaluation.*

3.4.5 Complete?

Step 23 of Fig. 3.8 is a decision block which represents decisions based on the findings of tests at steps 19, 21, and 22. Functions which fail step 19 and are found not properly allocated are returned to a suitable point in Phase I to be redefined, partitioned more narrowly, or redesigned. Functions which fail steps 21 and 22 are fed back for redesign in a similar manner.

Analysts determine whether the whole set of functions, as it arrives at step 23, is in fact a necessary and complete set describing the plant and its process states. The analysts examine the documentation for engineering and human factors functional design solutions. Questions are posed concerning the level of detail: Are the engineering and human factors subsystems described at levels of detail which are compatible from function to function? Is the level of detail adequate for the plant design

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*Step 22 differs from the earlier test 4 in step 19, which asked: "Is the human factors structure adequate?" That test asked whether the human factors hypothesis would meet the needs of man within the system as defined. This step (22) asks whether the human factors hypotheses are mutually consistent and constitute a good application of human factors science.

as a whole? (See Sect. 2.4.5.) If not, feed back to Phase I for further partition or development of detail.

Functions which pass steps 19 through 23 become elements of the final functional design.

3.4.6 Compute "Goodness of Allocation"

A "goodness of allocation" profile (step 24), provides a quantified estimate of the appropriateness of the allocation for each defined function. The method for this determination is described separately in Sect. 6 of this report.

3.4.7 Final Functional Design

Collectively, the functions which pass all tests of Phase II constitute a system functional design (step 25 of Fig. 3.8).

4. ALLOCATION OF FUNCTIONS

This section explains how to allocate functions to man and machine using a systematic procedure which consists of two major steps, hypothetical and deductive. These steps are part of the design process during the hypothetical and test phases, respectively, and are represented by steps 11 and 19 of Fig. 2.1. The step-by-step details of this method are itemized minutely in the body of this section rather than in an appendix because it is necessary to comprehend the method in detail in order to rigorously evaluate its merit.

4.1 STEP 11: HYPOTHESIZE ALLOCATION OF FUNCTIONS

This step makes a hypothetical allocation for a designated function as an intermediate step between hypothesizing engineering and human factors design solutions for the function.

To summarize earlier discussion (Sect. 3.3), after functions have been provisionally defined they are passed, one at a time, through the hypothetical design process. During that process, three closely linked hypotheses must be formed: (1) an engineering treatment (step 9), (2) an allocation of functions (step 11), and (3) a human factors treatment (step 14). The hypothesized engineering treatment provides a basis for the allocation of functions which assigns roles between the engineering subsystem and the human subsystem yet to be hypothesized. The allocation decision may do any or all of the following:

1. Force a reconsideration of the engineering hypothesis.

2. Specify future details of the engineering design.

3. Define the requirements for human control and provide the basis for the human factors hypothesis.

Hypothesized allocations define the boundary between the engineering and human factors subsystems and permit a human factors treatment to be hypothesized. A recommended procedure for formulating a hypothesized allocation of functions is shown in Fig. 4.1, which presents step 11 of Fig. 3.1 in greatly expanded detail.

4.1.1 General Method

The recommended procedure for allocating functions consists of 19 analysis and decision steps shown in Fig. 4.1 and described later in this section. The sequential application of these steps results in a hypothetical (provisional) decision concerning the allocation of functions to man and to machine. The following nine general principles apply to most of those steps.

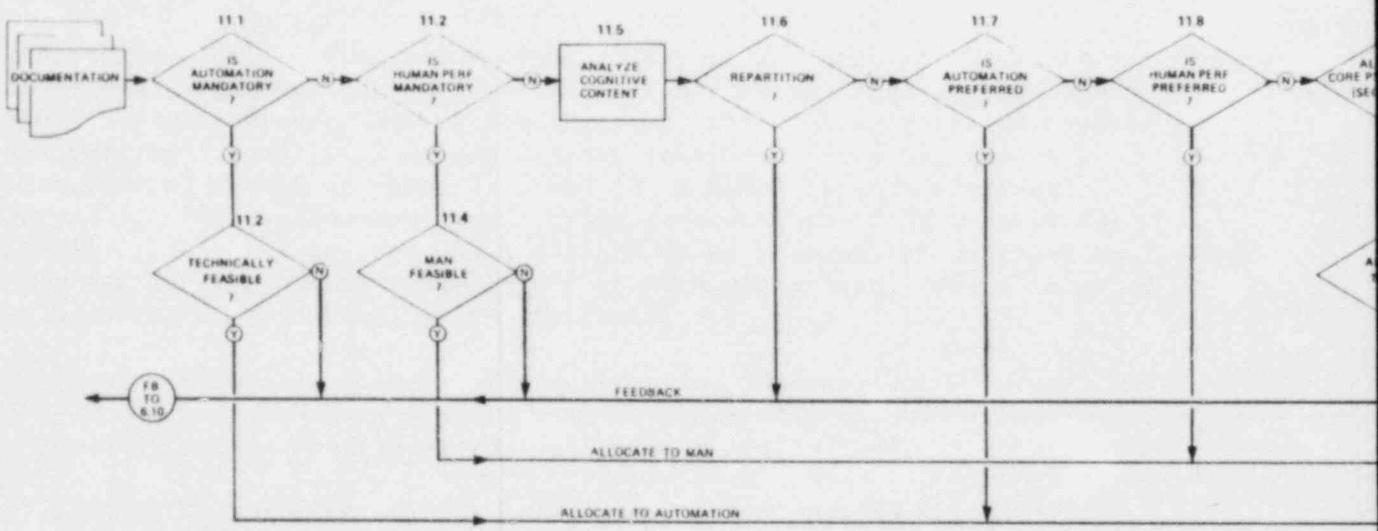

Fig. 4.1. Design step No. 11: Hypothe

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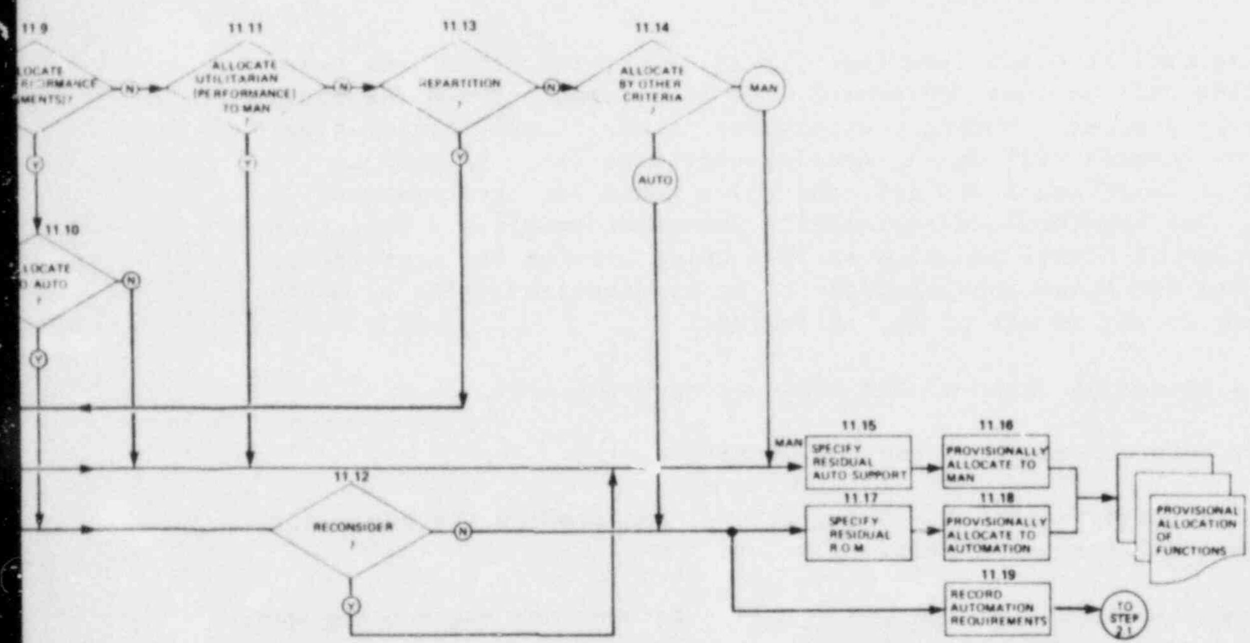

size allocation of functions.

1. Expert Judgment. Decisions made during the creative processes of design typically require multivariate judgments based on complex evaluations of probable utility versus probable risk. Allocation of functions also requires judgments concerning probable human performance, for which there are no reliable measurement tools. The team is therefore forced to rely ultimately on expert judgment as the only feasible way of making each hypothesized allocation.

   This is not to say that quantitative data will not be considered. Such data exist and must be used when available. These include:

   - Past performance of analogous systems.
   - Quantified engineering predictions.
   - Human factors experimental data (typically more suggestive than predictive).
   - Previous system cost data and future cost estimates in both time and dollars.
   - Input/output data for connecting subsystems of the design.

   Even where generous quantified data exist, however, they must be interpreted and weighed against the unquantified variables; thus each allocation step ultimately requires judgment, as was discussed in Sect. 2.5.

2. Multidisciplinary Team. Allocation judgments require several kinds of engineering and human factors expertise. A small, multidisciplinary team is recommended to make hypothetical allocations.

   A minimum team will include a senior "allocator" member who is not a member of either the engineering design team or the human factors design team and who may serve as chairman. This person should be an experienced engineering psychologist or equivalent. He or she will organize team meetings, prepare the agendas, chair the meetings, and make all final decisions concerning allocation. Allocators other than the chairman may also participate as allocator representatives. The chief of the overall design team (presumably a system engineer) may serve on the team, in which case he will serve as chairman and senior allocator. (See Sect. 3.2.4.)

   The team will also require one or more representatives each from the engineering design team and the human factors design team. The precise skills and experience required of them will depend on the specific functions being allocated and their technical characteristics. The roles of the team members are generally as follows:

   a. Engineering design members are expected to:

   - Explain the hypothetical engineering solution to other members of the team.

- Find and present all available quantified data on predicted engineering performance.

- Find and present quantified and descriptive data on analogous technology.

- Interpret the control requirements (step 10) to other members of the team, and discuss the general constraints and demands which the technology will impose on human users.

- Answer questions about the technology (the hypothetical engineering solution and analogous technology).

- Participate generally in team deliberations.

b. Human factors design members should:

- Provisionally estimate the reasonableness and suitability of each team decision in terms of its human factors implications.

- Provisionally estimate the feasibility and cost of the implied human factors system requirements (what human factors costs are affected by each decision?).

- Identify, present, and interpret quantified and descriptive historic data about the human factors effects of analogous technology.

- Participate generally in team deliberations.

- Assist allocator members in the analysis of core performance requirements (step 11.5, Fig. 4.1), or perform the analysis if there are no allocator members other than the chairman.

c. The senior allocator member shall:

- Control the agenda and prepare for meetings.

- Chair meetings.

- Make final decisions.

d. Other allocator representatives (if any) should:

- Assist in team deliberations on the basis of their specialized skills or experience.

- Perform the analysis of core performance requirements described by step 11.5 of Fig. 4.1, assisted by human factors representatives.

3. Analogous Technology. Expert judgment is assisted by comparing each proposed technology with analogous real cases. In fact, experience

with analogous technology is the principal basis for all invention and is essential in forming reliable design hypotheses. The ability to allocate functions will depend in large part on access to historic design data, including data about performance, problems, and cost. See also the discussion of analogous technology, Sect. 2.5.2, and institutional memory, Sect. 2.8.4.

4. Design Data Base. Data for allocation hypotheses are drawn from the design data base, step 26 in Fig. 3.1. These data include the following:

   - the entry conditions established at steps 1-5;
   - the identity of provisional functions, step 6;
   - the alternative engineering concepts and hypothetical solution, steps 8 and 9;
   - the description of the control requirements imposed by the engineering solution, step 10; and
   - data concerning analogous technology.

   As allocation hypotheses are formed they are recorded in the design data base along with the rationale for the allocation decision. Once in this data base, these data will become available to other members of the design organization and will be accessible whenever necessary to reconsider the allocation hypothesis.

5. Simplicity and Speed. The purpose of the hypothesis procedure is to reach a rapid approximation of a correct allocation. The allocation is hypothetical only; it will be tested at step 19 of Fig. 3.1, and the procedure may be repeated many times before a final functional design is achieved.

   Lengthy presentations and debate should be avoided; each panel session should proceed smoothly. The team should be able to assign a hypothetical allocation to a function in only a few minutes, especially during early iterations of the process.

6. Permissive Criterion. During this hypothetical allocation decision the goal is to find an optimal allocation, not to critique it. Furthermore, within a whole system design it will usually be necessary to accept some allocations that are less than optimal. Therefore, a permissive criterion will be exercised: each decision will be made on the basis of best first judgments, and will not be delayed by critical re-examination.*

*This rule will be reversed when we come to step 19; during that testing step, a conservative criterion will be applied.

7. Series Analysis. In general, the team will deal with provisional functions one at a time. Later (in step 19) the simultaneous effects of all functions will be examined, but here the goal is to achieve a hypothetically optimum allocation for ech functon individually.

   This does not mean, of course, that the team will disregard what it knows about functions already allocated. It will not make decisions which are clearly inconsistent with earlier ones or are unacceptable because of obvious interactions between functions.

8. Decision Matrix. The matrix shown in Fig. 4.2 is designed to clarify the logical basis for certain decision steps. (This matrix was first discussed in Sect. 2.7.3.) Shown in circles outside the matrix are the respective steps from Fig. 4.1 at which the contents of each region are allocated.

9. Decision-Making Procedure. The team will consider each function in an order selected by the chairman, proceeding approximately as follows:

   a. The decision steps shown in Fig. 4.1 will be completed in numerical order.* These steps are detailed in Sect. 4.1.2.

   b. Engineering members will describe the hypothetical engineering solution, its demands on users, and its analogous technologies (Sect. 4.1.1).

   c. Human factors members will discuss the apparent consequences of the solution on personnel (see Sect. 4.1.1).

   d. All members will suggest possible allocations of function, and will seek to achieve a consensus solution.

   e. The chairman will decide on a hypothetical allocation, not necessarily accepting the majority opinion. He or she will record that decision, including the decision rationale and any important non-concurrences.

   f. The method and criteria described in Sect. 4.1.1 will be applied in each of the steps shown in Fig. 4.1.

4.1.2 Step 11.1: Is Automation Mandatory?

This step identifies functions and subfunctions for which automation is mandatory. These are the functions which lie in region (U_h) of Fig. 4.2.

*Other sequences are acceptable so long as all decision steps are applied. However, the order shown is a rational sequence of decisions, and is recommended because of the sequence of data successively available in the decision data base.

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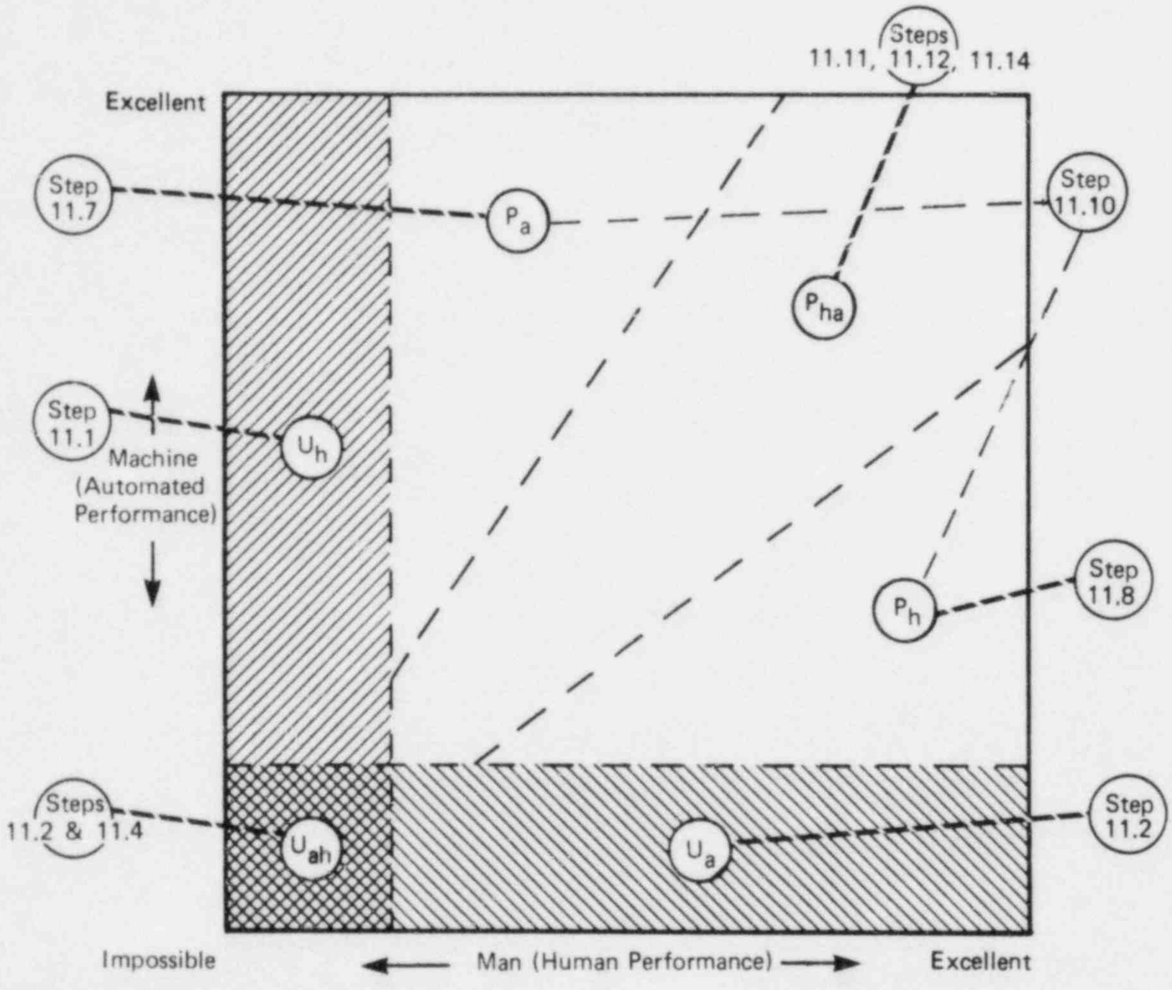

Fig. 4.2 Decision matrix for allocation of functions--relation to Analytic Steps.

The functions to be identified are those to be totally automated--that is, *all* included tasks *must* be automated, although some tasks may require a capability for human observation and intervention. That question will be dealt with by step 11.17, "Specify the Residual Role of Man."

4.1.2.1 Applicable Substeps and Questions:

a. Are Working Conditons Hostile to Man? Are any working conditions hazardous to man? Do environmental conditions permit the survival of man? In the NPP environment, temperature and radiation hazard are the principal limiting factors (see also Appendix A). If conditions are unsuited to man, the outcome is "yes."

b. Does the Function Include Tasks Which Man Cannot Perform? Does the function require speeds of response, levels of analysis, or other actions beyond the performance capabililties of man? (Use the guidelines of Appendix B). If required performance is clearly beyond the capabilities of man, use outcome "yes." Marginal cases will be considered later at steps 11.7 and 11.8.

c. Does Regulation or Law Require Automation? If so, use outcome "yes."

d. Does Safety Require Automation? If a policy dictates, or if on considered analysis it is decided that sfety functions should be initiated automatically without the participation of CR operators, the outcome is "yes."

4.1.2.2 Test Result

a. "Yes." If the overall outcome is "yes," proceed to step 11.2.

b. Partly "Yes." If automation is mandatory for parts of the function (e.g., for included subfunctions), the function must be returned through step 11.6 for repartition.

c. "No." If the outcome is "no," proceed to step 11.3.

4.1.3 Step 11.2: Automation Technically Feasible?

In some cases automation would be required to perform the function, but it is not technologially feasible. Such cases fall in region (U_{ah}) of Fig. 4.2. This decision is made principally on the advice of the engineering members of the allocation team. Automation is not technically feasible if

- No feasible engineering strategy exists.
- The costs of automation would be unreasonable.
- Development or delivery time would be unacceptable.

- The reliability of an automated solution would not meet function requirements.

4.1.3.1 Test Result

a. "Yes." If automation is technically feasible, the entire function is hypothetically allocated to automation, with no human participation. Go to the bus line "allocate to automation."

b. "No." If automation is not feasible, the function must be repartitioned, redefined, or assigned a new engineering solution. Return to step 6 or 9.

4.1.4 Step 11.3: Is Human Performance Mandatory?

This step reverses the logic of step 11.1 to identify functions and subfuctions for which the direct participation of man is mandatory. These functions fall in region (U_a) of Fig. 4.2. The functions to be identified by this step are those to be totally manual--that is, *all* tasks included here *must* be under human control, although some may require automated support at the task level. That question will be dealt with by step 11.15, "Specify Residual Automation Support."

4.1.4.1 Applicable Substeps and Questions:

a. Is Human Performance Required by Law or Regulation? If so, use outcome "yes."

b. Is Human Performance Required by Labor Agreement? If so, use outcome "yes."

c. Is Man Required to Maintain Policy-Level or On/Off Control? Refer to the discussion of this issue in Sect. 2.9. Human users must be able to make the basic policy and economic decisions which cause the plant to produce economically desired products and keep it within statutory safety standards. If a function falls in this category, use outcome "yes."

d. Is Automation Technically Infeasible? Using criteria in Sect. 4.1.2, is automation probably infeasible? If so, use outcome "yes."

4.1.4.2 Test Result

a. "Yes." If the outcome is "yes," go to step 11.4.

b. Partly "Yes." If human participation is mandatory for parts of the function (for included subfunctions), the function must be returned through step 1.6 for repartition.

c. "No." If the outcome is "no," go to step 11.5.

4.1.5 Step 11.4: Is Man A Feasible Solution?

In some cases human performance would be required, but performance requirements are beyond man's capability. These cases fall in area (U_{ah}) of Fig. 4.2. This decision is made primarily on the technical advice of the human factors members of the team. The criteria to be used are those previously cited in Sects. 4.1.2.1 and 4.1.2.2. If man is not a feasible solution, use outcome "no."

4.1.5.1 Test Result

a. "Yes." If human performance is feasible, the entire function is hypothetically allocated to man, without automation of any part. Go to the bus line "allocate to man."

b. "No." If human performance is not feasible, the function cannot be allocated. It must be repartitioned, redefined, or given another engineering solution. Go to step 6 or 9.

4.1.6 Step 11.5: Analyze Included Core Performance Requirements and Automatability

Before further decision steps are taken, it is advisable to analyze each function by breaking it down into the sensory, cognitive, and motor system behaviors required. (Refer to the discussion of core performance areas in Sect. 2.6.3, and to Appendix C for defining criteria.)

If the team includes allocators other than the chairman, this step is performed by the allocator team members, assisted by the human factors representatives. If there are no other allocator members, it is performed by the human factors representtives alone. Figure 4.3 illustrates the interactions of core performance areas as control actons are being performed.

4.1.6.1 Identification and Analysis

a. State in Which Core Performances are Required. For each function, examine the control requirements developed in step 10 of Fig. 3.1 and described in the control requirements matrix, step 10A. These data tell what control interventions the function will require in each predicted plant state. For each defined control requirement, estimate the core performance areas which must be exercised if man is to perform the function.

b. Identify Critical Core Performances. Most control actions and the core performances they require will be non-critical in that they can readily be performed by man. To simplify analysis, attention should focus only on

   - Critical core performance requirements, and

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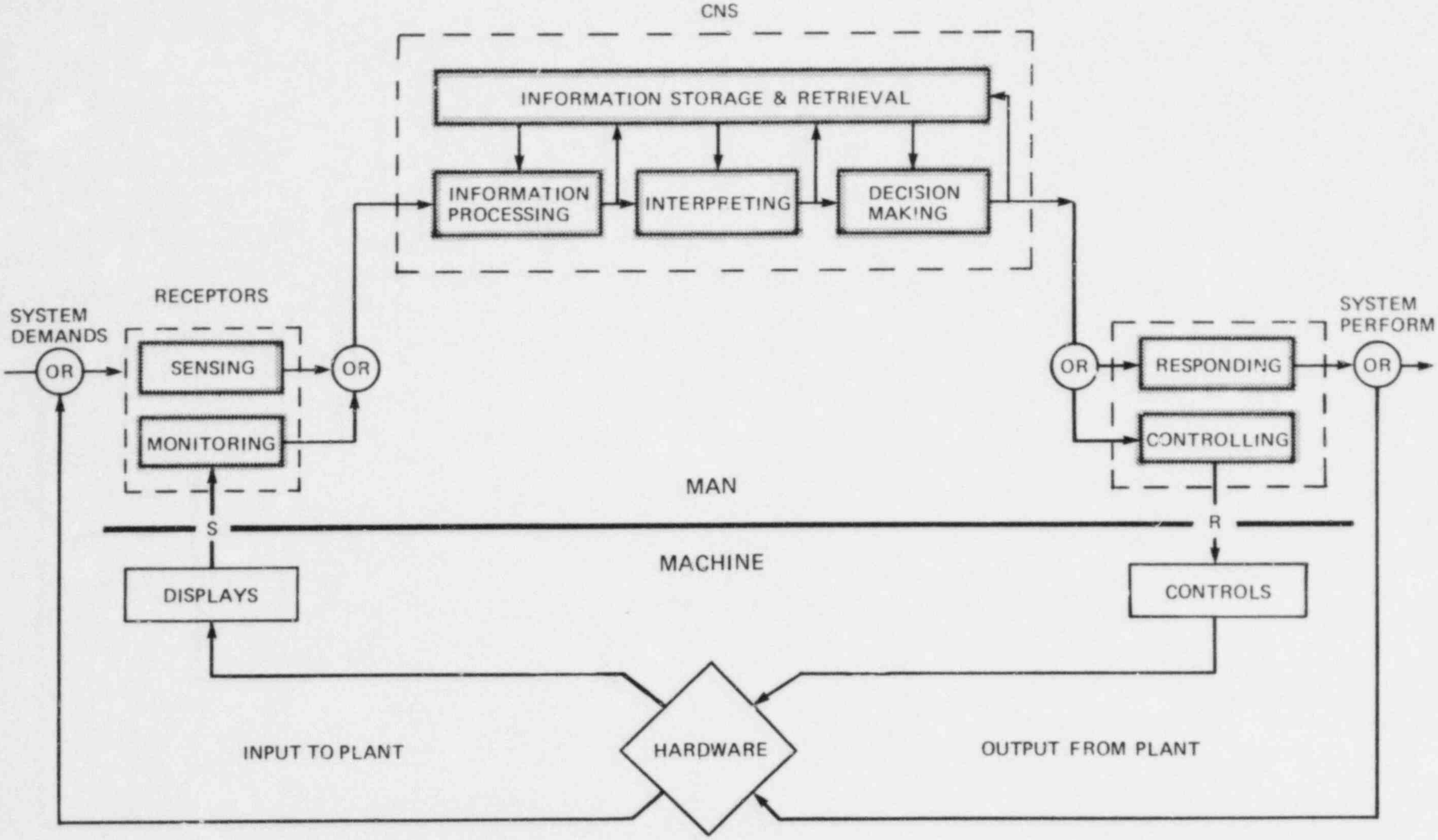

Fig. 4.3 A conceptual man-machine model emphasizing the core human performance areas.

- The total number of actions required per unit of time (frequency of tasks).

Identify those core performances and related control requirements which are critical, or possibly critical, and record them in the design data base.

c. Estimate the Suitability of Man. For each critical requirement, estimate how well man can perform. This is the horizontal dimension of the matrix in Fig. 4.2, "Man (human performance)." This estimate, which cannot be reasonably quantified, should be a descriptive statement that identifies problems, control requirements, and core performance areas.

In making this estimate the human factors representatives will take into consideration any human factors design decisions already hypothesized. For instance, if a working hypothesis has been established concerning crew size or taining level, that datum will affect how well man can meet the control requirements.

d. Estimate the Suitability of Automation. The engineering representatives will make an assessment of the feasibility and cost of automating control requirements analogous to (c) above. This is the vertical dimension of Fig. 4.2, "Machine (automated performance)." This estimate will be documented as a descriptive estimate for the suitability of automation, stating the following:

- Control requirements which impose critical technical limitations or costs.
- Description of the limitations.
- Identification of the information processing steps (Fig. 4.3) which are difficult to automate. These can include sensing, detection, pattern recognition, decision analysis, information storage or retrieval, and control execution. These steps are machine equivalents of the human core performance areas.
- Identification of those non-critical core performance steps in this section which automation may be able to perform well.

4.1.7 Step 11.6: Repartition

Analysis of core performance requirements may reveal cases in which a function will be difficult to allocate because it is too large or contains parts which are suited to different treatments. If so, the function should be repartitioned into subfunctions.

4.1.7.1 Repartition Criteria

a. Too Large. If a function contains too large a portion of the plant design to deal with easily, use outcome "yes."

b. Different Treatments. If a function contains two or more areas which appear to require different allocation treatments, use outcome "yes."

c. Similarity of Content. If a function contains more than one cluster of coherent subfunctions, it should be partitioned. That is, it should be repartitioned if it contains two or more parts which differ sharply when analyzed as outlined in Sect. 4.1.5. If this is the case, use outcome "yes."

4.1.7.2 Test Result

a. "Yes." If the outcome of step 11.6 is "yes," return to step 6 of Fig. 3.1 and repartition the function.

b. "No." If the outcome is "no," proceed to step 11.7.

Step 11.6 may actually be employed whenever it becomes clear that a function cannot be allocated successfully, or could be allocated more easily if broken into parts. This can happen during any step from 11.1 to 11.12.

4.1.8 Step 11.7: Is Automation Preferred?

This step identifies functions for which the automation of all included tasks is clearly preferred, because automation will perform more reliably than human control. These cases lie within region (P_a) of Fig. 4.2. (Refer also to Sects. 2.7 and 4.1.6.)

4.1.8.1 Criteria for Preferred Automation

a. Included Cases. This step identifies those functions for which automation is clearly preferred (i.e., automation can perform them better than man). This can include both (a) cases in which automation technology is highly acceptable (reliable, effective, inexpensive) and human performance imposes some problems, and (b) cases in which automation is marginally effective or expensive, but humans are expected to perform even more poorly.

b. Role of Man. This step should identify those functions in which all control tasks should be automated, although there may be a requirement for man to monitor instrumentation or intervene during emergencies. In other words, man is *outside* the control loop. See Fig. 4.4.

4.1.8.2 Test Result

a. "Yes." If the outcome is "yes," go to the bus line marked "allocate to automation."

b. "No." If the outcome is "no," go to step 11.8.

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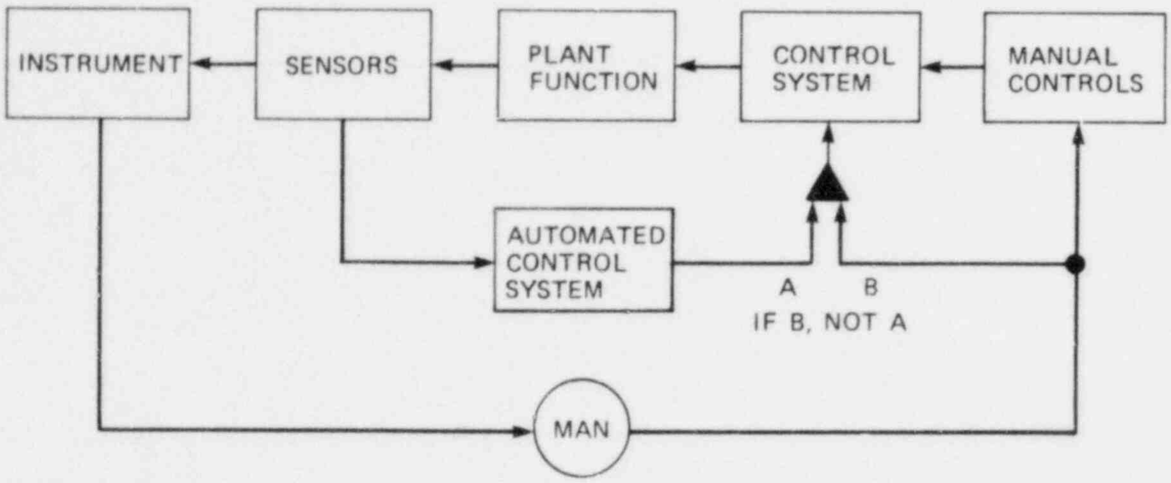

A plant or function in this configuration is normally controlled by the automatic control system. Man is outside the primary control loop, but can monitor the process through instrumentation. If man chooses to intervene by operating manual controls that action overrides the automated control system.

Fig. 4.4. Man outside the control loop.

4.1.9 Step 11.8: Is Human Performance Preferred?

This step is the obverse of step 11.7. It identifies functions for which human performance of all control tasks is clearly preferred, because man can perform more reliably than automation. These cases lie within region (P_h) of Fig. 4.2. (Refer also to Sects. 2.7 and 4.1.6.)

4.1.9.1 Criteria for Preferred Human Control

a. Included Cases. This case identifies functions for which human control is clearly preferred. The rationale of Sect. 4.1.7.1 applies, with the roles of man and machine reversed.

b. Role of Man. Functions identified are those in which all included control tasks should be manually controlled, although some tasks may profit from automated support, as will be provided by step 11.15. (See also Sect. 2.9.)

4.1.9.2 Test Result

a. "Yes." If the outcome is "yes," go to the bus line "allocate to man."

b. "No." If the outcome is "no," go to step 11.9.

4.1.10 Step 11.9: Allocate Core Performance Segments?

A large proportion of functions contain control requirements which should be accomplished with some information processing steps under human control and some steps automated. In other words, certain core performance areas (Fig. 4.3) require automation. This step results in allocating functions partly to automation and partly to man by a subdivision of task steps. These are allocated using criteria described for step 11.10. If such allocation is appropriate, the outcome is "yes."

4.1.10.1 Test Result

a. "Yes." If the outcome is "yes," go th step 11.10.

b. "No." If the outcome is "no," this function will not be allocated by core performance segments. Proceed to step 11.11.

4.1.11 Step 11.10: Allocate Core Performance Segments to Man or Automation

The source data for this step are the analytic data from step 11.5.

4.1.11.1 Allocations to Automation

a. Input Segments. The blocks on Fig. 4.3 marked "sensing" and "monitoring" represent input functions. These core performances may be automated in part by providing self-actuated

- Monitoring of alarms and out-of-tolerence conditions.
- Displaying and intelligent configuring of system information to maximize understanding of the information displayed and minimize acquisition time.
- Information processing capability external to the human in support of his own processing.

b. Central Nervous System (CNS) Processes. The blocks "information processing," "interpreting," and "decision making" may be automated all or in part by providing self-actuated

- analysis of input data
- display of recommended procedural steps (some of which may in turn initiate subsequences of their own)
- decision and diagnostic assistance

c. Memory. Some of the major causes of human overload and thus error are a consequence of the limits of short-term memory and the limits to the storage and retrieval rates of long-term memory. The burden on these resources can be lessened by providing

- Automated hold-until-canceled data devices. An annunciator is a simple form of such a device.
- Buffer devices to support human short-term memory.
- Information systems to support long-term memory.
- Automatic information logging.

d. Output Processes. The blocks "responding" and "controlling" can be automated all or in part by providing

- set-point controllers
- sequence controllers
- computer control subsystems (which can implement complex variations of the first two)

Those parts of the control cycle identified as appropriate to automate are recorded descriptively, stating

- control requirements that apply
- human core performance areas that should be automated or provided with automatic support
- the general automation strategy that should be applied (i.e, what it should do and what technical solution is implied)

Outcome "yes" places the selected parts of the control cycle in region P_a of Fig. 4.2. A "no" outcome represents the balance of information processing steps in the control cycle, which remain allocated to man. Outcome "no" places the remaining parts of the decision cycle in region P_h of Fig. 4.3.

4.1.11.2 Test Result

a. "Yes." If the outcome is "yes," go to the bus line marked "allocate to automation.

b. "No." If the outcome is "no," go to the bus line marked "allocate to man."

4.1.12 Step 11.11: Allocate Utilitarian Control Requirements to Man

This step allocates utilitarian tasks to man. The principle of utilitarian performance is that the operating crew is present and paid for, and it is therefore reasonable to assign certain roles to them. This process may provide a pattern of activity for the crew which leads to job satisfaction and contributes critically important cognitive support.

The principle of cognitive support is that each operator needs to know the status and trends in the plant. Operators perform their control tasks principally by consulting procedures and their mental model of the plant. This mental model is a memory of the plant's processing structure, its typical behaviors, and its specific last known states. It permits the operator to understand plant processes, to recognize changes in condition, to predict the consequences of control actions, and to diagnose abnormalities. A major problem of automated systems is that by relieving the operator of control tasks, they deprive him of much information. "Cognitive support" refers to job activity deliberately planned to keep the operator informed about and active in controlllling the plant, in order to maintain an adequate mental model. (Refer to the discusson of cognitive support in Sect. 2.6.5.)

Step 11.11 examined functions which have not yet been allocated, and allocates utilitarian control requirements to man, with three goals:

- contribute to cognitive support
- enhance job satisfaction
- reduce costs through reduced automation

4.1.12.1 Criteria for Allocation

a. Is the Operator Overloaded? The human factors representatives identify points at which operators are not fully engaged, taking into consideration what has been hypothetically determined about crew size and previous allocations to man.

b. Are the Tasks Suitable Candidates? Each function is examined for control tasks which meet selection criteria as follows:

   (1) Not demeaning: Tasks which are trivial, demeaning, or would lead to boredom are not selected.

   (2) Not excessively difficult: Tasks which would lead to cognitive overload or to performance error should, by this point, have been allocated to automation (steps 11.1 and 11.7). Nevertheless, such tasks should not be selected.

   (3) Matrix location (Fig. 4.2). Selected tasks should be in the upper right of region (P_{ha}) of Fig. 4.2--tasks which can be well performed by either man or automation.

c. Are the Tasks Useful to Job Satisfacton or Cognitive Support? In selecting control requirements for allocation, consideration should be given to the requirements for job satisfaction and cognitive support.

4.1.12.2 Test Result

Use outcome "yes" for functions and parts of functions (control requirements) that can be allocated to man as utilitarian performance. Use "no" for those that cannot.

a. "Yes." If the outcome "yes" occurs, go to the bus line "allocate to man."

b. "No." If the outcome "no" occurs, go to step 11.12.

4.1.13 Step 11.12: Reconsider for Cognitive Support

This step reconsiders tasks provisionally allocated to automation. These tasks are reconsidered if there appears to be a requirement for a greater degree of cognitive support. (See also Sect. 2.6.5).

4.1.13.1 Criteria for Reconsideration

a. Is There a Requirement for Added Cognitive Support? The human factors representatives identify requirements for cognitive support, to the extent the emerging system design permits. Early in the allocation process and design cycle there will be few data available except the engineering concept (step 1), role of man (step 2), and analogous technology in the design data base (step 26).

   Cognitive support should ensure a continuous awareness of the status and trend of each engineering subsystem during each plant state. Safety-critical and time-critical subsystems require a more precise awareness. Although this is a fairly complex judgment, it should not require extensive analysis. Documentation should identify plant subsystems and states which are, or are not, described sufficiently in the operator's mental model.

b. Allocations to Automation. The allocation team should particularly examine those functions and tasks previously allocated to automation. Does automation deprive the operator of information? Is there adequate remaining task activity to provide sufficient cognitive support regarding plant status? The team should selectively reconsider past allocations to automation, to ensure a pattern of operator activity which promotes an adequate mental model of the plant.

4.1.13.2 Test Result

a. "Yes." Reallocated tasks and functions go to the bus line "allocate to man."

b. "No." Allocations previously made to automation continue to be so allocated. Proceed to step 11.17.

4.1.14 Step 11.13: Repartition

This is the last point at which it may be appropriate to reject a function and return it for repartition, redefinition, or reconsideraton of the engineering solution. Users of the procedure are reminded that this action may be taken at any time during the decision sequence from steps 11.1 to 11.13. [Refer to the discussion of the first repartition step (11.6) in Sect. 4.1.7.]

4.1.15 Step 11.14: Allocation by Other Criteria

Steps 11.1 through 11.13 exercise all identified critical criteria for allocation. Any functions and tasks remaining unallocated are presumably cases in which allocation to either man or automation is completely acceptable from the point of view of both engineering and human factors design. These functions and control tasks may therefore be allocated on the basis of any other criteria of interest to management or the design team. All such functions and control tasks should lie in region (P_{ha}) of the matrix in Fig. 4.2. Other criteria to be used can include the following:

1. Relative cost of human or automated options.

2. Consistency with earlier allocation and design practice.

3. Available technologies.

4. Crew preferences.

5. Management preferences.

6. Designer preferences.

4.1.16 Step 11.15: Specify Residual Automation Support

All steps which result in a hypothetical allocaton of functions to man are connected to the bus line "allocate to man," and terminate in this step. This step is a final check of functions allocated to man, and it ensures that the conditions of allocation provide for appropriate automated support of the functions allocated to man.

In this step is the recognition that although man participates in a task, it is very rarely intended that he perform it without some level of mechanical support.* Indeed, if the plant is operated from a control

*See ref. 21 for further discussion of automation and operator functions.

room (as in the case of a NPP), all control is automated to the extent that it is remote. There is no direct observation of the plant process and no direct application of force to the controls. Therefore, at this step we will examine each function allocated to man to ensure that no unnecessary burden is placed on the operator, multiple levels of access are specified where appropriate, and automated support provides the maximum possible degree of plant stability without human control action.

1. Automated Data Display. Examine each function and specify points where automated display will simplify the core performance requirements for sensing, monitoring, and decision making (see Fig. 4.3).

2. Set-Point and Sequence Controllers. Examine each function and specify points where unnecessary manipulation of analog controls can be avoided by using set-point controllers, or where common switch-and-valve sequencing can be simplified by automatic switching.

3. "Dead Man" Controls. Examine each function. What happens if the operator fails to perform required functions? Can appropriate automation make the plant stable under these conditions?

4. Multiple Levels of Control Access. In many systems, a hierarchy of control functions will be provided by the designers. Operator access to each level or layer in the hierarchy may provide additional backup capability to accommodate degradation of upper level function and provide for emergency reconfiguration. The further up the hierarchy operator control is exercised, the more integrated the control action becomes. Thus at high levels a single action can engage, disengage, or modify many subsystems. Examine each level and function within that level to determine the most effective access points.

5. Consistent Level of Automation. Based on design guidance (steps 1, 2, and 3), the control room should present to the operating crew a reasonably consistent level of automated support. Examine each function to ensure that automation decisions were based on uniform criteria. Change any allocations that are seriously inconsistent, unless there is a clear and compelling reason for the inconsistency.

4.1.17 Step 11.16: Provisionally Allocate to Man

The hypothetical allocations that reach this point are provisionally allocated to man. Each allocation here is provisional because each will be subjected to a test at step 19 (Sect. 4.2), and because each may be changed as the result of changes in the engineering or human design hypothesis. These allocations, and the rationale on which they were made, will be entered into the design data base.

4.1.18 Step 11.17: Specify the Residual Role of Man

All types which result in a hypothetical allocation of functions to automation terminate at this step, which specifies man's role in automated functions. This step is a final check of functions allocated to automation, and assures that the conditions of allocation are specified so as not to preclude necessary human access to controls.

This step recognizes that while automation of many of the control requirements is desirable, it is very rarely intended to exclude man altogether. Ultimate policy control must remain allocated to man (see also Sect. 2.9). Therefore, at this step each function allocated to automation will be examined to ensure that

- Man retains necessary emergency control.
- Consistency of treatment is reasonable from function to function.
- Multiple levels of access are specified where appropriate.
- Man retains policy-level control.

4.1.18.1 Reconsider Abnormal Conditions

Examine each function in relation to each plant state, and in relation to the abnormal conditions which can originate from that state. Compare these data with the defined role of man in step 3, which provides general policy concerning man's intervention into abnormal states. Does the hypothetical degree of automation interfere with man's necessary emergency role? (a) Will displayed data provide an adequate basis for the required diagnostic judgments? (b) Will it be adequate to support required emergency symptomatic interventions? (c) Will control capabilities permit man to intervene as required? (d) Will they permit man to reconfigure for required maintenance? If these conditons do not exist, specify an increased residual role of man to meet policy guidance.

4.1.18.2 Specify a Consistent Level of Automation

Ensure that a reasonably consistent level of automation across plant systems is planned, except when there is a clear reason to specify otherwise. Specify a level consistent with step 11.13 (Sect. 4.1.15).

4.1.18.3 Specify Multiple Levels of Control Access

Examine each function in a manner consistent with step 11.15 (Sect. 4.1.15.4), and specify any required multiple levels of control access.

4.1.18.4 Specify Policy-Level Control

Any industrial system exists to meet specific economic and social requirements (see Sect. 2.9). The absolute minimum set of controls in a highly automated plant is that set which assures the plant's owners that it can be made to produce the product desired, at desired times and desired rates of production. This has not been a problem in semi-automated industries, but it may be a consideration in future highly automated designs. Specify the required minimum allocation of policy-level control functions to man.

4.1.19 Step 11.18: Provisionally Allocate to Automation

Hypothetical allocations which reach this point are allocated to automation. The allocation here is provisional, because each allocation will be subjected to a test at step 19 (Sect. 4.2), and because it may be changed as the result of changes in the engineering or human design hypotheses. Enter these allocations, and the rationale for them, into the design data base.

4.1.20 Step 11.19: Record Automation Requirements

Each time an allocation is made to automation, that allocation includes an implied requirement for engineering development of automatic controls. At this step, list those requirements.

All team members review the allocations, function by function. They identify cases where an allocation requires development of automated controls, and ensure that team members are in agreement concerning what is to be automated and the level of technology to be achieved. The engineering members are responsible for writing the functional specifications necessary to meet these requirements.

These functional specifications may be (a) performance statements, which describe (in general terms) what automation will be required to do, or (b) descriptions in terms of analogous technology. (It is not yet time to specify hardware or software solutions.)

These data go to step 21 (engineering test), where they are used to test the hypothetical engineering design by asking: "Is the required control automation achievable?" If so, they become part of the engineering requirements to be developed during future iterations of the design cycle. These data are, of course, entered into the design data base.

4.2 STEP 19: DEDUCTIVE EVALUATION OF ALLOCATION OF FUNCTIONS

This phase provides for deductive testing and evaluation of the hypothetical allocations made at step 11. The viability of those allocations depends on their being appropriately related to viable engineering and human factors designs. Therefore, allocation decisions (step 11) must be evaluated concurrently with the related hypothetical engineering and human factors designs (Fig. 3.1, steps 9 and 14).

4.2.1 General Method

The recommended evaluation procedure exercises the six test steps shown in Fig. 4.5, which is an expansion of Fig. 3.1, step 19. In each step a

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Fig. 4.5. Design step 19: evaluate allocation of functions deductively.

small interdisciplinary evaluation team follows an ordered evaluation procedure using data from the design data base. Allocations and design hypotheses which are found faulty are returned for redesign. The following general principles should be applied to all six decision steps. These principles are essentially the same as those in step 11 of Sect. 4.1.1, except where noted below.

1. Expert judgment. Expert judgment is, in effect, required three times: (1) It is required in estimating the future psychological requirements of a plant which has not yet been designed. (2) It is required to estimate the future skills, knowledge, and psychological response limitations of a plant crew which has not yet been selected. (3) It is required to estimate the multivariate characteristics of the human operator, including his or her limitations. This is a field in which quantitative analyses have not been very successful (even for existing systems with known characteristics).

2. Multidisiciplinary Team. A minimum team consists of an engineering psychologist as the chairman, with possibly one or more other allocation of functions representatives. The design representatives include one or more engineering designers and one or more human factors designers.

   The roles of team members are as follows: The senior engineering psychologist (chairman) organizes the sessions, prepares data and an agenda, chairs the sessions, and makes final decisions. As each hypothetically allocated function is considered, the engineering member(s) ensure that all panel members understand the engineering solution and that the control requirements are properly estimated. They advise on the proposed control display and automation technologies, and assist in assessing the effects of the engineering design on each of the core performance requirements. The human factors design representatives ensure that the hypothesized human factors structure is the one which is actually being assumed, and they advise on the effects of training, selection, procedures, crew structure, organization, and other human factors upon the ability of operators to perform. The allocation of functions representatives ensure that the effects of "unburdening" are considered, as was specified earlier at hypothesis step 11.9, "allocate core performance segments" (Sect. 4.1.10).

3. Analogous technology. Expert judgment is assisted and made feasible by previous experience with analogous cases. Such analogy should be used to predict the human requirements that a given function will impose.

4. The design data base. Evaluation uses data from the design data base, including

   - The list of functions, their hypothesized engineering solutions, and their hypothesized human factors solutions. These data are available from the documentation base (see Step 18 of Fig. 3.1).

- Documents entered by the engineering design team which describe analogous plants and component technology, including their historic problems and costs.

5. Conservative Criterion. The criterion for decisions will be conservatism. Functions and subsystems will not be permitted unless it is reasonably certain that: (a) a good allocation to man and machine has been made; (b) the engineering hypothesis on which the allocation is based places reasonable demands on and provides reasonable support to man; and (c) the human factors hypothesis meets the requirements of the allocation.

6. Decision procedure. The team will in each case discuss the functions to ensure that they are fully understood in reference to the test in progress. Available quantified and empirical data will be examined. Each of the unquantifiable variables of human capability and of unknown future technology will be identified and its effect on the design estimated. Analogous technology will be discussed.

   Following these informational steps, team members will make individual judgments as to whether the function (or whole system) under study passes the test, stating their reasons and the decision rationale. A *limited* discussion to reach a consensus will be attempted attempted. Without further attempt to force a consensus, and without being required to accept the majority opinion, the chairman will make a prompt decision. If a function or system fails to pass the test, the team will record the reasons for its failure.

7. Series and simultaneous analysis. In each test the hypothetically allocated functions and their associated design hypotheses are evaluated, first one function at a time and then simultaneously by plant function, to determine their total effect during the control of each function.

The following paragraphs describe in detail the six test steps of step 19.

4.2.2 Step 19.1: Can Man Meet the Core Performance Requirements?

This test examines the hypothesized allocation of functions and asks whether man (the NPP operator) will be able to perform the functions allo cated to him, considering the hypothesized engineering and human factors subsystems.

In this test man is viewed as an engineering component, one which senses plant conditions from instrumentation, makes control decisions, and executes control actions, just as an automated device might do. At this point we *do not* consider the whole man--his physical support requirements and vulnerabilities, the effects of emotion, fatigue, and competing interests. These will be considered by step 19.2.

a. Analyze the Required Core Performances. The total set of performance demands on man can best be estimated with the assistance of a man-machine model with which the successive sensory, processing, and response requirements of a task can be recognized and classified. Figure 4.3 models operator performance in terms of eight core performance areas (which was explained in detail in Sect. 2.7).

In preparation for this test, a human factors expert or psychologist evaluates each function as it is hypothetically allocated, and estimates the load which control tasks will place on each of the core performance functions. This analysis can reexamine the detailed guidance offered for step 11.9, and can examine the records of prior analysis of steps 11.5 and 11.9 from the design data base. (Refer also to Appendix C).

b. Perform Series and Simultaneous Analysis. Hypothetically allocated functions are evaluated using the design data base as a source of data. The allocation of each function is first evaluated individually and in series, on its own merits, asking the question, "Can man perform the control requirements of this function as allocated?" Then all functions are evaluated in their collective demands on the operator, asking, "Can man perform all requirements imposed on him during each predicted plant state?" In the first (series) analysis, each function is evaluated based on the assumption that one operator will respond to the entire function. In the second (simultaneous) analysis, all functions together are evaluated against the capabilities of the control room crew, considering hypothetical crew size, individual capabilities and training, and the availability of technical assistance and supervisor support.

c. Test Procedure. The team discusses each function serially to ensure that the hypothetical engineering and human factors solutions are fully understood. The hypothetical allocation of functions is examined for its effect on each core performance area. The guidelines in Sect. 4.1.9 and Appendix C are applied.

Team members, including the engineering and human factors design representatives, make individual judgments concerning whether man can perform the function as it is hypothetically designed, taking core performance areas one by one. They state their conclusions and attempt to reach a consensus position; any undecided case is resolved by the chairman.

If all hypothetical system functions pass this test serially, they are evaluated again, by plant state, for their simultaneous effect--the cumulative psychological loads imposed by all functions together.

d. Test Results

1. Failed: If any hypothetical allocation of functions fails step 19.1, or if any plant state fails the "simultaneous" function test, one or more functions must be returned for reconsideration

of steps 6, 9, 11, or 14 of Fig 3.1. A function can fail because of

- improper partitioning (step 6)
- unsatisfactory psychological demands imposed by the engineering hypotheses (step 9)
- inadequate hypothetical human factors solution (step 14)

2. Passed: Functions which pass this test may continue to step 19.2.

4.2.3 Step 19.2: Can Man Meet Human Performance Requirements?

This step continues to test the abililty of human operators to meet the demands and constraints of the system as hypothetically allocated and designed. It widens the question by examining man (the operator) more broadly. Here man is viewed in reference to his physical, emotional, and social requirements, and the job is viewed collectively rather than in terms of single man-machine transactions.

a. General Method. The general method of evaluation in this step is similar to that used in step 19.1, and the principles are detailed in Sect. 4.2.1.

b. Scope. This step is required to consider all demands upon man except: (a) simple perceptual, cognitive, and motor information processing requirements (the core performance areas treated earlier in step 19.1), and (b) the long-term question of job satisfaction, which will be treated in step 19.6.

This step is therefore very inclusive, and must consider all demands made on man which are predictable using the current disciplines in physiology, engineering psychology, and human factors science. A checklist of issues to consider will be offered below, but it is not meant to limit the range of inquiry. The evaluation team should seek to identify any excessive demand or constraint imposed by the hypothetical system which is detectable on the basis of either applied experience or scientific analysis.

c. Checklist. The following issues should be considered. (Refer also to Appendices A and B.)

- Psychological/physiological environment: shift length, job coherence, learning/performance requirements, and stress levels.
- Physical environment: heat, lighting, noise, glare, presence of radiation, etc.
- Social structure: inter-/intra-group characteristics, work team structure, and interpersonal interaction and support.

- Organizational policy and structure: channels of communication, supervisory structure, rewards system, and operator autonomy/responsibility.

d. Test Result

1. Failed. If a hypothetical function fails this test on any issue discussed in Sect. 4.2.3, or if any plant state fails the simultaneous function test, one or more functions must be returned for reconsideration of steps 6, 9, 11, or 14 of Fig. 3.1.

2. Passed. Functions which pass this test proceed to step 19.3.

4.2.4 Step 19.3: Is the Cost Tradeoff Acceptable?

The test in step 19.3 evaluates whether the design as hypothesized in steps 9 and 14 makes an optimum balance of cost between engineering and human factors development. In particular, it asks whether the hypothetical engineering and human factors solutions can be achieved at an acceptable cost.

4.2.4.1 Test Method

a. General Method. The general method of evaluation is parallel to that used in Step 19.1, and the principles are detailed in Sect. 4.2.1a.

b. Specific Method. The specific method includes the following procedural steps: (a) Re-examine the hypothetical engineering and human factors solutions (steps 9 and 14). (b) Estimate the levels of development effort imposed by these solutions. (c) Anticipate development problems. (d) Detect case of gross imbalance. (e) Detect cases where the solution may not be achievable. (f) Detect cases where the cost of development may be unacceptably high.

c. Team Orientation. The engineering and human factors design representatives are responsible for assuring that team members understand the following matters:

- The hypothetical engineering and human factors design solutions (steps 9 and 14).

- The degree to which those solutions are tested designs, depart from prior designs, or require new development.

- The implications of cost of acquisition, cost of development, and development time (in general or camparative terms--not necessarily dollars).

- Actual dollar costs for analogous past developments (if available).

- Technological hazard. What chance is there that the proposed solution will encounter development problems? Include the human factors solution: Can you really achieve the training or procedures capability proposed? Will it really perform as described?

- Consider full life cycle costs, as well as immediate development and procurement costs.

4.2.4.2 Items to be Considered

a. Identify Overlooked Tradeoffs. Consider each function in sequence. Are there any obvious improvements in engineering design which would reduce human factors cost (e.g., automate to reduce crew size and reduce training cost)? Are there technology costs which could be reduced by allocation to man (e.g., utilitarian performance, step 11.9)? Consider only major and obvious cases--do not nitpick the design.

b. Is There Any Gross Imbalance of Cost? Examine each function to see if the designers have increased system cost by overemphasizing technology. Conversely, have they increased human cost by underexploiting technology? Refer to the level of technology guidance provided by the engineering concept (Fig. 3.1, step 2).

c. Has Technology Been Overestimated? Examine each function to see if there is a chance that the solutions may not be achievable, or may encounter unacceptable development problems.

d. Can Technology Be Developed in Time? Can each hypothesized engineering or human factors solution be developed, debugged, and delivered in time?

e. Are Costs Acceptable? Is there a chance that the development or procurement costs of hypothetical engineering or human factors technology will be unacceptably high? Consider each function individually, then consider the design as a whole.

   Special attention should be given to training costs, because when unrealistic costs have been hypothesized, the usual outcome is as follows: (1) at some point in development, either management raises an objection or a period of project economy forces retrenchment. (2) When this happens, management looks first to human factors items, such as training and simulators, to cut costs. Prime system hardware is less likely to be affected. (3) As a result, high cost items, especially trining programs, are replaced with less costly ones of more limited effectiveness. (4) The consequence is an imbalance of man and machine: The human factors design may depend on instrument, control, or automation technology which was not provided, or the engineering design may assume a training/crew/ procedure capability which was not achieved.

f. Is Technology Consistent? Costs may not be defensible if one function demands a level of technology inconsistent with that of the system as a whole. Examine the hypothetical design for functons which are treated at an obviously inconsistent level of technology, or at a level other than that supported by the engineering concept (step 2).

4.2.4.3 Test Result

a. Failed. A function fails this test if there is a gross imbalance of technology between man and machine, if the balance selected causes unnecessary system cost, if the technical expectations will be hard to achieve, or if technology costs may not be acceptable. If the test is failed, either the function or the design as a whole should be returned to step 6, 9, 10, or 14 or Fig. 3.1, as necessary. The pass/fail decision is made by the team chairman after he has heard the opinions of the team members.

b. Passed. Functions which pass this test may continue to step 19.4.

4.2.5 Step 19.4: Is the Human Factors Structure Adequate?

This step of Fig. 4.5 inquires whether the hypothetical human factors solution wil actually meet the system demands for human performance.

Remember that step 11, allocation of functions, was based on certain assumptions concerning the organization, numbers, ability, skill, and training of operating and supervisory personnel. Step 14, hypothesize human factors solution, required a supporting human subsystem design which would assure the availability of an adequate organization, numbers, ability, skill, and training.

This step will test whether the human factors hypothesis is adequate to the needs imposed by allocation of functions to man. (Step 21 will test the human factors solution for its quality and achievability.)

4.2.5.1 Method and Content

a. General Method. The general method of evaluation is parallel to that used in Step 19.1, and the principles applied are detailed in Sect. 4.2.1a.

b. Special Considerations. This test will determine whether the hypothetical human subsystem design can be reasonably assumed to meet its objectives in the following areas:

- Can the hypothetical organization be expected to provide personnel at the times and places required?
- Is supervisory and consultative support adequate?
- Is the division of roles between plant and control room suitable to enable implementation of functions that may be anticipated for future use but not currently planned?

- Is crew size adequate at all times?
- Are specified individual abilities equal to anticipated demand?
- Are specified skill and experience levels equal to anticipated demand?
- Are specified training levels equal to anticipated demand?
- Are specified documentation and procedures equal to the crews' anticipated needs?

The answers to the foregoing questions will depend on all features of the hypothesized human factors subsystem design, including organization, training, procedures, personnel selection, and personnel advancement.

4.2.5.2 Test Result

a. Failed. If the design fails this test, either individual functions or the design as a whole are returned for simplification of the human performance requirements imposed by steps 9 and 10 of Fig. 3.1, or for human factors solution redesign at step 14.

b. Passed. If this test is passed, proceed to step 19.5.

4.2.6 Step 19.5: Is Cognitive Support Adequate?

This step determines whether the hypothetical design provides the control room operator with sufficient information to maintain a continuous and adequate mental model of the plant and systems. At any time operators may be required to make judgments or to take control actions based on knowledge of the plant and its structure, status, and behavior. This knowledge constitutes a mental model which operators will use continuously to predict how plant processes will proceed, as well as to predict the effect of any control actions taken. In emergencies, those mental models provide a means to detect abnormal conditions, to diagnose their cause, and to intervene to minimize the consequences.

How well these mental models are maintained depends on the operator's training and, more particularly, on recent operating experience. That experience must be adequate to provide frequent remainders of the plant's structure and continuous information about its important process variables. "Cognitive support" is that part of the operator's job which is deliberately designed to supply to him the information necessary to his maintaining an adequate mental model.

1. General Method. The general method of evaluation used in this step is also parallel to that used in step 19.1, and the principles are detailed in Sect. 4.2.1a.

2. Test Result

a. Failed. If the hypothetical design fails this test, certain functions or the entire design are returned to step 9, 10, or 14 of Fig. 3.1 for redesign.

b. Passed. If passed, proceed to step 19.6.

4.2.7 Step 19.6: Is Job Satisfaction Optimum?

Steps 19.1 through 19.5 of Fig. 4.5 tested whether the hypothetical man/machine solution is an acceptable allocation and is not precluded by human factors limitations. This step asks whether man, on a continuing basis, will be satisfied to perform the job as designed. Moreover, it asks whether tasks have been allocated to man or machine in such a way as to optimize man's satisfaction.

1. General Method. Again the general method of evaluation used is parallel to that used in step 19.1, and all except item (b) of the principles detailed in Sect. 4.2.1a are applied. In this case analysis considers functions simultaneously only--not individually in series.

2. Test Result

a. Failed. If the design fails this test, it is returned for reconsideration of step 6, 9, 11, or 14.

b. Passed. If this test is passed, step 19 is completed. When all hypothetical functions and their associated engineering and human factors functions have passed this and prior steps, proceed to steps 20 and 21.

5. ASSESSMENT OF ALLOCATION IN AN EXISTING CONTROL ROOM DESIGN

This section describes a procedure and demonstration that uses the test logic reported in Sect. 4.2 (step 19 of Fig. 3.1) to evaluate the allocation of functions in an existing CR design. This demonstration was conducted in response to the need of the Nuclear Regulatory Commission (NRC) for a procedure which might be used to identify unsafe allocations of function in existing nuclear power plants.

The methodology reported in Sects. 3 and 4 applies only to plants under design, not to those already in existence. In the research described in this section, BTI developed a procedure by which the deductive (test) phase of the allocation procedure could be adapted to the evaluation of an existing NPP CR, and possibly to the design documents for a CR under development. This method was then applied to one segment of a hypothetical NPP design. Elements of existing U.S. NPP designs were combined to produce a document describing the heating, ventilating, and air conditioning system (HVAC) of a hypothetical NPP, "Grand Tower No. 2." Control functions for the HVAC segment of the hypothetical plant were then evaluated using the test logic of the methodology in step 19 of Fig. 3.1.

This evaluation produced two products: (1) a descriptive assessment of the functions concerned, in respect to their possible effect on plant safety, and (2) a quantified profile score for the functions, evaluating "goodness of allocation."

This section describes the procedure for the descriptive assessment and reports the results of the demonstration.

Section 6 will describe the procedure for producting a quantified profile score, and will report the results of that part of the demonstration.

5.1 ANALYSIS OF THE PROBLEM

The principal objective of the research described in this report was development of a method for allocating control functions during NPP design. The authors recognize, however, that the *de facto* moratorium on NPP construction in the U.S. limits short-term application to post-design systems. Thus NRC's regulatory interest will probably focus on how to identify serious safety deficiencies in existing designs, and to determine which of them can be corrected by modifications at a justifiable cost. It was therefore desirable to find a means by which the general methodology developed in this research could be used to evaluate an existing CR design.

5.1.1 Obstacles to Post-Design Review

1. Documentation. The methodology presented in this report depends heavily on good documentation, as described for the design data base,

step 26 of Fig. 3.1. It requires preserving key working documentation from the earliest days of concept design, and includes a record of the identification of functions and the rationale for their allocation.

However, practice in the nuclear power industry does not now formally identify either control functions or the rationale for man versus automation decisions. In fact, most early design documents are not preserved. The documentation which is actually available for most NPPs will not support their evaluation by the methodology in Sects. 1 through 3.

2. Identifying Functions. A further obstacle to evaluating an existing plant is that its functional structures are hard to identify. The functions of a plant are not necessarily unique and can be defined and partitioned in many ways. Because a "function" is actually an artificial construct of the designer (see Sect. 2.4.7), it is not possible to learn what functions the designers had in mind by purely observing an existing control room. Consequently, before we can evaluate the allocation of control functions we will need a method for defining functions from the evidence available in an existing plant (or perhaps even in a design which is completed but not yet built).

3. Limited Objectives. Another problem is that the objectives of a CR design review are not the same as the objectives that led the design team. Many options remain open while a plant is being designed, where the design objective is to achieve optimum performance (in reference to social and technical requirements) against cost. By contrast, there are fewer options open and the objectives are more limited when evaluating an existing plant to ensure public safety.

   a. Cost. Cost, a primary consideration during design, is only a secondary one during the evaluation of an existing design, when both capital and operating costs have already been committed and perhaps partly paid. Furthermore, cost is not a matter of direct regulatory interest. Cost of changes to the design must be considered; however, this is considered after review has occurred.

   b. Optimum Design. Redesign of the control systems and equipment is not a step in the review process of a completed design. It serves no purpose, as far as a regulatory review is concerned, to find that the design could have been better. Rather than searching for optimums, the review should determine whether minimum criteria have been met.

   c. Safety. The question of importance is whether control functions have been safely allocated to man or to automation. This raises questions of degree, because few obviously dangerous allocations will be found. Most safety problems will result from the cumulative effect of many poor allocations which overload cognitive processes, stress the crew, deprive operators of information, or decrease job satisfaction. In other words, there is a problem of distinguishing between poor allocations which are not significant (nitpicking the design), those that are marginally unsatisfactory, and those that are dangerous.

5.1.2 Advantages of Post-Design Review

There are some advantages when an existing design is evaluated. During design it is not possible to fully foresee what the future plant will be like or how it will behave, whereas it is possible to see an existing plant and observe its behavior. Although the documentation may not be optimun, the following resources should be available for an operating plant:

1. A visible plant and control room

2. Plant personnel--operators, supervisors, trainers, managers

3. Procedures

4. Final design documents

5. Operating and maintenance history

It is reasonable to assume that these resources will provide a basis for evaluation, even without any original design documentation. In fact, these resources each tend to provide a fairly thorough reflection of the allocation of functions being evaluated. It should be possible to evaluate a CR given the CR itself and any two of the resources.

During functional design (Sect. 3), it is necessary to deal with the plant in the abstract. For economy of effort during that phase, functions are designed only to a certain level of detail (see Sect. 2.4.5), and identification of specific components and specific human tasks is avoided. By contrast, in an existing plant specific components and tasks are the easiest things to observe. The problem is rather to discover the underlying general functions. Economy of effort is therefore served by defining a larger set of functions, and functions closer to the detailed design level, than would normally be defined during the functional design phase.

5.2 ELEMENTS OF THE SOLUTION

Given the problem as just described, BTI considered various elements of the original methodology for possible adaptation to the evaluation of an existing CR.

5.2.1 Use a Portion of Step 19

The methodology described in Sects. 3 and 4 is a two-step process which includes a creative hypothesis phase (step 11 of Fig. 3.1) followed by a deductive test (step 19). It seems that step 11 could apply only to the invention of an optimal allocation during plant design. Step 19, by contrast, is specifically intended to test a hypothetical allocation for a future plant and should be adaptable to testing a real allocation in a real plant.

5.2.2 Omit Substeps 19.3, 19.4, and 19.6

Step 19 included six tests to be applied in sequence. As shown in Fig. 5.1 (which is a revision of Fig. 4.5), three of those six tests will not apply to the evaluation of an existing CR.

1. Cost Tradeoffs. Design cost tradeoffs, step 19.3, do not apply.

2. Human Factors Structure. During design it is essential to ensure that demands placed on the operating crew are supported by appropriate training, procedures, crew size, etc. In fact, a satisfactory human factors plan is a required condition for some allocations of control functions. Step 19.4 is required during original design because there is often a tradeoff: Human performance problems can be alleviated either by better equipment design or by better human factors organizational support.

   In an existing plant, however, the equipment design options are no longer open, and the issue is no longer a question of whether the allocation of functions tradeoff is appropriate. Provided that human performance is feasible (steps 19.1 and 19.2), the remaining question is whether crew structure, training, procedures, etc. are adequate. These questions are already addressed by NRC in other ways and should not be addressed redundantly here. In any case, there are established ways of evaluating these matters based on task analysis, not definition of functions. Test 19.4 therefore should be omitted.

3. Job Satisfaction. Job satisfaction is an issue similar to the above two. There are effective ways to measure job satisfaction (step 19.6), a condition that results from many causes in addition to proper allocation of control functions. In a post-design review, an assessment of job satisfaction should be done by survey. Test 19.6 therefore should be omitted.

5.2.3 Retain Substeps 19.1, 19.2, and 19.5

The remaining steps do apply, and they should provide the basis for a method for evaluating an existing NPP CR design. Figure 5.2 presents the detailed sequence of these tests. Refer to Sects. 4.2.1, 4.2.2, and 4.2.5 for detailed descriptions of their content.

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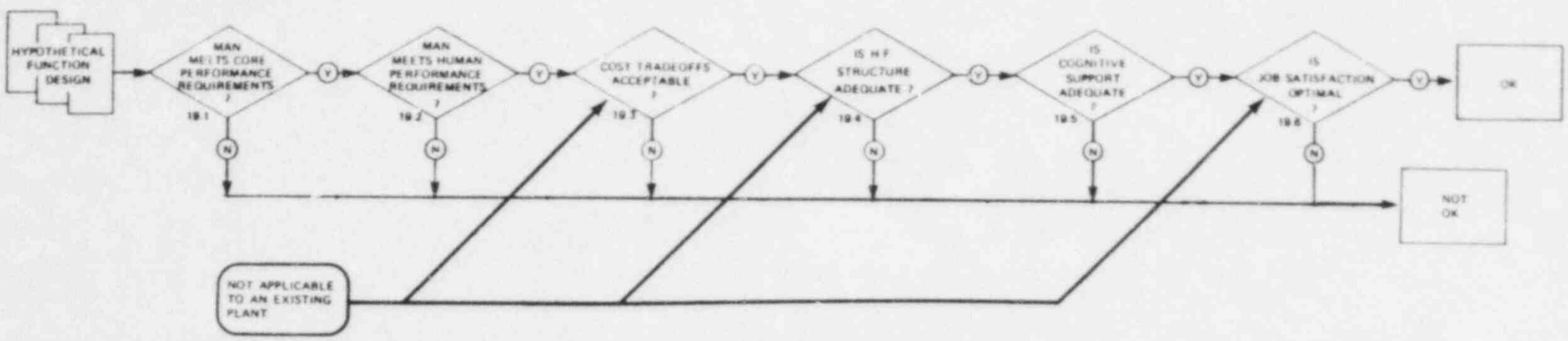

Fig. 5.1. Elements of a solution--design step 19.

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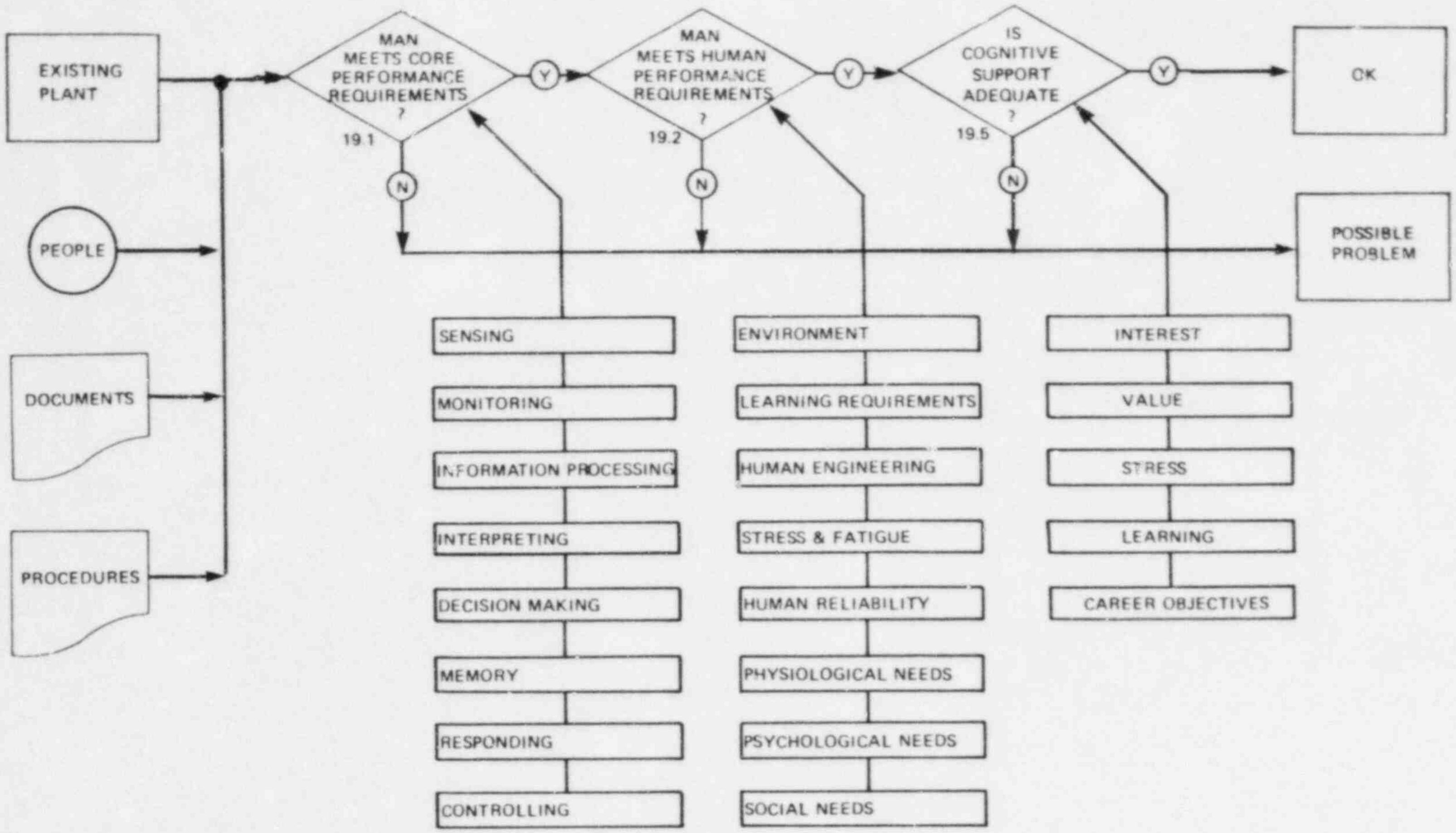

Fig. 5.2. Sequence of tests in evaluating an existing plant.

5.3 DEVELOPING A METHODOLOGY

Based on the analysis just described, BTI developed an interim methodology for evaluating the allocation of control functions in an existing control room. The primary objectives were to develop a demonstration rather than a final method, and to develop two related procedures, one to produce a descriptive assessment and one to produce a quantified profile score that could be applied to both an existing plant and one still being designed.

The first step was to determine whether the methodology reported in Sect. 4.2 (deductive test of a design hypothesis) could be adapted to evaluation of an existing NPP CR. Hypothesis indicated that a procedure could be developed by which available data (the sources cited in Sect. 5) could be used, both to identify control functions and to evaluate the appropriateness of their allocation to man or automation. This would require that

1. A reproducible and reliable procedure could be developed.
2. The procedure could identify the control functions of the plant.
3. The procedure would differentiate between good and bad allocations, and would produce data of sufficient resolution to be of regulatory use.
4. The procedure would be valid for its included procedural steps.
5. The procedure would be able to identify a reasonably complete set of functions.
6. The procedure would be able to idenitfy genuine safety (or human performance) problems.

It was not intended or expected that this demonstration procedure would be suitable in its present form for use in evaluating real NPP CRs. The objective was limited to demonstrating that such a procedure is feasible. To develop a regulatory procedure would require at least the following:

1. Develop the procedure further.
2. Field test the procedure.
3. Provide benchmark scales to standardize observations.
4. Calibrate the subtests against real NPPs.
5. Provide an objective basis for determining levels of acceptability.

The first specific objective was to produce a procedure for descriptive evaluation of CR functions. This procedure would provide assessment data which listed the CR functions, identified the ways in which they were allocated, and evaluated the allocations as either satisfactory (within standards) or not satisfactory. A descriptive comment would be required to explain why allocations were not satisfactory.

It was considered that such a procedure might be feasible with a test/-retest or interrater reliability (for trained observers) of .80 to .95.

A second specific objective was to demonstrate the achievability of a quantified score for "goodness of allocation." It was hypothesized that a judgmental procedure could produce individual rating data by subtest and by function, and that these data could be averaged or integrated to produce plant profiles for goodness of allocation, either by test category or by function.

These data would be diagnostic in that they would indicate on a numerical scale what characteristics of an allocation were weak or strong, either by human factors issue or by control function. It was considered that such data might be feasible at a level of test/retest or interrater reliability somewhat lower than the reliability of descriptive data, possibly in the range .65 to .85.

A procedure for producing such data is reported in Sect. 6.

It was hypothesized that evaluation (for both kinds of data) would depend on a judgmental procedure conducted by qualified and trained observers. This conclusion is not surprising, considering earlier comments about dependence on judgment during design. Expert judgment is unavoidable, and it can be made reliable and valid by (1) formalized decision procedures, (2) trained observers, (3) consensual judgments, and (4) the use of benchmark scales. (Developing benchmark scales was beyond the scope of this project.)

5.4 GENERAL PROCEDURE

The general procedure used is illustrated by the steps in Fig. 5.3.

Block 1: Sources. Four sources of accessible data are shown in blocks 1.1 through 1.4 of Fig. 5.3.

Block 2: Collect Data. To minimize intrusion at the plant, actual on-site observation should be limited. Data are to be collected by: (1) observation, (2) questionnaires, (3) collecting existing documents, and (4) photography. Block 2 includes a first visit to the plant site to collect documents and raw data.

Block 3: Source Documents. Block 3 represents the data collected by block 2. These include completed data collection forms and documentary data such as plant functional flow, control layout, procedures, and photography. These source documents are used for off-site analysis.

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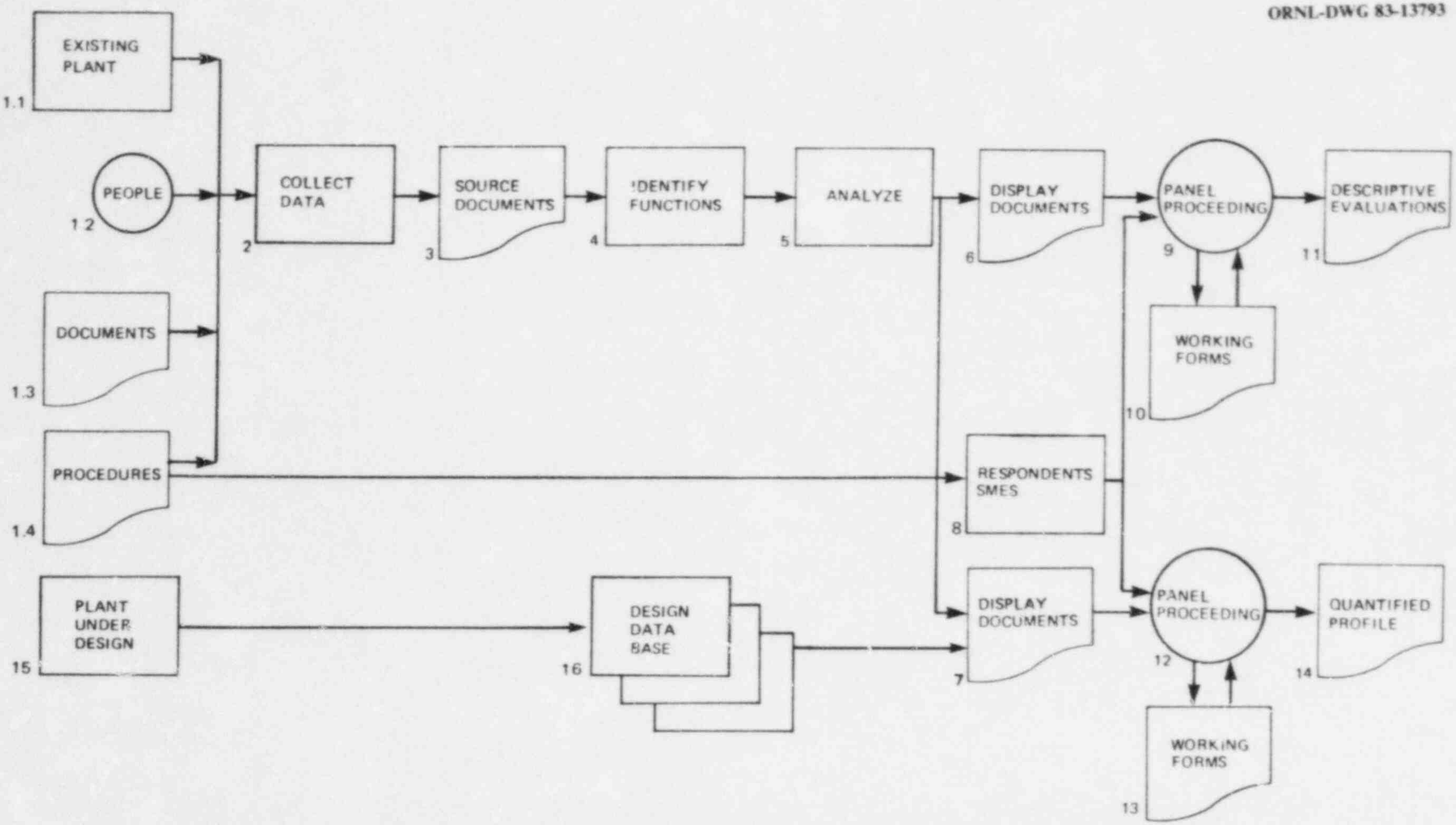

Fig. 5.3. General procedure for evaluating allocation of functions at an existing nuclear power plant.

Block 4: Identify Functions. As a next step analysts working off-site and using the source documents identify and list the control room functions.

Block 5: Analyze. Using the source documents off-site, three kinds of analysis are performed. These steps are referred to as "table-top" analysis:

1. Functions identified in block 4 are provisionally described in terms of their apparent allocation to man or automation. These will be verified or corrected later.

2. Data are extracted and reduced for further analysis.

3. Preliminary quantified scores and observations are made based on documentation. These will be verified or corrected later during panel procedings.

Block 6: Display Documents (1). One set of user documents is produced to support the panel proceedings for descriptive evaluation (block 9).

Block 7: Display Documents (2). Another set of user documents is produced to support the panel proceedings for a quantified profile score (block 12). Both sets of display documents are designed to provide the following:

1. An agenda for analysis based on the identified plant functions.

2. Effective display of the data collected at block 2.

3. Preliminary table-top analysis data prepared by block 5, to be confirmed or corrected by the panel.

4. A form on which to enter working decisions.

Block 8: Respondents/Subject Matter Experts (SMEs). In a real evaluation the panel would meet on-site, where they can have access to SMEs (block 8). These respondents may include CR operators, supervisors, plant operators, designers, or trainers.

Block 9: Panel Proceeding. Panels meet on or near the site being evaluated in order to have access to the real plant and the SMEs when necessary.

Block 10: Working Forms. As the panels proceed they produce working documents, in part by making entries on the display documents.

Block 11: Descriptive Evaluation. The panel produces the descriptive evaluation described in Sect. 4.3.1.1.

Block 12: Panel Proceedings. Panels meet to produce a quantified score. This procedure is discussed in Sect. 6.

Block 13: Working Forms. The panel again produces working forms.

Block 14: Quantified Profile. The panel proceeding contains the quantified profile score described earlier. (This process will be discussed in detail in Sect. 6.) As mentioned earlier, the quantified profile procedure is adaptable to either an existing plant or a plant under design.

Block 15: Plant Under Design. The procedure of block sequence 15, 16, 7, 12, 13, and 14 applies to a plant undergoing original design.

Block 16: Design Data Base. In the case of a plant undergoing original design, display documents are produced from data in the design data base (Fig. 3.1, block 26), rather than by blocks 1 through 5.

5.5 INPUT DATA

The initial problem was to find a plant for evaluation. It was recognized that the owners of an operating NPP would not be likely to permit an experiment which would require intrusive data collection and possibly detect design weaknesses. In the absence of access to a real plant, BTI was able to take advantage of plant design documentation coincidentally available from another project.

5.5.1 Heating, Ventilating, and Air Conditioning (HVAC) Control Documents

A limited collection of documents were available describing the control logic and physical/functional breakdown for the HVAC system of an existing BWR design (Figs. 5.4 and 5.5 are examples). BioTechnology, Inc., secured permission of the owners to use these documents, on condition that details be changed to alter plant identity and that the owners remain anonymous. BioTechnology, Inc., verified that the HVAC concerned was linked to plant safety in ways that made it a useful research target. Based on these documents and on other r al-world data as explained below, BTI constructed a composite, prototypical HVAC system for the imaginary BWR "Grand Tower No. 2." These resource documents provided the input data shown in blocks 1.1 through 1.4 of Fig. 5.3.

5.5.2 Source Data

1. Plant: For this test, the plant was represented by a control panel design mockup which was available for inspection at the offices of the design vendor. This, along with functional flow documents, provided simulated data to represent the plant (block 1.1).

2. People: Access to staff and operators (SMEs) was simulated by the availability of members of the design staff. This provided simulated data representing block 2, people.

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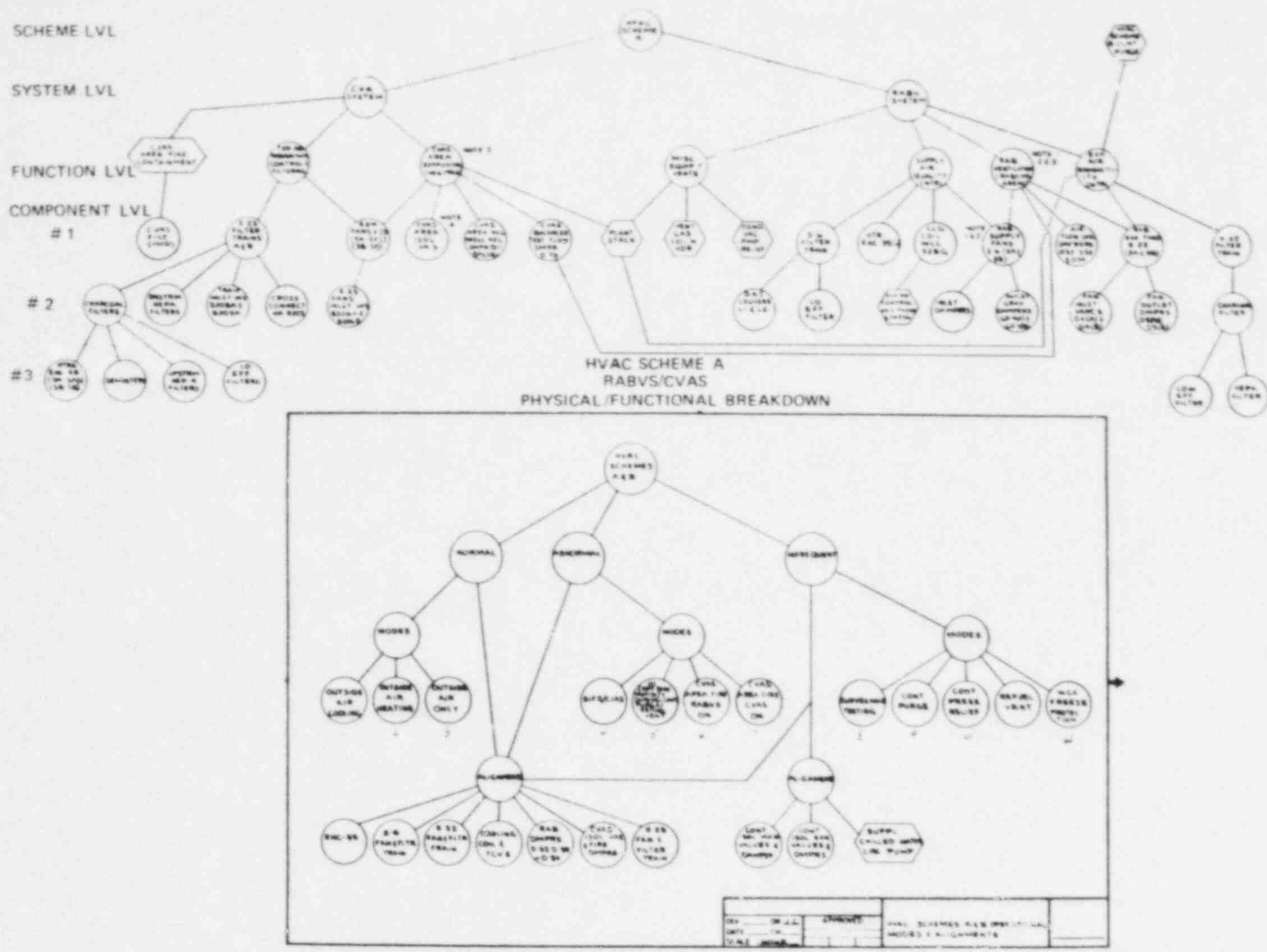

Fig. 5.4. HVAC Physical and functional breakdown, Grand Tower No. 2.

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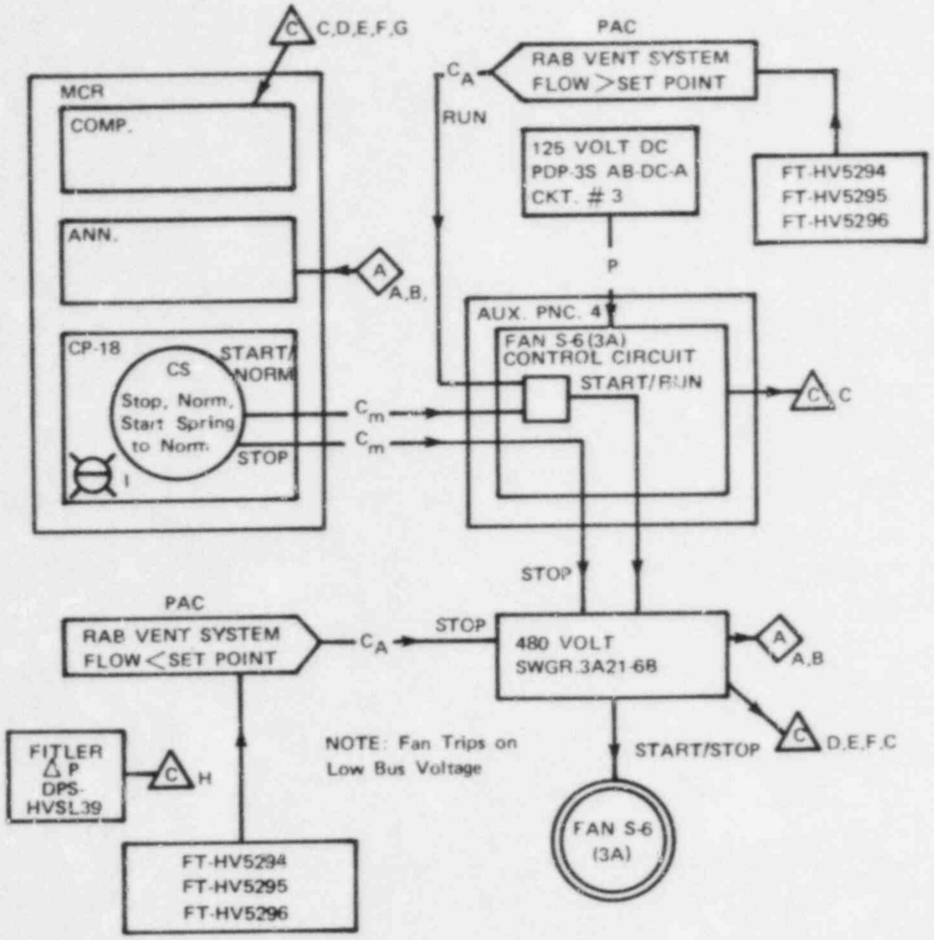
SHEET ___ OF ______

CLIENT ______
PROJECT ______
SUBJECT ______

OFS NO. ______ DEPT. NO. ______
BY ______ DATE ______
CHECKED BY ______ DATE ______



SUB-SCRIPT	DESCRIPTION	TYPE	REMARKS
A	RAB SUPPLY FAN A TRIP/TROUBLE	A	B0705
B	SS XFMR 3A21 GROUND/ TEMP. HI	B	C0806
C	RAB VS SPLY. FAN MANU TRIP	C	D52103
D	RAB VS SPLY FAN A OC/OULD	C	D52104
E	RAB VS SPLY. FAN A GND	C	D32108
F	RAB VS SPLY. FAN BKR. STATUS	C	D52100
G	RAB VS SPLY. TRN FAN A AMPLS	C	A52100
	RAB VS SPLY. TRN. FILTER AP	C	D52102
	FAN STATUS LIGHTS	L	

REF. CWD 1103 REV. 2
1127 REV. 6

LOGIC DIAGRAM PAGE 1

Fig. 5.5. HVAC RAD Control Logic, Grand Tower No. 2.

3. Documents: Documents were available and provided the data of block 1.3.

4. Procedures: BioTechnology, Inc., identified procedures on hand which were compatible in most details with the target plant and documentation. These simulated the data of block 1.4.

5.6 DOCUMENTARY AND INTERVIEW DATA COLLECTION

The next step was to perform the data collection specified in block 2 of Fig. 5.3. Figures 5.4 and 5.5 indicate the documentary data collected.

Figure 5.6 is a sample page from a hypothetical interview form intended for use in a structured interview, the interviewer recording the comments. Although no actual interview procedure was developed, SMEs were questioned, and they provided comments such as would normally be offered in a real interview.

5.7 SOURCE DOCUMENTS

Available at this point were the documents just described, panel layouts, procedures, and continued access to one SME. These are the source documents of block 3 of Fig. 5.3.

5.8 IDENTIFY FUNCTIONS

Functions were identified by progressively partitioning HVAC function. These, unfortunately, closely paralleled the system engineering breakdown; it had been hoped that overlapping HVAC and equipment systems functions would be discovered.

Figure 5.7 illustrates how the breakdown of HVAC function was structured, and Figs. 5.8 and 5.9 are sample pages from a function partition form. Note that as functions were broken down to progressively more detailed levels, the separate roles of equipment and operator became easily describable.

Figure 5.10 is a sample page from a function allocation form. Although this analysis was actually made to the component level. it would not be carried to this level of detail if the demonstration were to be repeated.

5.9 ANALYSIS

This is the table-top analysis specified in block 5 of Fig. 5.3. It prepares data for the panel proceeding, and it is conducted off-site to reduce costs and minimize the intrusiveness of the analysis. As actually conducted, it is believed to have been needlessly complex; any procedure meant for practical use would be developed in a simpler form. Nevertheless, the actual procedure employed is reported here.

QUESTIONS	COMMENTS
13. Are there any obvious or apparent constraints which work conditions, equipment design, work shifts, procedures, training, etc. impose upon good performance?	
14. Are there situations in which operators are forced to "shift gears" so often that overall performance suffers?	
15. Are there complaints about boredom?	
16. Do any particular functions require so much effort or attention that they interfere with other functions?	

Fig. 5.6. Sample interview sheet.

ORNL-DWG 83-13796

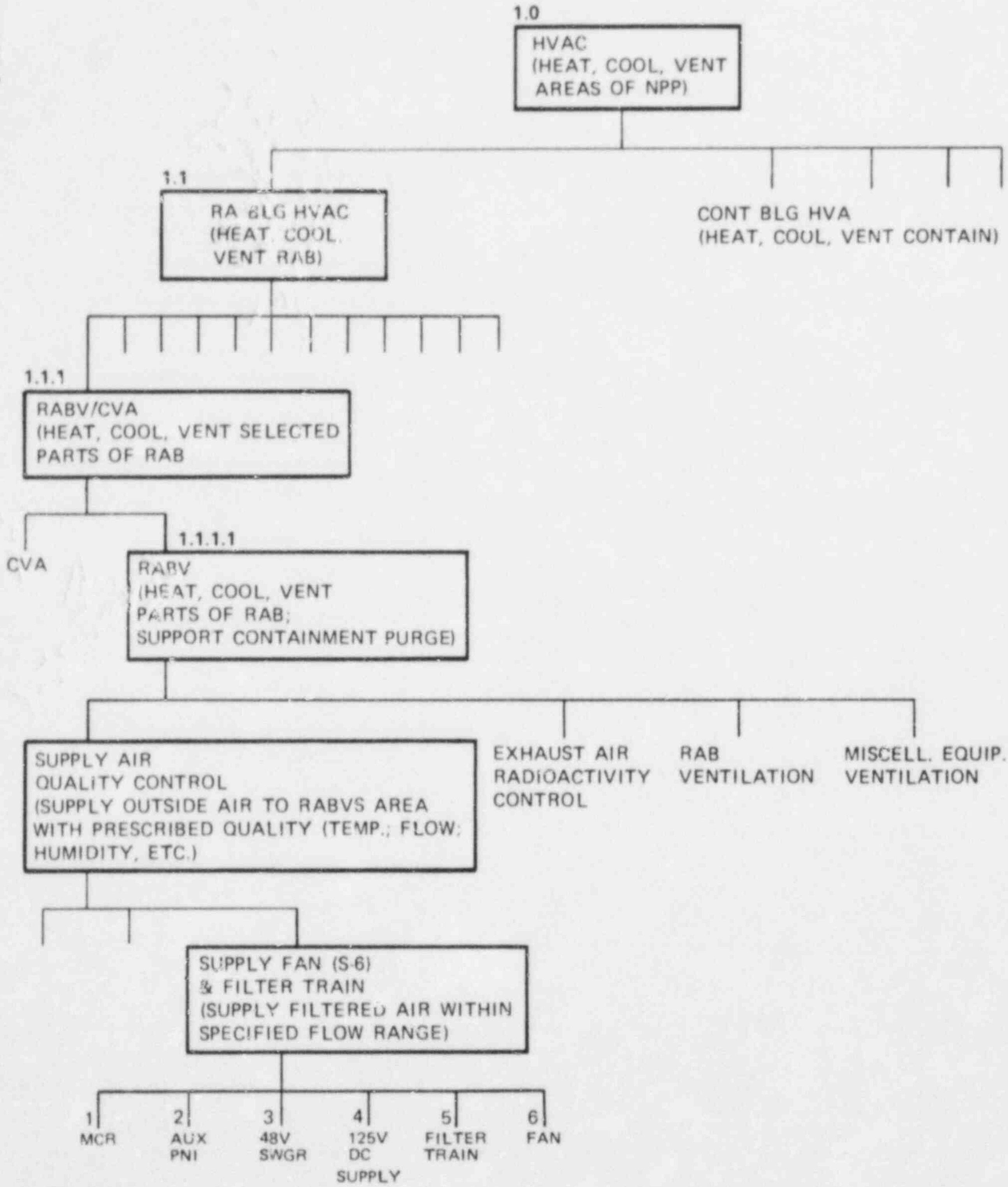


Fig. 5.7. Functions partition diagram.

ENGINEERING SUBSYSTEM LEVEL 1.0 HVAC

PLANT FUNCTION TO HEAT, COOL, VENT SAFETY AND NON-SAFETY AREAS OF NPP

PLANT/UNIT GRAND TOWER NO 2

ENGINEERING SUBSYSTEM

ANALYST J. SMITH

SUBLEVEL	FUNCTION	EQUIPMENT	OPERATOR ROLE
1.1 REACTOR AUXILIARY BUILDING HVAC	1.1 TO HEAT, COOL, VENT RAB	1.1 VARIOUS FANS, VALVES, DAMPERS, FILTERS, COOLERS, HEATERS, AND CONTROLS, DISPLAYS, ANNUNCIATORS FOR EQUIPMENT OPERATION	1.1 TO MAINTAIN REQUIRED BUILDING PARAMETERS DURING ALL MODES OF PLANT/SYSTEM OPERATION BY OPERATING COMPONENTS, MONITORING SUBSYSTEMS STATUS AND PERFORMING NECESSARY CONTROL ACTIONS IN RESPONSE TO SUBSYSTEM STATUS CHANGES FROM A CENTRAL CONTROL ROOM
1.2 CONTAINMENT BUILDING HVAC	1.2 TO HEAT, COOL, VENT CONTAINMENT BUILDING	1.2 ..	
↓ ETC.	↓ ETC.	↓ ETC.	↓ ETC.

Fig. 5.8. Function partition form - Sheet 1.

ENGINEERING SUBSYSTEM LEVEL 1.1.1.1 RABV

PLANT FUNCTION TO COOL, HEAT AND VENT PARTS OF THE RAB DURING NORMAL OPERATION AND ASSIST THE CONTAINMENT PURGE SYSTEM IN EXHAUSTING DURING INFREQUENT SYSTEM POSITION

PLANT/UNIT GRAND TOWER NO. 2

ENGINEERING SUBSYSTEM HVAC

ANALYST J. SMITH

SUBLEVEL	FUNCTION	EQUIPMENT	OPERATOR ROLE
1.1.1.1 SUPPLY AIR QUALITY CONTROL	TO CONTROL THE QUALITY OF THE INLET SUPPLY AIR TO RABVS AREAS (IE MAINTAIN PERSCRIBED AIR TEMP/PRESSURE, HUMIDITY, FLOW & PURITY)	HTR (EHC-35)/(CONTROL VALVES) COOLING COIL (WCC 328-6); R&B SUPPLY FANS (S-6) & S-6 FILTER TRAIN	TO OPERATE SUPPLY FANS AND MONITOR TO INSURE INLET AIR QUALITY
1.1.1.2 EXHAUST AIR RADIOACTIVITY CONTROL	TO EXHAUST RABVS AREAS & CONTROLS THE LEVEL OF RADIOACTIVITY BY ROUTING THE EXHAUST AIR THRU FILTERS BEFORE DISCHARGING THE AIR THRU THE PLANT STACK	RAB EXHAUST FANS (E-22); E-22 FILTER TRAIN AND PLANT STACK	TO OPERATE EXHAUST FANS AND MONITOR FILTERS TRAIN TO INSURE RADIOACTIVITY REMOVAL
1.1.1.3 RAB VENTILATION (RAB/CVAS AREAS)	TO CONTROL AIR FLOW (CFM) FROM DIFFERENT AREAS OF THE RAB BY CONTROLLING DAMPER POSITIONS AND TO TEST CVAS-PRESSURE CAPABILITY	RAB SUPPLY FANS (S-6); AIR FLOW CONTROL DAMPERS; D-32 TO 39 RAB EXHAUST FANS (E-22); CVAS BALANCED TEST FLOW DAMPER D-73	TO MONITOR RAB PARAMETERS (PRESSURE, TEMP, HUMIDITY) TO INSURE THEY ARE WITHIN LIMITS AND OPERATE TEST FLOW DAMPER DURING TEST
1.1.1.4 MISCEL. EQUIPMENT VENTS*	TO EXHAUST THE CONDENSER VACUUM PUMP THRU THE E-22 EXHAUST FANS & FILTER TRAINS ON SENSING HIGH RADIOACTIVITY IN THE CONDENSER; ALSO CONTINUOUSLY EXHAUST THE VENT GAS COLLECTION HEADER TO THE E-22 EXHAUST FANS AND FILTER TRAINS	PLANT STACK; VENT GAS COOLER & HEATER; CONDENSER VACUUM PUMP RELIEF VALVES	TO MONITOR CONDENSER VACUUM PUMP AND VENT GAS COLLECTION HEADER DISCHARGE RADIATION LEVEL

* NOT UNDER RABVS CONTROL RABVS ONLY USED AS FILTERED OUTLET TO PLANT STACK

Fig. 5.9. Function partition form - Sheet 4.

SUBSYSTEM LEVEL SUPPLY FAN S-6 FILTER TRAIN (A+B)

FUNCTION TO SUPPLY FILTERED AIR TO THE RABVS AREAS WITHIN A SPECIFIED FLOW RANGE

COMPONENT TYPE	EQUIPMENT FUNCTION	OPERATOR FUNCTION
MCR COMPUTER DISPLAY	TO PROVIDE STATUS INFORMATION ON SUPPLY FAN S-6 + FILTER TRAIN	A.) TO RESPOND TO COMPUTER DISPLAY WHEN OTHER INPUT INDICATE POSSIBLE PROBLEMS WITH SUPPLY FANS + FILTER TRAINS
ANNUNCIATORS A+B	TO SUPPLY WARNINGS OF RAB SUPPLY FAN A TRIP/TROUBLE/ TO SUPPLY WARNING OF SSX FMR 3-A 21 GROUND/ TEMP "HI"	B.) TO RESPOND TO + ACKNOWLEDGE ANNUNCIATOR ALARMS (+ RE-ESTABLISH SYSTEM FUNCTIONING) - TO VERIFY PROPER FAN OPERATION UPON STARTING FAN
S-6 FAN CONTROL SWITCH + INDICATOR LIGHTS (RED-GREEN)	TO PROVIDE A MEANS FOR INITIATING, MAINTAINING, TERMINATING, + INDICATING, OPERATION OF S-6 SUPPLY FANS + ASSOCIATED FILTER TRAIN	C.) TO OPERATE THE SWITCH DURING REQUIRED MODES OF OPERATION TO THE REQUIRED POSITION + SCAN INDICATOR LIGHTS FOR PROPER OPERATION OF SWITCH
AUX PNL S-6 FAN CONTROL CIRCUIT	TO PRODUCE START/STOP CONTROL SIGNAL BASED ON LOGIC INPUTS	NONE
480V SWITCH GEAR ANNUNCIATOR SIGNALS + COMPUTER INPUT	TO START/STOP S-6 SUPPLY FAN	D.) TO OPERATE S-6 SUPPLY FAN CONTROL SWITCH DURING ABNORMAL STATE OF PLANT OPERATION

Fig. 5.10. Function allocation form

5.9.1 Operator Requirements Identification Form

Figure 5.11 is a sample page from a form used to initially identify the core performance requirements imposed by each control function requirement. Note that this form is an expanded version of Fig. 5.10. It includes a set of columns representing "core performance area elements." These elements are an expanded taxonomy of core performance areas (as described in Sect. 2.6.1 and elsewhere). The taxonomy is derived from concurrent work being performed by BTI in CR task analysis, and is indebted in part to a taxonomy by Berliner (ref. 22). On this form a BTI analyst marked an initial assessment as to which core performance elements were demanded by each control functional requirement.

5.9.2 Activity to Map Core Performance

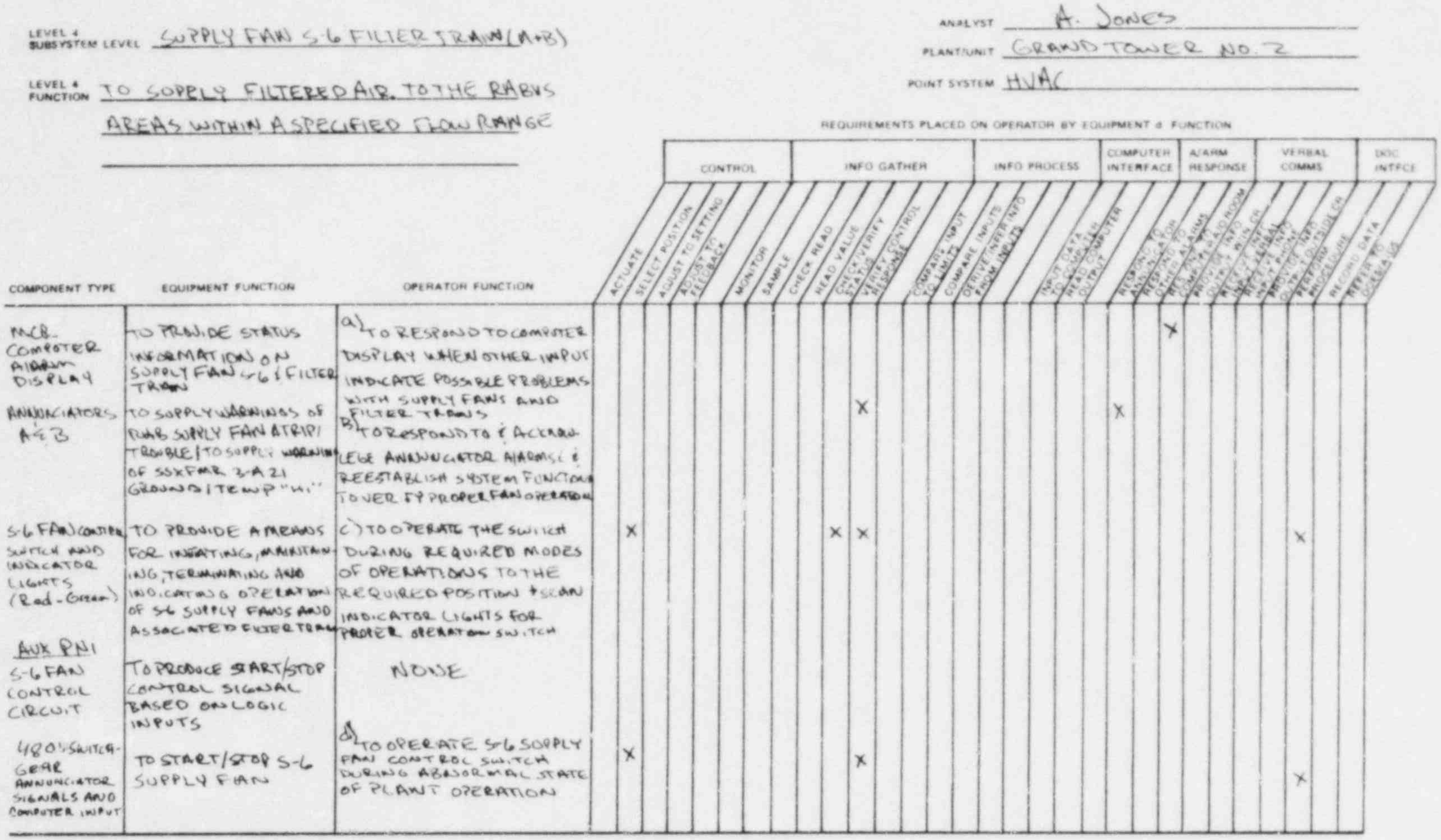
Figure 5.12 is a sample page from a worksheet used to generate a "mapping function," by which the temporal sequence of control events was related to operator core performance areas. The "Activity Sequence" column on the left is a sequential activity taxonomy derived from task analyses, a set of generic perceptual, cognitive, and psychomotor steps arranged in the order in which they usually occur. This taxonomy was considered useful as a menu, the use of which could force the identification of operator task-level requirements which might otherwise escape identification. A possible alternative to the use of such a menu would be the use, in the same column, of real task analysis data if such data were available.

Using this form, the analyst considered each functional operator performance requirement recorded on the Function Allocation Form (Fig. 5.10). Relying on documentation and his knowledge of CR behaviors, the analyst noted whether each of the activity sequence behaviors was or was not required. He then checked those columns which represented the core performance elements involved in required behaviors. The use of this form represents and simulates a computer-driven menu analysis, which would make this type of analysis feasible in a real CR evaluation.

Note that the number of occurrences in each core performance element column are added at the bottom of the page (or by the computer program). This cumulative total becomes a mapping function by which activity sequence information is mapped into a profile of demand placed on the core performance elements.

5.9.3 Core Performance Summary

Mapping function data were summarized and displayed for further analysis on the form shown in Fig. 5.13. This form lists identified functions at the left, followed by two demand profiles for each function. The small cells represent the cumulative totals, for each core performance element, of instances in which that element was identified as being required. The larger cells contain an adjusted percentage of occurrences by core performance area.



LEVEL 4 SUBSYSTEM LEVEL: SUPPLY FAN S-6 FILTER TRAIN (A+B)

LEVEL 4 FUNCTION: TO SUPPLY FILTERED AIR TO THE RABVS AREAS WITHIN A SPECIFIED FLOW RANGE

ANALYST: A. JONES

PLANT/UNIT: GRAND TOWER NO. 2

POINT SYSTEM: HVAC

REQUIREMENTS PLACED ON OPERATOR BY EQUIPMENT & FUNCTION: CONTROL (ACTUATE, SELECT POSITION, ADJUST TO SETTING, ADJUST TO FEEDBACK, MONITOR, SAMPLE); INFO GATHER (CHECK READ, READ VALUE, CHECK/VERIFY STATUS, VERIFY CONTROL RESPONSE); INFO PROCESS (COMPARE INPUT TO LIMITS, COMPARE INPUTS, DERIVE/INFER INFO FROM INPUTS); COMPUTER INTERFACE (INPUT DATA TO COMPUTER, READ COMPUTER OUTPUT); ALARM RESPONSE (RESPOND TO ANNUNCIATOR, RESPOND TO OTHER ALARMS); VERBAL COMMS; DOC INTFCE (PERFORM PROCEDURE, RECORD DATA, REFER TO DOCUMENTS)

COMPONENT TYPE	EQUIPMENT FUNCTION	OPERATOR FUNCTION
MCB COMPUTER ALARM DISPLAY	TO PROVIDE STATUS INFORMATION ON SUPPLY FAN S-6 & FILTER TRAIN	a) TO RESPOND TO COMPUTER DISPLAY WHEN OTHER INPUT INDICATE POSSIBLE PROBLEMS WITH SUPPLY FANS AND FILTER TRAINS
ANNUNCIATORS A&B	TO SUPPLY WARNINGS OF RAB SUPPLY FAN A TRIP/TROUBLE / TO SUPPLY WARNING OF SSXFMR 3-A21 GROUNDS/TEMP "HI"	b) TO RESPOND TO & ACKNOWLEGE ANNUNCIATOR ALARMS & REESTABLISH SYSTEM FUNCTION TO VERIFY PROPER FAN OPERATION
S-6 FAN CONTROL SWITCH AND INDICATOR LIGHTS (Red - Green)	TO PROVIDE A MEANS FOR INITIATING, MAINTAINING, TERMINATING AND INDICATING OPERATION OF S-6 SUPPLY FANS AND ASSOCIATED FILTER TRAIN	c) TO OPERATE THE SWITCH DURING REQUIRED MODES OF OPERATIONS TO THE REQUIRED POSITION & SCAN INDICATOR LIGHTS FOR PROPER OPERATION SWITCH
AUX RNI S-6 FAN CONTROL CIRCUIT	TO PRODUCE START/STOP CONTROL SIGNAL BASED ON LOGIC INPUTS	NONE
480V SWITCHGEAR ANNUNCIATOR SIGNALS AND COMPUTER INPUT	TO START/STOP S-6 SUPPLY FAN	d) TO OPERATE S-6 SUPPLY FAN CONTROL SWITCH DURING ABNORMAL STATE OF PLANT OPERATION

Fig. 5.11. Cognitive requirements identification form.

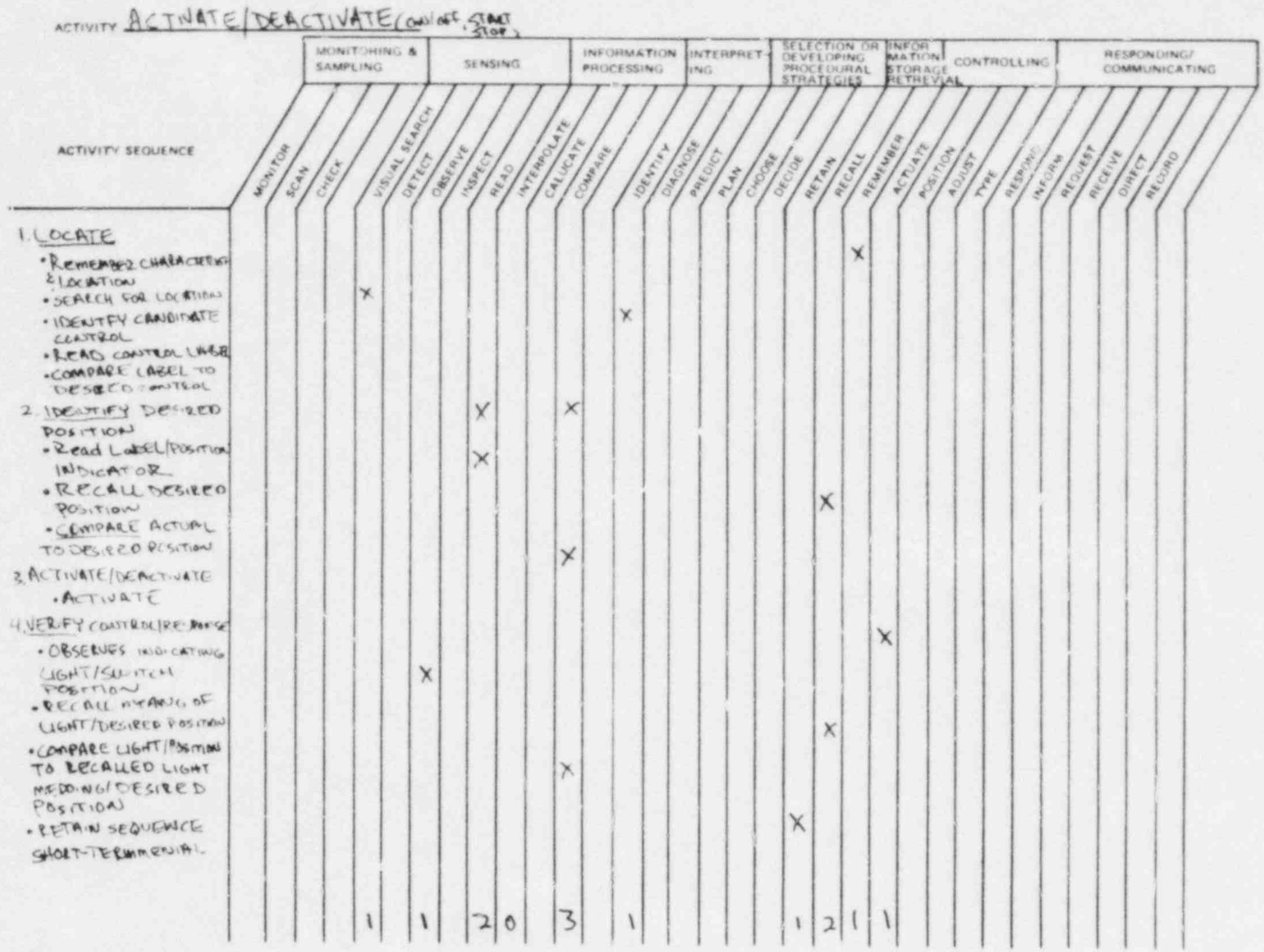


Fig. 5.12. Mapping function generator form.

SUBSYSTEM HVAC

MAJOR SUBSYSTEM

FUNCTION PARTITION NO.	DESCRIPTION MAN RATED SUBSYSTEM FUNCITONS	MONITOHING &SAMPLING (MONITOR, SCAN, CHECK)	SENSING (VISUAL SEARCH, DETECT, OBSERVE, INSPECT, READ)	INFORMATION PROCESSING (INTERPOLATE, CALUCATE, COMPARE)	INTERPRETING (IDENTIFY, DIAGNOSE, PREDICT)	SELECTION OR DEVELOPING PROCEDUHAL STRATEGIES (PLAN, CHOOSE, DECIDE)	INFORMATION STORAGE RETREVIAL (RETAIN, RECALL, REMEMBER)	CONTHOLLING (ACTUATE, POSITION, ADJUST, TYPE)	RESPONDING/ COMMUNICATING (RESPOND, INFORM, REQUEST, RECEIVE, DIRECT, RECORD)
1.1.1.1.1.	TO SUPPPY FILTERED AIR TO RABW AREAS WITHIN A SPECIFIED FLOW RANGE	0%	27%	12%	18%	2%	35%	4%	1%
		0 0 6	10 1 7 0 9	0 0 12 1	14 2 0	0 1 0.7	13 6 16	2 0 1 0	0 0.7 0 0 [illegible] 0.7
1.1.1.1.2	TO MAINTAIN MINIMUM DISCHARGE AIR TEMPERATURE OF 50°F	0%	26%	13%	11%	0%	31%	8%	11%
		0 0 0	10 5 3 0 8	2 0 11 0	11 0 0	0 0 0	11 11 8	6 2 0 0	3 2 0 3 2 2
1.1.1.1.3	TO MAINTAIN MAXIMUM DISCHARGE AIR TEMPERATURE OF 104°F	0%	24%	6%	25%	3%	38%	3%	0%
		0 0 0	9 3 3 0 9	0 0 6 3	16 6 0	0 0 3	16 6 16	3 0 0 0	0 0 0 0 0 0
1.1.1.2.1	FILTER EXHAUST AIR FROM RAS FOR REMOVAL OF PARTICULATE AND RADIOACTIVITY	0%	24%	15%	21%	2%	36%	4%	2%
		0 0 0	9 1 4 0 10	1 2 12 2	17 2 0	0 0 2	14 5 17	2 1 0 1	0 0 0 0 1 1
1.1.1.3.2	TO TEST CVAS NEGATIVE PRESSURE CAPACITY	0%	24%	5%	36%	3%	33%	3%	0%
		0 0 0	13 3 0 0 8	0 0 5 5	28 3 0	0 0 3	10 0 23	0 0 0 3	0 0 0 0 0 0

Fig. 5.13. Core performance summary sheet.

5.9.4 Interview Summary Form

Figure 5.14 is a sample page from a summary form whi n was not actually used, but such as would be required to summarize interview data and transfer the summaries to the appropriate display documents.

Form A-24

Highlight items	Refer to:
1. Two operators report that HVAC alarms during emergency shutdown are a nuisance, since actions can usually be deferred as much as an hour.	19.1, 19.2
2. Five operators observed that HVAC annuciators are "not important" or "don't tell me much."	19.1
------------------- etc. ----------------------	

Fig. 5.14. Interview Transfer Summary Form

5.10 DISPLAY DOCUMENTS

Analysis results were prepared as display documents for use in the evaluation panel proceedings specified in block 6 of Fig. 5.3.

5.10.1 Core Performance Area (CPA) Requirements Profile

The data from Figs. 5.11 and 5.12 are displayed in Fig. 5.15, the Core Performance Area Requirements Profile. This form contains

1. The function partition number from Fig. 5.8.
2. The function description from Fig. 5.9.
3. Descriptive operator performance statements from Fig. 5.10.
4. Levels of CPA demand, expressed as a graph of occurrences by element and as percentges by area from Fig. 5.13.
5. Comments by field or table-top analysts.
6. Comments extracted from questionnaires, via Fig. 5.14.

Figure 5.15 was the principle display document used in assessing test 19.1 of Fig. 5.2, "Does man meet core performance requirements?"

5.10.2 Human Performance Requirements Assessment

Figure 5.16 presents a display document used in assessing test 19.2, "Does man meet human performance requirements?" This form uses a different taxonomy in the left column, derived in part from Swain and Guttman (ref. 8). Ths taxonomy provides a menu of potential performance constraints and forces the analyst to consider them systematically. The analyst estimates the level of demand or constraint for each function evaluated and for each line of the performance taxonomy. Low, medium, and high levels of involvement were assigned the arbitrary values 1, 3, and 5 and summed by major category. Adjusted percentages of total estimated demand were then computed by category. Analyst comments were entered, and comments from questionnaire summaries (Fig. 5.14) were added.

5.10.3 Cognitive Support Assessment

Figure 5.17 represents the third display document, which was used in conjunction with Fig. 5.15 to assess test 19.5 in Fig. 5.2, "Is cognitive support adequate?" This is considered to be the least satisfactory display document, in that the menu on the left is recognized to be inadequate. The form contains the table-top analyst's assessment of points of strength or weakness in cogntive support of function, plus analyst comments and pertinent questionnaire responses from Fig. 5.14.

5.11 PANEL PROCEEDING

A panel of three human factors analysts met to perform a final assessment of the adequacy of allocation of control functions in the prototypical NPP subsystem being evaluated as specified in block 9 of Fig. 5.3. The panel was assisted by an SME, a design engineer familiar with the HVAC system concerned.

The meeting simulated an ideal case, in which a panel would meet at the plant being evaluated and would have access to the plant and control room as required.

5.11.1 Respondents--SMEs

The SME simulated an ideal case, in which the panel would have access to at least three categories of SMEs: operators, members of the plant engineering staff, and members of the plant training staff.

SUBSYSTEM FUNCTION/ OPERATOR PERFORMANCES			LEVEL OF DEMAND 1 LOW	3 MED	5 HIGH	RAW SCORES	LEVEL OF DEMAND OF OPERATION	MONITORS COMMENTS	OPERATORS/STAFF COMMENTS
TO SUPPLY FILTERED AIR TO RABV AERAS WITHIN A SPECIFIED FLOW RANGE OPERATOR PERFORMANCE TO RESPOND TO COMPUTER DISPLAY VALUES TO RESPOND TO ANNUNCIATOR ALARMS TO ACKNOWLEDGE ALARMS TO VERIFY PROPER FANS OPERATION UPON FAN START-UP TO OPERTOR FOR CONTROL SWITCH AND OBSERVE INDICATOR LIGHTS TO OPERATE S-6 PAN CONTROL SWITCH	MONITORING & SAMPLING	MONITOR				—			
		SCAN				—			
		CHECK				—	0%		
	SENSING	SEARCH		X		3			
		DETECT	X			1			
		OBSERVE			X	5	60%		
		INSPECT				—			
		READ		X		3			
	INFORMATION PROCESSING	INTERPOLATE				—	60%		
		CALCULATE				—			
		COMPARE		X		3			
	INTERPRETING	ENCODE/DECODE			X	5	73%		
		IDENTIFY	X			1			
		DIAGNOSE			X	5			
		PREDICT				—			
	SELECTION OR DEVELOPING PROCEDUAL STRATEGIES	PLAN				—	80%		
		CHOOSE			X	5			
		DECIDE		X		3			
	INFORMATION STORAGE & RETRIEVAL	RETAIN		X		3	73%		
		RECALL		X		3			
		REMEMBER			X	5			
	CONTROLLING	ACTUATE	X			1			
		POSITION				—	20%		
		ADJUST	X			1			
		TYPE				—			
	RESPONDING/ COMMUNICATING	RESPOND				—			
		INFORM	X			1			
		REQUEST				—	20%		
		RECEIVE				—			
		DIRECT				—			
		RECORD	X			1			

Fig. 5.15. Core Performance Area (CPA) requirements profile.

SUBSYSTEM FUNCTION

OPERATOR PERFORMANCES

HUMAN PERFORMANCE FACTORS	DEMAND OR CONSTRAINT 1 LO	3 MED	5 HI	SCORES	ANALYST COMMENTS	OPERATORS STAFF COMMENTS
PSYCHOLOGICAL/PHYSIOLOGICAL						
1. OPERATOR AGE				—		
2. OPERATOR SEX						
3. OPERATOR HEIGHT						
4. OPERATOR WEIGHT						
5. OPERATOR BODY SIZE & SHAPE						
6. MONOTONY & BOREDOM	X			1		
7. FREQUENCY & REPETITION	X			1		
8. FEEDBACK & REINFORCEMENT (TOO MUCH/LITTLE)	X			1		
9. DECISION MAKING		X		3		
10. DISTRACTION		X		3		
11. LONG VIGILANCE PERIODS			X	5x3	NUMEROUS COMPUTER & ANNUNCIATOR ALARMS	
12. POTENTIAL FOR HIGH RISK OF FAILURE		X		3	SOUNDING SIMULTANEOUSLY PLACE HIGH CONSTRAINT	
13. MENTAL/PHYSICAL STRESS/FATIGUE		X		3	ON OPERATOR	
14. CONSTRICTION OF MOVEMENT						
15. PAIN/DISCOMFORT	X			1		
16. PSYCH-PHYSIOL. FACTORS FROM PERFORMING SIMULTANEOUS FUNCTIONS		X		3		
17.				68%		
18.						
PHYSICAL						
1. TEMPERATURE & HUMIDITY				—		
2. LIGHT	X			1		
3. NOISE & VIBRATION		X		3	NOISE LEVEL IN CR CAUSES SOME DEGREE OF CONSTRAINT / ANNOYANCE	
4. RADIATION						
5. APPLICATION OF EXCESSIVE PHYSICAL FORCE				—		
6. CONTINUOUS TASK PERFORMANCE	X			1		
7. SPEED OF TASK PERFORMANCE		X		3		
8. PRECISION OF TASK PERFORMANCE		X		3		
9. COMPLEXITY OF TASK PERFORMANCE		X		3		
10. WORK STATION DESIGN	X			1		
11. EQUIPMENT DESIGN OR LOCATION	X			1		
12. AVAILABILITY/ADEQUACY TOOLS EQUIP.				—		
13. WORK HOURS/BREAKS	X			1		
14. AIR QUALITY						
15. WORK SPACE CLEANLINESS						
16. PHYSICAL FACTORS FROM PERFORMING SIMULTANEOUS FUNCTIONS				35%		
SOCIAL ORGANIZATIONAL						
1. CREW SIZE/STRUCTURE	X			1		
2. AMOUNT, TYPE, QUALITY OF SUPERVISION	X			1		
3. WRITTEN VERBAL COMMUNICATIONS		X		3	LACK OF CLEAR	
4. REWARD RECOGNITION SYSTEM	✓			1	COMPLETE OP's FOR	
5. AUTHORITY RESPONSIBILITY		X		3	THIS SYSTEM IN	
6. PRODURES			X	5x3	GENERAL	
7. PREVIOUS TRAINING EXPERIENCE		X		3		
8. SOCIAL FACTORS FROM PERFORMANCE SIMULTANEOUS FUNCTIONS		X		3		
				75%		

Fig. 5.16. Human performance requirements assessment.

SUBSYSTEM FUNCTION & OPERATOR PERFORMANCES	FACTOR	COMMENT ?			ANALYST COMMENTS	QUESTIONAIRE COMMENTS
		WEAK	NO COMMENT	STRONG		
TO TEST CVAS NEGATIVE PRESSURE CAPABILITY	<u>CHALLENGE</u>					
	LEVEL OF INTEREST	X			LEVEL OF DEMAND IS MINIMAL	NOT INTERESTING (ONE OPERATOR)
	DIFFICULTY	X				
	DECISION VALUE		X			NOT IMPORTANT TO SAFETY (ONE OPERATOR)
	REFERENCE TO KEY PARAMETER CHANGE			X		
<u>OPERATOR PERFORMANCE</u>						
TO RESPOND TO PARAMETER ALARMS AND TO READ COMPUTER DISPLAY VALUES WHEN OTHER INPUTS WOULD INDICATE POSSIBLE PROBLEMS WITH THE DAMPER.	<u>ADEQUACY OF MENTAL MODEL</u>					
	COBERENCE		X		OPERATORS APPEAR TO UNDERSTAND FULLY AT ALL TIMES	
	COMPLETNESS		X			
	CURRENCY		X			

Fig. 5.17. Cognitive support assessment sheet.

5.11.2 Working Forms

Working forms were generated as specified in Block 10, but they are of no technical interest since all data were later transferred to the descriptive evaluation of block 11.

5.11.3 Procedure

Panel procedure resembled that recommended in Sect. 4.1 for allocation during design. Decisions are made by expert judgment of a multidisciplinary team, in reference to analogous cases. The team begins by considering each function for understanding only: find out what happens to the plant, the control system, and the operating crews. SMEs are questioned and may volunteer information and opinions. The team then considers the human factors dimensions of each function for tests 19.1, 19.2, and 19.5. Human factors members suggest an evaluation for each function, seek a consensus, and, in case of uncertainty, the senior member makes a final decision. At this point either the plant staff SMEs or the junior human factors members may file a dissenting opinion, which becomes part of the record.

The panel simulated this procedure to the extent that it was feasible to do so.

5.12 DESCRIPTIVE EVALUATION

Details of this evaluation are presented in Figs. 5.18 and 5.19.

5.12.1 Evaluation Summary Sheet

In the summary sheet (Fig. 5.18), five functions are listed at the left by function code and description. The three "test" columns represent descriptive finds of tests 19.1, 19.2, and 19.5. Each time the panel found a significant weakness in the allocation of function, a numbered note was entered in the column and row concerned. Note that in 8 of 15 cells no significant problem was identified.

5.12.2 Numbered Evaluation Notes

The specific observations of the team were entered as descriptive notes, shown in Fig. 5.19. Note that these are unevaluated comments. The problem of calibrating the seriousness of a problem and establishing a cutoff for acceptability remains unsolved.

5.13 SUMMARY

The demonstration described in this section verified that selected tests from step 19 can be applied to an existing design to produce significant findings regarding suitability of allocation. It did not, however, demonstrate that the method is yet suitable for regulatory use.

PLANT: Grand Tower No. 2 | DATE: 24 FEB. 83 | SHEET NO. 1

SUBSYSTEM FUNCTION		TEST		
FUNCTION NO.	FUNCTION DESCRIPTION	19.1 Core Performance Requirements	19.2 Human Performance Requirements	19.5 Cognitive Support
1.1	Supply filtered air to RABV subareas within specified flow range	(1)	(2)	—
1.2	Maintain minimum discharge air temperature of 50°F	—	—	—
1.3	Maintain maximum discharge air temperature of 104°F	—	(3)(4)	(5)
2.1	Filter exhaust air from RAB for removal of particles and radioactivity	—	(6)	—
3.2	Test CVAS negative pressure capacity	(7)		(8)

Fig. 5.18. Summary sheet - descriptive evaluation of functions.

NOTE	FUNCTION	TEST	COMMENT	SHEET NO. 1
(1)	1.1	19.1	Decode of alarms should be automated. This relatively simple function requires excessive cognitive encode-decode loading. Especially during emergency shutdown and post-shutdown activity (return plant to normal), there are a high number of annunciator alarms and requirements to interpret meter or recorder displays. These conflict with other, more critical cognitive requirements needed to achieve safe shutdown. Decode of alarms/displays should be automated. Dissenting opinion (Plant engineer). Number of annunciators per event no greater than established practice in the NPP industry, and does not confuse well trained operators.	
(2)	1.1	19.2	Excess psychological stress. Numerous apparently unnecessary alarms and redundant displays (see note (1)), during rare occurrence of RABVS overheat and/or fan failure, creates operator stress, distraction during emergencies. Note that a delayed response to most of these alarms is acceptable.	
(3)	1.3	19.2	Psychological and physiological limits possibly exceeded. Responses to this function, reacting to high or high temperature alarms will likely occur during other emergencies in more safety-critical controls. This creates simultaneous control demands, mental stress, distraction, conflict in decision-making, and difficulty of physical access across the control room area.	
(4)	1.3	19.5	Operators mental models are probably inadequate to support required performance. Operators experience difficulty in understanding the relatively simple dynamics of HVAC cooling and flow, due apparently to an inadequate mental model of HVAC. More frequent operator intervention should be required during normal operations.	
(5)	2.1	19.2	Requirement to communicate improperly allocated to operator. Operator must telephone NEO to obtain information or status of exhaust filter trains after an alarm (asking: has problem been corrected). Allocate to computer display.	
(6)	3.2	19.1	Unnecessary operator decode loading. See also notes (1), (2), and (4). Instruments and annunciator displays are more complex than the subsystem they represent. However, practice is consistent with norms for the industry.	
(7)	3.2	19.5	Operators not adequately supported by information. Despite large number of annunciators and displays, operators are unable to answer questions about CVAS pressure status promptly. Operators cannot describe CVAS function as a whole. Need integrating information and activity.	

Fig. 5.19. Numbered evaluation notes [Form 2(R)].

6. QUANTIFYING GOODNESS OF ALLOCATION

This section describes an experiment conducted in conjunction with the demonstration reported in Sect. 5, which explored the feasibility of a method for assigning quantified scores to goodness of allocation.

6.1 SUMMARY

BioTechnology, Inc., developed a procedure which can be used as an adjunct to methods reported in Sects. 4 and 5.

The procedure developed by BTI measures the relative suitability of an allocation of CR functions to man or machine. It produces a gross mean allocation score for the CR as a whole, a profile score by major control functions, and a profile score by evaluation variables. To the extent that it provides a set of profile subscores, the method is diagnostic and can be used either to improve a developing design or to pinpoint weaknesses in the design of an existing CR.

The method developed can be applied either during design of a plant process system or to an existing NPP CR. The method applied during system design is represented by block 24, "compute goodness of allocation," in Fig. 3.1, and by the block sequence 15, 16, 7, 8, 12, 13, and 14 in Fig. 5.3. The method applied to an existing CR is represented by the block sequence 1-6 and 8-11 in Fig. 5.3.

The procedure was demonstrated by application to a prototypical existing CR in the demonstration reported in Sect. 5.

A quantified scoring system for goodness of allocation is feasible and probably useful. However, such a quantified score cannot be as valuable as the descriptive evaluations reported in Sects. 4.2 and 5, because it probably cannot achieve the same levels of validity or reliability. Furthermore, substantial development effort will be required to refine the procedure, develop scaling tools, and calibrate the goodness scores. The method is recommended as an adjunct to the descriptive evaluations described in Sects. 4.2 and 5.

6.2 REQUIREMENT

It was considered desirable to develop a measurement of goodness of allocation which could supplement the categorical measures provided earlier, and which might permit scalar comparison between features of a design or between different designs. Section 4.2 provided descriptive evaluation of features of a design during design development, and Sect. 5 provided a descriptive evaluation of an existing CR design. These were recommended as the primary modes of evaluation, since descriptive data directly suggest the means by which problems may be corrected, and because allocation of functions is difficult to quantify.

In fact, as was noted in Sect. 2.5, so many man and machine variables are at work within the issue of allocation of control functions that all cannot be identified, much less quantified reliably. Therefore any attempt to quantify goodness of allocation must be approached with caution. A describable feature of design can often be affirmed as good or bad, but the degree of good or bad is difficult to scale. Any quantified measure for goodness of allocation will be less reliable, less dependably valid, and possibly less completely diagnostic than an equivalent set of descriptive statements.

Nevertheless, the authors recognized that a quantified evaluation scale was desirable. Furthermore, most things which can be described comparatively can also be scaled. BioTechnology, Inc., therefore developed an experimental scaling technique which uses the deductive test phase of the allocation methodology (Sect. 4.2) in a manner paralleling that of Sect. 5.

The method for quantifying goodness of allocation was then demonstrated as reported in Sect. 5.

6.3 METHOD

The general method was as follows:

1. Simple Scales: Because of the uncertainty with which the variables concerned can be quantified, the individual input data are derived from low resolution Lickert (descriptive) scales, typically evaluating each single feature of design on a five-point scale.

2. Judgmental Measure: Individual input data are provided by expert judges, using the scales.

3. Summation of Subtests: A large number of measurement points are established by systematically breaking down the principle variables into their included component variables, and making separate judgments concerning each variable. This ensures that all pertinent subvariables will be considered and the effects of random errors in judgment will be minimized.

4. Summation of Judges: Measures are separately applied by each of several trained judges, and are then summed to reduce human error or bias.

5. Value Weighting: The final effects of any datum are multiplied, where applicable, by a factor reflecting the criticality of that datum to plant safety.

6. Control by a Protocol: A protocol is provided to control data collection and analysis.

7. Assume Future Calibration: The method presumes that included variables can be measured and can produce differentiated scores which

have face validity and which do not contradict the general judgment of experts. This method is not assumed to be correctly calibrated, either internally or in its output scores. Several recognized methods for calibrating such a method do exist; original input measurements can be calibrated using benchmark scales; the computational algorithm can be calibrated by statistical procedures; or output scales can be calibated against industry norms. Calibration, however, will require time, effort, and access to a sample of NPP control rooms.

8. Assume Automation of the Protocol: Because many individual measurements must be provided, it is assumed that any full-scale evaluation would be automated and that the protocol would be administered using a menu-driven scoring procedure.

6.4 MAJOR VARIABLES

The six major variables identified as pertinent correspond to the six tests of Sect. 4 (see Fig. 4.5). All six variables apply to a plant during the process of design, but only three apply to a plant already built, as was discussed in Sect. 5.2.2. Figures 6.1 and 6.2 illustrate this distinction.

6.4.1 Evaluation During Design

Figure 6.1 reflects the procedure for measuring goodness of allocation during the development of a system design. The following paragraph numbers refer to the numbers encircled on the figure.

1. A panel of expert raters uses partially analyzed source documents (the display documents shown as block 9 on Fig. 5.3) to score all six variables, subtests 19.1 through 19.6. Each plant function is scored using a taxonomy of included issues (subvariables) for each subtest.

2. Subscores are recorded for each subtest.

3. Adjusted percentage means are computed for each function and for each variable (subtest).

4. Means for the functions are multiplied by a function weight representing the estimated importance of that function to plant safety.

5. Scores are reported as folows:

   - An overall system rating is computed as a mean of the weighted function scores.

   - A profile by function is developed using the unweighted function means.

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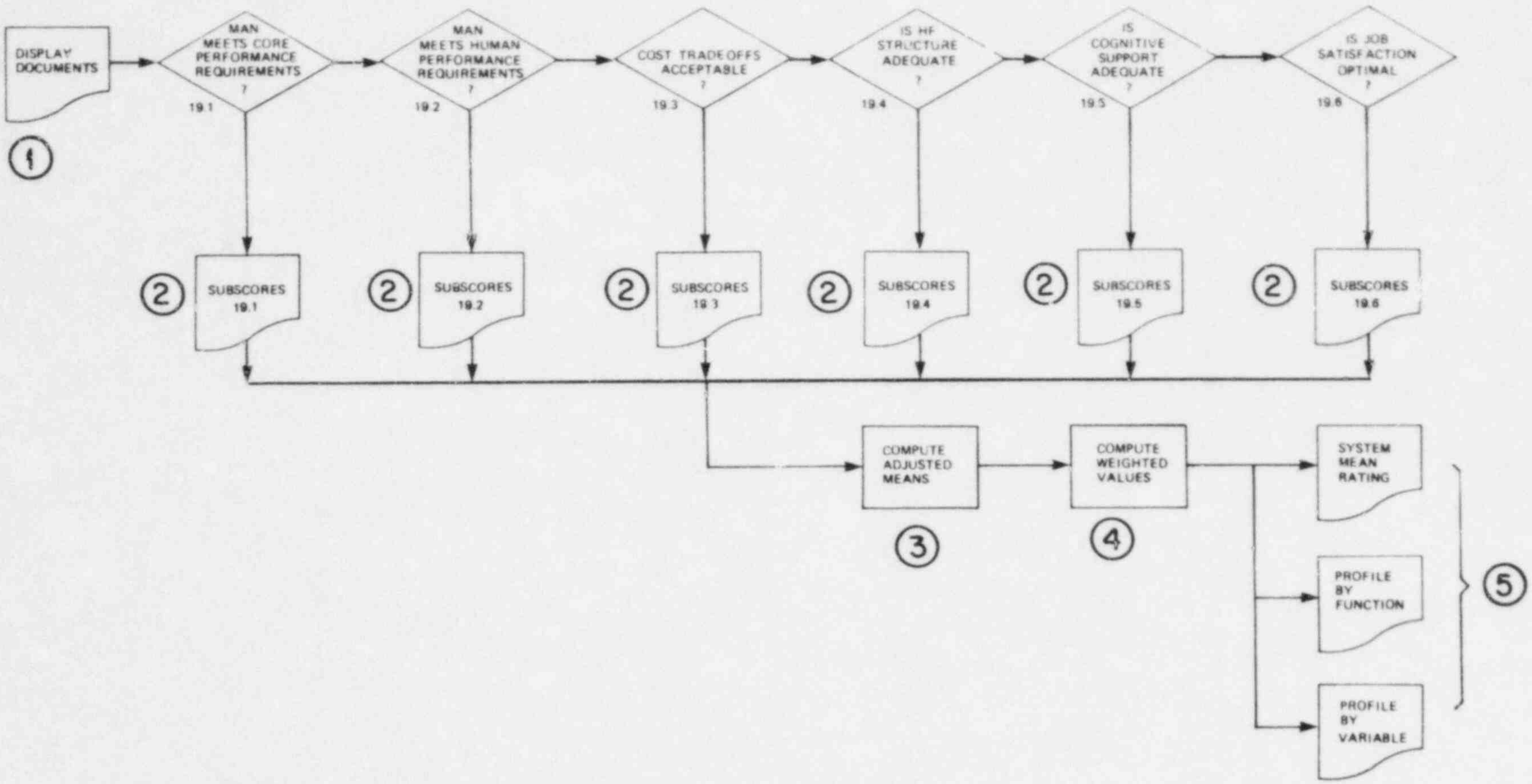

Fig. 6.1. Evaluate allocation of functions to produce a quantified profile score during system design.

ORNL-DWG 83-13798

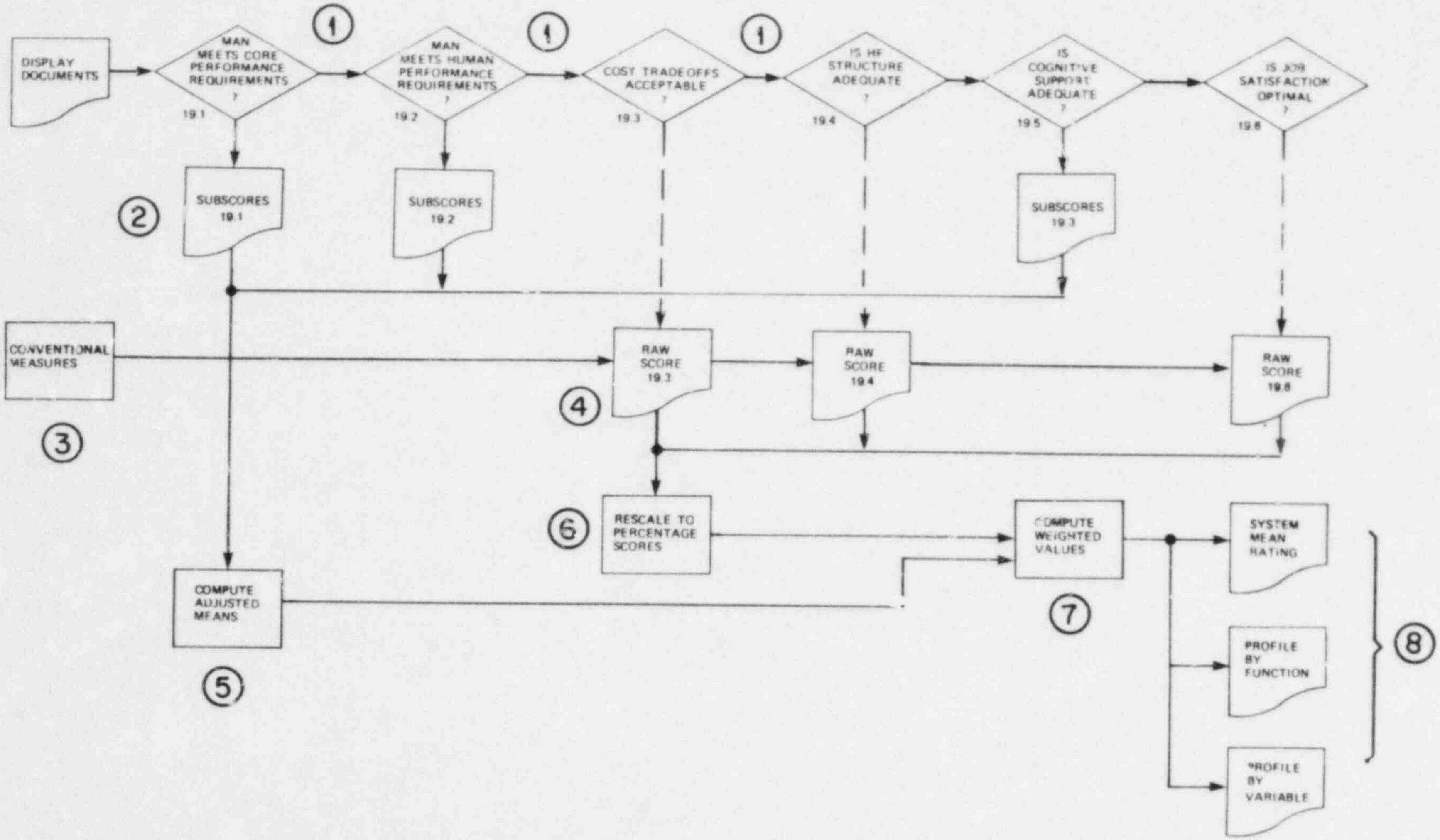

Fig. 6.2. Evaluate allocation of functions to produce a quantified profile score for an existing NPP control room.

- A profile by variable is developed using the unweighted variable means.

The above procedure applied to plant design. This is not the procedure reported in this section (Sect. 5). The experiment reported here was conducted for an existing plant, and used the procedure described in Sect. 6.4.2 below.

6.4.2 Evaluation of an Existing Plant

For evaluation of an existing plant, only tests 19.1, 19.2, and 19.5 apply. Sections 5.1 and 5.2 explain the logic for omitting the other three tests. Furthermore, in an existing plant the variables represented by tests 19.3, 19.4, and 19.6 can be measured more easily and reliably by conventional means. Figure 6.2 illustrates the test logic and procedure used in an existing CR. The following paragraph numbers refer to the encircled numbers on the figure.

1. Three variables (19.1, 19.2, and 19.3) are evaluated by a panel of expert raters using partially analyzed source data (the display documents shown as block 7 on Fig. 5.3). The panel provides scores for the three variables (subtests) concerned. Each plant function is scored using a taxonomy of included subvariables for each subtest.

2. Subscores are recorded by subtest.

3. Conventional measures are used to measure the following variables:

   - 19.3 - Cost/value acceptability of the allocation

   - 19.4 - Adequacy of the human factors support (training, job design, etc.)

   - 19.6 - Job satisfaction

4. Raw scores are recorded for the above variables.

5. Adjusted mean scores by variable and by function are computed for tests 19.1, 19,2, and 19.5.

6. Raw scores for tests 19.3, 19.4, and 19.6 are adjusted to a common percentage scale.

7. Values by function are weighted, using estimates of the criticality to plant safety of each function concerned.

8. The following output scores are reported:

   - A system rating, which is a mean of mean weighted function scores for tests 19.1, 19.2, and 19.5, and of rescaled raw scores for variables 19.3, 19.4, and 19.5.

- A profile by function of unweighted mean scores.

- A profile by variable of unweighted mean scores and of rescaled raw scores.

This procedure was developed and tested in the experiment reported here. Actual methodology and a demonstrated rating were performed for tests 19.1, 19.2, and 19.5 only. Tests 19.3, 19.4, and 19.6 use established evaluation techniques that do not require development. Arbitrary values were assumed for the weighted raw scores of those three tests, and those same values were used in further computations.

6.4.3 Summary Sheet

Figure 6.3 is the summary sheet on which these data were recorded for display and final computation. The following paragraph numbers refer to those encircled on the figure.

1. Functions are listed in columns.

2. For variables 19.1, 19.2, and 19.5, subvariable ratings are entered by function and by subvariable.

3. Means are computed and adjusted to a percentage score by variable and function.

4. Subsystem and plant-wide means are computed by variable.

5. For variables 19.3, 19.4, and 19.6, differentiating by function is not appropriate; in any case, only plant-wide scores are available.

6. The means of mean variable scores are computed by function.

7. The mean scores are multiplied by the estimated criticality of each function, where criticality is defined as seriousness to safety if a function is not properly performed.

8. The weighted mean value is recorded as a safety score.

9. A plant score, which is the mean of safety scores by function, is reported.

10. Scores in the column "x x f" provide a profile score for goodness of allocation by function.

11. Scores in the row "x x test" provide a profile for goodness of allocation by variable (test).

PLANT: Grand Tower No. 2	DATE:	SHEET NO.

NO.	DESCRIPTION ❶	19.1 Core Performance A B C D E F G H	19.1 $\bar{X}$	19.2 Human Performance A B C	19.2 $\bar{X}$	1.93 Cost Value	19.4 Human Factors	19.5 Cognitive Support A B C	19.5 $\bar{X}$	19.6 Job Satisfaction	$\bar{X}\bar{X}$ t	Criticality	Safety Score
1.1	Supply filtered air to RABV subareas within specified flow range	❷	❸	❷	❸			❷	❸		❻	❼	❽
1.2	Maintain minimum discharge air temperature of 50°F												
1.3	Maintain maximum discharge air temperature of 104°F												
2.1	Filter exhaust air from RAB for removal of particles and radioactivity												
3.2	Test CVAS negative pressure capacity												
$\bar{X}\bar{X}$ Test			❹		❹		❺		❹	⓫			
Plant Mean Scores													Weighted ❾

Fig. 6.3. Summary sheet--quantified goodness of allocation profile score.

6.5 SUBTESTS

6.5.1 Subtask 19.1: Does Man Meet Core Performance Requirements?

Subtests A through H (see Fig. 6.3) are the eight core performance areas (CPAs) first described in Sect. 2.6.3 and further defined in terms of included core performance elements in Sect. 5.9. The data entered on the Summary Form are produced by the rating panel, which uses source data (including the CPA requirements profile shown in Fig. 5.15). The panel rates each CPA on a scale from 0 to 5 for the level of demands imposed on an operating crew, where 0 means that core performance is not exercised at all and 5 means the core performance requirement approaches the perceptual, cognitive, or neuromotor limits of man, however briefly that may occur.

Zero scores were entered as a dash and not included in the computation of means. Scores 1-5 were converted to the inverted (reciprocal) scale 5-1, so that high performance demands would produce a low suitability score. These data were entered in area 1 of Fig. 6.3.

6.5.2 Subtest 19.2: Does Man Meet Human Performance Requirements?

Subtests A, B, and C are the three subvariables "Psychological-Physiological," "Physical," and "Social Organization" shown in Fig. 5.16. Note that these are further divided into 16, 16, and 8 subterms, respectively, and have been partially analyzed by those subterms. The panel rated each of these on a scale of 0 to 5 for human performance demands, and recorded the data on a reciprocal scale as described earlier.

6.5.3 Subtest 19.5: Is Cognitive Support Adequate?

Subtests A, B, and C are the individual variables "adequacy of displays," "involvement in key changes," and "level of sustained interest." These are not congruent with categories shown on the comparable Cognitive Support Assessment Sheet, Fig. 5.17. Again, assessment was on a 0 to 5 scale and the procedure identical to that of the previous subtests.

6.6 DEMONSTRATION DATA

The scores applied to the prototypical BWR "Grand Tower No. 2" produced the evaluation shown in Fig. 6.4. These data are generally consistent with the descriptive evaluation reported in Sect. 5.

PLANT: Grand Tower No. 2	DATE:	SHEET NO.

NO.	DESCRIPTION	19.1 Core Performance A B C D E F G H	$\bar{X}$	19.2 Human Performance A B C	$\bar{X}$	1.93 Cost Value	19.4 Human Factors	19.5 Cognitive Support A B C	$\bar{X}$	19.6 Job Satisfaction	$\overline{XX}$ f	Criticality	Safety Score
1.1	Supply filtered air to RABV subareas within specified flow range	- 5 1 1 2 5 5 5	69	1 5 3	60			4 4 4	80		69.7	2	139.4
1.2	Maintain minimum discharge air temperature of 50°F	-545 - 333	77	545	93			343	67		79.0	1	79.0
1.3	Maintain maximum discharge air temperature of 104°F	-423 - 344 -	67	133	47			523	67		60.3	2	120.6
2.1	Filter exhaust air from RAB for removal of particles and radioactivity	- 532 3345	71	133	47			545	93		70.3	3	210.9
3.2	Test CVAS negative pressure capacity	- 332 123 -	47	345	80			353	73		66.7	2	133.4
$\overline{XX}$ Test			66		65	81	78		76	88			683.3
Plant Mean Scores													Weighted 75.3

Fig. 6.4. Demonstration data.

7. CONCLUSIONS

This section briefly summarizes conclusions of the research reported and offers recommendations for continued research.

7.1 METHODOLOGY FOR ALLOCATION OF FUNCTIONS

Sections 2, 3, and 4 report a methodology for allocating control functions to man or to automation. Literature reviews revealed that reported methodologies were inadequate in several respects, but particularly in that (1) they assumed the availability of human performance data which do not exist, (2) they did not deal adequately with cognitive performance requirements, and (3) they did not provide an interaction of hypothesis and test.

The method reported here is believed to overcome those limitations and is particularly adapted to the nuclear power industry. Its use will certainly improve control room design, since past practice in the industry has neglected any direct consideration of the allocation of control functions question, and any systematic procedure for such considerations will therefore be an improvement. The particular procedure recommended here is considered approaching optimal for the industry, one which will be both economical and practical to apply.

It is suggested that in the near future this method be applied to the design of NPP automated display systems, automated control system designs, and control room redesigns. It might also be applied to control systems for the fossil power industry.

7.2 EVALUATION OF EXISTING CONTROL ROOM (CR) DESIGNS

The demonstration reported in Sect. 5 provides a tentative model for evaluating the allocation of control functions in an existing NPP control room, particularly as that allocation affects safety of control. It was demonstrated that the logic of Sect. 4.2 can be applied to an existing control room and will differentiate among good and poor allocations. However, the method will require additional development in order to be suitable for regulatory use. Still needed are a proven, low-cost procedure, a means of calibration, and development of standards for acceptable/unacceptable allocation.

7.3 QUANTIFYING GOODNESS OF ALLOCATION

The experiment reported in Sect. 6 revealed that it is feasible to quantify goodness of allocation, and that the scores can be used to produce quantified profile scores. Those scores are diagnostic in regard to the identifying of good and poor allocations by functions, or identifying the causes of poor allocation. This method of quantification is recommended as an adjunct to either the method for allocation during design or the model for evaluating an existing control room.

7.4 RECOMMENDED ADDITIONAL RESEARCH AND DEVELOPMENT

The method presented here for allocating control functions should be tested by actual application during the design process. As a first step it should be reviewed by experienced design engineers, and their comments should be used to improve the terminology and realism of the method before it is applied. Since no new NPP control rooms are currently proposed for design, the applied test could be in (1) a retrofit or redesign, (2) an advanced control/display system, (3) a fossile plant control room, (4) a process control industry other than electric power, or (5) a high-technology control system in the space or defense industries.

The method for evaluating an existing CR should be developed for regulatory use. A major obstacle to doing so is that, ideally, further development should be conducted using real-plant control rooms as test vehicles. However, access to real NPPs is notably difficult to secure. By whatever means, the evaluative procedure should be developed in a form practical for field use, and should be supported by benchmark scales based on real cases of good-to-poor allocation. Such scales can provide the basis for calibrating measurements, establishing norms, and setting standards.

Other research and development needs were also identified. First, NRC's recent support of research on cognitive modeling of the NPP operator contributed substantially to the methods of this report (ref. 23); further research is needed to provide more detailed models, validate them, and standardize the terms used in decribing both human information processing and the parallel functions of automatic control. Second, there is a startling shortage of quantified design data on human cognitive speeds and capacities. A substantial body of such data probably exists but is not readily available because it is scattered in obscure research. Other data might be developed by academic researchers if the problem were more widely recognized. A handbook on perception and human performance now under development for the U.S. Air Force suggests what might be accomplished if the questions were addressed systematically.

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Appendix A
Checklist of Conditions Hostile to Man

Condition	Reference
Radiation	A-1
Heat/Cold/Humidity	A-2
	A-3
	A-4
Noise	A-5
Oxygen Level	A-6
Toxicity	A-7
Vibration	A-8

0 25 rems	25–100 rems	100–200 rems	200–300 rems	300–600 rems	600 rems or more
Immediate Effects					
No detectable clinical effects	Slight transient reductions in lymphocytes and neutrophils	Nausea and fatigue with possible vomiting above 125 rems.*	Nausea and vomiting on first day	Nausea, vomiting, and diarrhea in first few hours	Nausea, vomiting, and diarrhea in first few hours
	Disabling sickness not common; exposed individuals should be able to proceed with usual duties	Reduction in lymphocytes and neutrophils with delayed recovery	Latent period up to 2 weeks or perhaps longer	Latent period with no definite symptoms, perhaps as long as 1 week	Short latent period with no definite symptoms in some cases during first week
Delayed Effects					
Delayed effects may occur	Delayed effects possible but serious effects on average individual very improbable	Delayed effects may shorten life expectancy in the order of 1%	Following latent period, the following symptoms appear but are not severe: loss of appetite and general malaise, sore throat, pallor, petechiae, diarrhea, moderate emaciation	Epilation, loss of appetite, general malaise, and fever during second week, followed by hemorrhage, purpura, petechiae, inflammation of mouth and throat, diarrhea, and emaciation in the third week	Diarrhea, hemorrhage, purpura, inflammation of mouth and throat, fever toward end of first week. Rapid emaciation and death as early as the second week, with eventual death of up to 100% of exposed individuals
			Recovery likely in about 3 months unless complicated by poor previous health or superimposed injuries or infections	Some deaths in 2 to 6 weeks. Possible eventual death to 50% of the exposed individuals for about 500 rems	

Fig. A.1. Effects of acute whole-body external radiation exposure (from Woodson, 1981).

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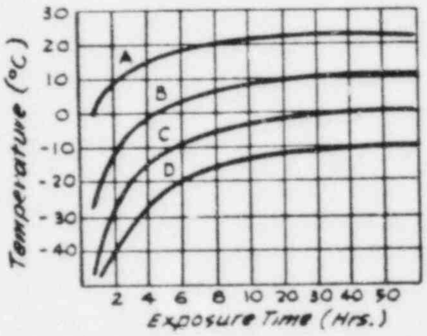

Legend:

A--1-clo (light coveralls)
B--2-clo (woolen underwear, coveralls, and jacket)
C--3-clo (intermediate-weight flight clothing)
D--4-clo (heavy flight clothing)

Subjects were seated and performing light work. Air velocity, approximately 200 ft/min; barometric pressure, 1 atm.

Fig. A.2. Tolerance to low temperature (from Woodson, 1981).

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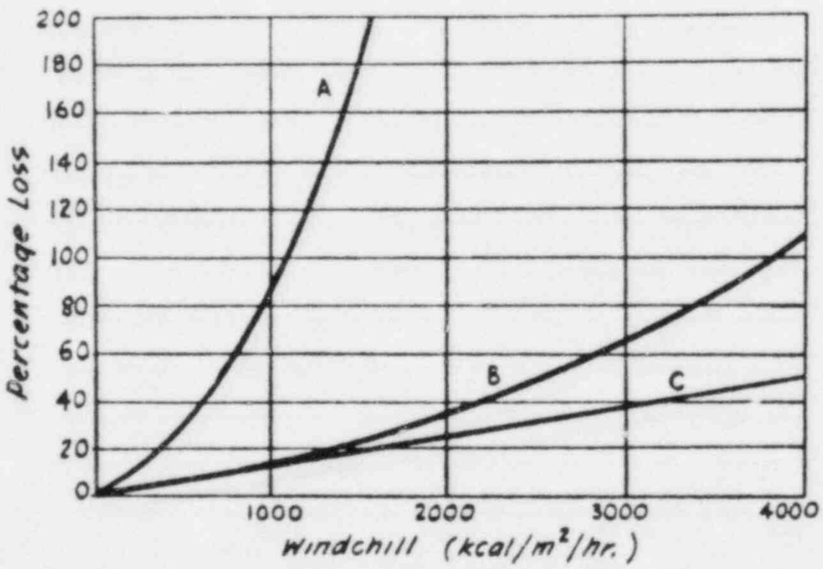

Legend:

A--tactile sensitivity, bare hand
B--simple visual reaction time
C--manual skill

Fig. A.3. Effects of cold on selected task performances.

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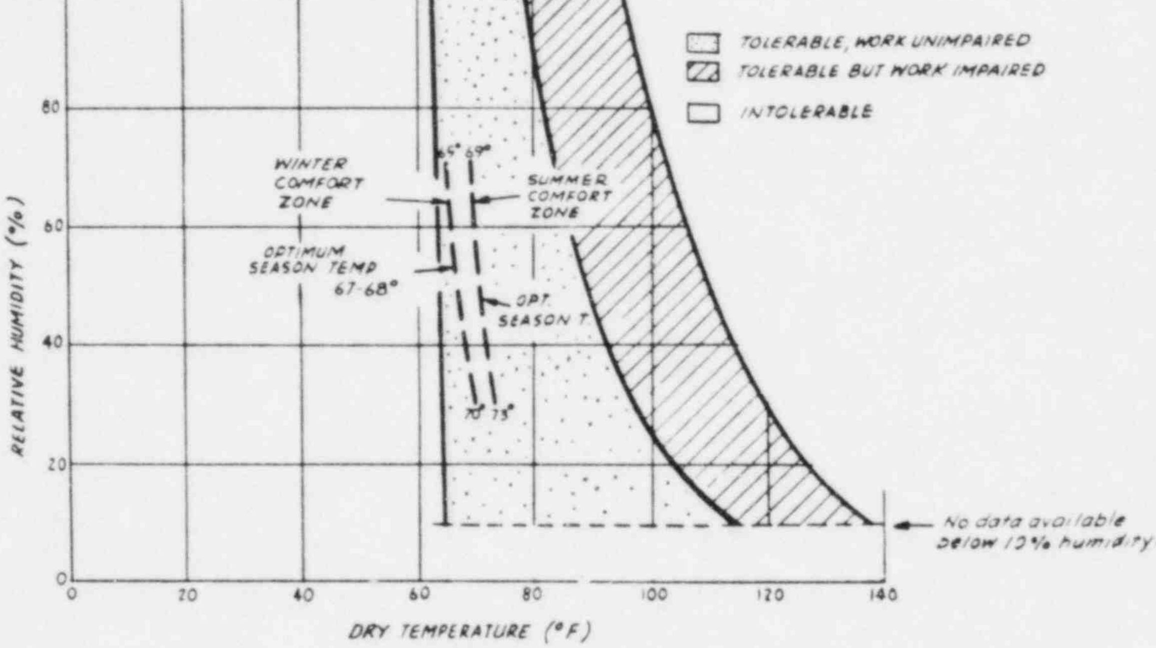

Fig. A-4. Temperature-humidity tolerability (with conventional clothing) (from Woodson, 1981).

When noise levels exceed 100 dB, potentially serious consequences occur, as shown below.

Noise Level, dB	Spectrum	Duration	Effects
105	Jet engine	2 min	Reduced visual acuity, stereoscopic acuity and near-point accommodation and permanent hearing loss when exposure continues over a long period (months)
110	Machinery noise	8 hr	Chronic fatigue and digestive disorders
120	Broadband	1 hr	Loss of equilibrium
150	1-100 Hz	2 min	Reduced visual acuity, chest-wall vibration, changes in respiratory rhythm, and a "gagging" sensation*

*Subjects were wearing so-called protective aids to prevent hearing loss.

Fig. A.5. Potential effects of high noise levels (from Woodson, 1981).

Partial Pressure of Oxygen, mm of Hg	Percent of Oxygen in Dry Air at Sea Level Pressure	Effect
		Oxygen Excess
456	60	Onset of oxygen poisoning after some hours
167	22	Limit set in RN to control fire hazard in charcoal filters in nuclear submarines
		Normal
160	21	Normal atmospheric level
		Oxygen Lack
137	18	Accepted limit of alertness. Loss of night vision. Earliest sign—dilation of the pupils
114	15	Performance seriously impaired. Hallucinations, excitation, apathy
100	13	Coordination impaired. Emotional upset
84	11	Paralysis, loss of memory. Irreversible unconsciousness
46	6	Death before symptoms apparent

Note: The effect of falling oxygen is insidious, because it dulls the brain and prevents realization of danger

Fig. A.6. Effects of high and low oxygen levels (from Woodson, 1981).

The table below presents a partial list of chemical substances and their action on the skin.

Agent	Reaction
Acids:	
Acetic	Dermatitis and ulcers
Carbolic	Irritation and erosion, eczema, and anesthesia
Chromic	Ulcers (chrome holes on the skin), inflammation, and perforation of the nasal septum
Hydrochloric	Irritation and ulceration
Hydrofluoric	Severe burning, erosion ulcers, and blisters
Lactic	Ulcers (if strong solution)
Nitric	Severe burns and ulcers
Oxalic	Local caustic action on the skin
Sulfuric	Corrosive action on the skin and severe inflammation of the mucous membranes
Alkalis:	
Calcium cyanamide	Irritation and ulceration
Calcium oxide	Dermatitis, burns, and ulcers
Potassium hydroxide	Severe burning, persistent ulcers, and loss of fingernails
Sodium hydroxide	
Sodium silicate	Thickening of the skin and ulcers on the fingers
Sodium or potassium cyanide	Blisters and ulcers
Salts:	
Antimony and its compounds	Irritation and eczematous eruptions
Arsenic	Skin darkening, perforation of the nasal septum, eczema around the mouth and nose, and possible loss of nails or hair
Barium	Eczema and cyanosis of skin
Bromine	Brownish stains and skin erruptions
Chromium (hexavalent compounds)	Chrome holes on the skin, perforation of the nasal septum, and eczematous eruptions
Mercury compounds	Corrosion and irritation and mercurial eczema
Sodium	Burns and ulcers
Zinc chloride	Ulcers of the skin and nasal septum
Solvents:	
Acetone	Dry (defatted) skin
Benzene	Dry (defatted) skin
Carbon disulfide	Dry (defatted) skin
Chlorinated phenols	Severe eruptions
Petroleum distillates	Acne and epithelioma
Trichlorethylene	Dry, cracked skin
Turpentine	Red, blistered skin and eczema
Dyes:	
Chlorinated compounds	Blisterlike eruptions
Dinitrochlorobenzene	Blisterlike eruptions
Nitro and nitroso compounds	Red skin and eczematous eruptions
Phenyl hydrazine	Blisterlike skin eruptions
Insecticides:	
Chlorophenols	Red skin, and blisters
Creosote	Pustular eczema, warts, and epithelioma
Fluorides	Severe burns and dermatitis
Pyrethrum	Red skin, blisters, and pimples
Rotenone	Red skin and blisters
Resins:	
Coal tar, pitch, and asphalt	Acute dermatitis, acne, inflammation, epitheliomatous cancer, eczema, and ulcers
Synthetics, e.g., phenol-formaldehyde	Extremely red and itchy skin
Synthetic waxes, e.g., chloronaphthalenes and chlorodiphenyls	Dermatitis and acne

Fig. A.7. Skin reaction to chemical substances (from Woodson, 1981).

Vibration Conditions	Measures	Effect	Source
		Biodynamic Mechanisms	
±0.15–0.35 *g* at 0.9–6.5 Hz, low amplitude	Whole body vertical vibration: hand tremor, body equilibrium, foot pressure	Foot pressure constancy impaired at 3.5 to 6.5 Hz; error increase with intensity; no residual effects	Schmitz, Simons, and Boettcher, 1960
±ng, ±ng for ½ hr	Body sway equilibrium	No effects	Hornick, Boettcher, and Simons, 1961
±*g*, 2–20 Hz (intensities = ⅓ short-term tolerance limits)	Control of pitch and roll of a chair	Wide individual differences; decrement between 3 and 12 Hz, worst at 6 Hz	Coermann, Magid, and Lange, 1962
±*g* at 0, 2, 5, and 8 Hz	Orientation (orienting body position to face targets at 15, 30, and 60° from reference plane)	Only small decrement in accuracy; mean error < 0.5°	Ayoub, c. 1969
±0.03 – ±0.41 *g* at 0, 3, 5, and 8 Hz	Leg muscular power (on bicycle ergometer)	No effects	Harrison, 1969
Various peak-to-peak accelerations at 1 Hz with 3 Hz, and 2 Hz with 6 Hz	Arm-hand steadiness	Positional errors significantly related to rms and frequency of vibration; 90% of error was periodic; 1 Hz with 3 Hz combination produced larger error; small (0.5–1 *g*) differences in acceleration had no effect	Clarke et al., 1965
		Psychomotor Performance	
±0.25 *g* at 2.4–9.5 Hz	Time to pick up markers and place in small circular areas	Completion time worst at 3.4 and 4.8 Hz	Guignard and Irving, 1960
±0.5 rms *g* at 2–30 Hz (13 Hz peak power)	Digital decimal input with push button, toggle switch, rotary switch, and thumbwheel controls	Accuracy unaffected; insert times increased by 4%; push buttons and toggle switches were most rapidly used, with the former preferred; thumbwheels were most accurate	Dean et al., 1967
0, 0.2, 0.4, 0.6, and 0.8 rms *g*, for 5 min	Same	No effects for 0.2 and 0.4 rms *g*, significant increase in insert time for 0.6 and 0.8 rms *g*, speed: push buttons >*rotary switches > thumbwheels; error rate: push buttons highest and thumbwheels lowest for high intensity vibrations	Dean, Farrell, and Hitt, 1967
±*g*, and ±*g* at 0.33 and 0.80 Hz at amplitude of ±6.3 and ±7.0 in	Nut and bolt assembly and disassembly; placement of probe through various sized holes	No effects at 0.33 Hz; time required increased by 30% at 0.80 Hz with no increase in accuracy	Seeman and Williams, 1966
		Speech Intelligibility	
±*g* at 10, 20, 30, 40, and 50 Hz	Intelligibility	Most effect at 10 and 20 Hz	Nixon, 1962
0.5 *g*, sinusoidal at 6 Hz; 0.75 *g* at 4 and 8 Hz; 1.0 *g*, at 2–20 Hz	Intelligibility and quality	No effect on intelligibility at 65 dB; "quality" poorer than control condition	Nixon and Sommer, 1963
		Audition	
5-Hz sinusoidal, 5-Hz random amplitude, 4- to 12-Hz random frequency	Frequency (pitch) change (1200 for 1600 Hz) at 86-dB tones of 0.25-s duration every second—detection	No effect	Weisz, Goddard, and Allen, 1965
±*g*,	1200 Hz at 86 dB presented every 0.25 s for 1 s against a 74-dB, 30- to 3000-Hz white noise; pitch change at 86 dB (1600 for 1200 Hz)—detection	No effect	Holland, 1966
+1 *g*, ±0.7 *g* at 15 Hz (amplitude 0.036 in) for 30 min	TTS determined as function of vibration and noise versus noise alone (acoustical frequencies from 250–6000 Hz)	Extremely small vibration effect at low tone frequencies only	Guignard and Coles, 1965
		Higher Mental Processes	
±0.15 – 0.35 *g* at 2.5 and 3.5 Hz	Mental addition	No effect	Schmitz, Simons, and Boettcher, 1960
±*g* at 5, 7, and 11 Hz	Pattern matching and discrimination	No effect	Buckhout, 1964
0.40 rms *g*, random vibration	Navigational tasks in simulated low-altitude, high-speed flight	No effect	Schohan, Rawson, and Soliday, 1965; Soliday and Schohan, 1965
No vibration, no noise; no vibration, noise only; vibration plus noise; postvibration: +4.0 *g* at 70 Hz	Continuous counting at a given rate	Decrement, especially during 5–7 min of exposure; residual effects noted; 70% of decrement attributed to vibration (30% to noise); Ss over 36 showed greater decrement	Ioseliani, 1967

*Symbol > here indicates faster than.

Fig. A.8. Effects of vibration on human performance (from Woodson, 1981).

Appendix B
Checklist for Human Limitations/Tasks Man Cannot Perform

Condition	Reference
Strength and Endurance	B-1
Reaction Time	B-2
	B-3
Control Output Rates	B-4
Sensory Channel Capacity	B-5
	B-6
Signal Detection	B-7
	B-8
	B-9
	B-10
	B-11
Memory--Short-Term	--
Memory--Long-Term	--

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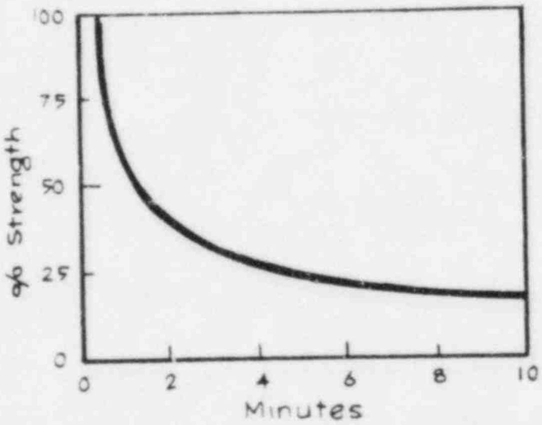

Typical endurance time in relation to force requirements.

Fig. B.1. Human physical strength and endurance (from Woodson, 1981).

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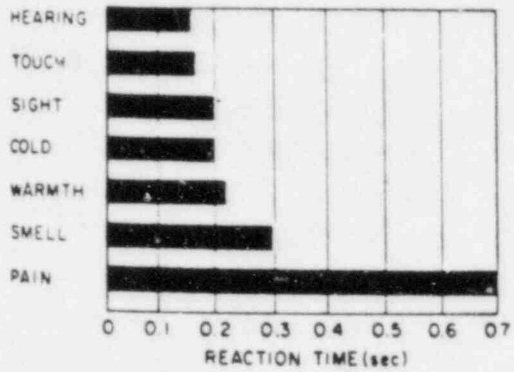

Note: Signals should not occur at rates faster than about two per second unless some means are provided for anticipating the signal. Avoid alerting periods shorter than 0.1 s.

Fig. B.2. Reaction time comparisons of sensory input channels (from Woodson, 1981).

As one might expect, when the number of response choices increases, the reaction time is lengthened. The table below illustrates this point.

Number of Choices	Mean Reaction Time, s
1	0.20
2	0.35
3	0.40
4	0.45
5	0.50
6	0.55
7	0.60
8	0.60
9	0.65
10	0.65

Fig. B.3. Effect of number of response choices (from Woodson, 1981).

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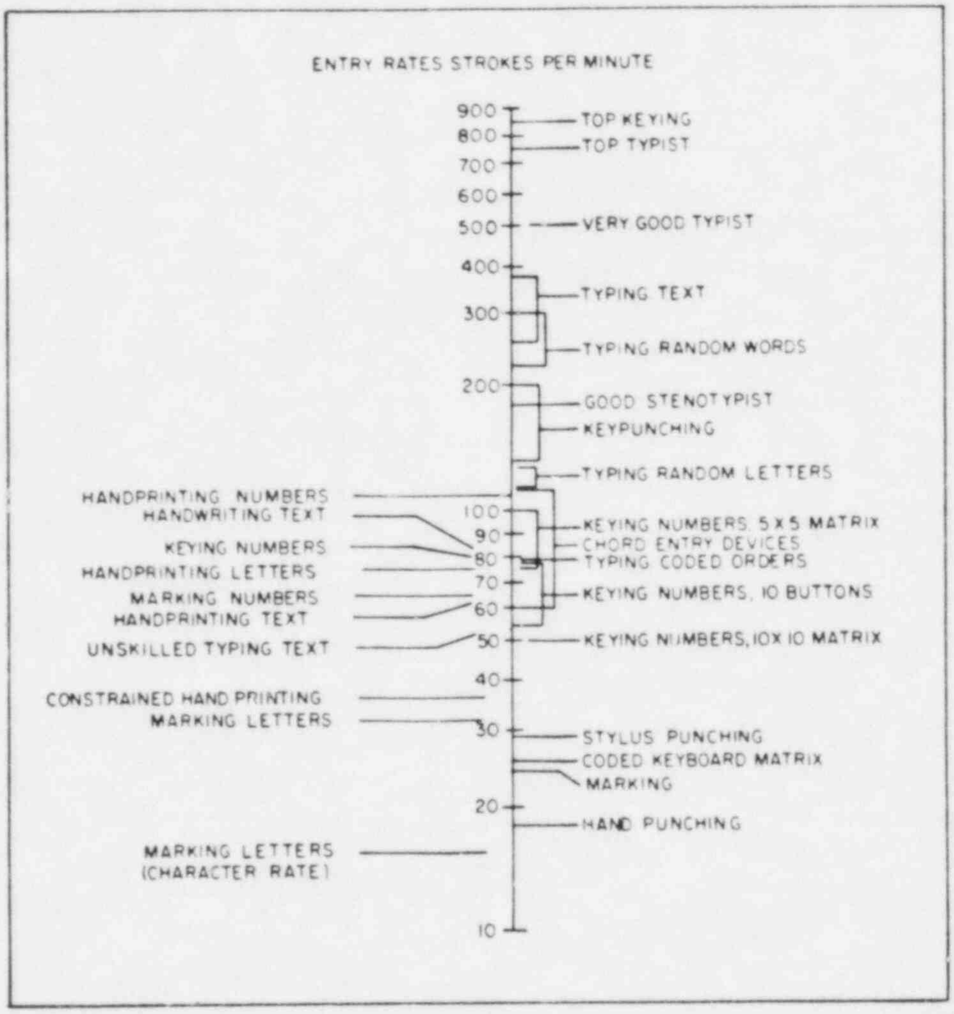

Fig. B.4. Representative manual entry rates (adapted from Devoe, 1967).

Stimulus dimension	Channel capacity (bits)	Discriminable categories	Investigator
Size, brightness, and hue (varied together).	4.1*	18	Eriksen (1954).
Frequency, intensity, rate of interruption, on-time fraction, total duration, and spatial location.	7.2	150	Pollack & Ficks (1954).
Colors of equal luminance........	3.6	13	Halsey & Chapanis (1954).
Loudness and pitch..............	3.1	9	Pollack (1953).
Position of points in a square (no grid).	4.6	24	Klemmer & Frick (1953).

* Note: The capacity of each dimension separately was approximately 2.7 bits.

Fig. B.5. Sensory channel capacity for multidimensional stimuli (from Van Cott & Kinkade, 1972).

Sense	Stimulus dimension	Channel capacity (bits)	Discrim-inable categories	Investigator
Vision	Dot position (in space)	3.25	10	Hake & Garner (1951).
	Dot position (in space)	3.2	10	Coonan & Klemmer (in Miller, 1956).
	Size of squares	2.2	5	Eriksen & Hake (1955).
	Dominant wavelength	3.1	9	Eriksen & Hake (1955).
	Luminance	2.3	5	Eriksen & Hake (1955).
	Area	2.6	6	Pollack (in Miller, 1956).
	Line length	2.6–3.0	7–8	Pollack (in Miller, 1956).
	Direction of line inclination.	2.8–3.3	7–11	Pollack (in Miller, 1956).
	Line curvature	1.6–2.2	4–5	Pollack (in Miller, 1956).
Taste	Salt concentrations	1.9	4	Beebe-Center et al. (1955).
Audition	Intensity	2.3	5	Garner (1953).
	Pitch	2.5	7	Pollack (1952, 1953).
Vibration (on chest)	Intensity	2.0	4	Geldard (in Miller, 1956).
	Duration	2.3	5	Geldard (in Miller, 1956).
	Location	2.8	7	Geldard (in Miller, 1956).
Electrical shock (skin).	Intensity	1.7	3	Hawker (1960).
	Durations	1.8	3	Hawker & Warn (1961).

Fig. B.6. Sensory channel capacity for different unidimensional stimuli (from Van Cott & Kinkade, 1972).

Improved probability of detection		
Simultaneous presentation of signals to dual channels		Buckner & McGrath (1963), Gruber (1964).
Men monitoring display in pairs; members of pairs permitted to speak with one another; 10 minutes rest each 30 minutes of work; random schedule inspection by supervisor.		Bergum & Lehr (1962).
Introduction of artificial signals during vigilance period to which a response is required.		Garvey, Taylor & Newlin (1959), Faulkner (1962).
Introduction of knowledge of results of artificial signals		Baker (1960).
Artificial signals identical to real signals		Wilkinson (1964).
Decreased probability of correct detections		
Introduction of artificial signals for which a response is not required.		Colquhoun (1961).
Excessive or impoverished task load on operator		Poulton (1960).
Introduction of a secondary display monitoring task		Jerison (1963), O'Hanlon & Schmidt (1964), Ware, Baker & Sheldon (1964), Wiener (1964).
Operator reports only signals of which he is sure		Broadbent & Gregory (1963).
Change in probability of detection with time		
A short pretest period followed by infrequently appearing signals during vigilance.	High initial probability of detection, falling off rapidly.	Colquhuon & Baddeley (1964).
Few pretest signals before vigilance period.	Reduces decrement in probability of detection with time.	Colquhuon & Baddeley (1964).
Prolonged continuous vigilance	Decreases probability of correct signal detection.	Mackworth & Taylor (1963).

Fig. B.7. Task conditions affecting signal detectability during prolonged vigilance (from Van Cott & Kinkade, 1972).

Sensation	Number discriminable
Brightness.............	570 discriminable intensities, white light.
Loudness...............	325 discriminable intensities, 2,000 Hz.
Vibration..............	15 discriminable amplitudes in chest region using broad contact vibrator with 0.05-0.5 mm amplitude limits.

Fig. B-8. Relative discrimination of physical intensities (after Mowbray and Gebhard, 1958).

Sensation	Number discriminable
Hues..................	128 discriminable hues at medium intensities.
White light............	375 discriminable interruption rates between 1-45 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Pure tones.............	1,800 discriminable tones between 20 Hz and 20,000 Hz at 60-dB loudness.
Interrupted white noise..	460 discriminable interruption rates between 1-45 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Mechanical vibration....	180 discriminable frequencies between 1 and 320 Hz.

Fig. B.9. Relative discrimination of frequency (after Mowbray and Gebhard, 1958).

Stimulus	Lower Limit	Upper Limit
Color (hue)	300 nm (300×10^{-9} m.)	800 nm.
Interrupted white light	Unlimited	50 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Pure tones	20 Hz	20,000 Hz.
Mechanical vibration	Unlimited	10,000 Hz at high intensities.

Fig. B-10. Frequency-sensitivity ranges of the senses (adapted from Mowbry and Gebhard, 1958).

Sensation	Smallest detectable (threshold)	Largest tolerable or practical
Sight	10^{-6} mL.	10^{4} mL.
Hearing	2×10^{-4} dynes/cm^2	$<10^{3}$ dynes/cm^2.
Mechanical vibration	25×10^{-5} mm average amplitude at the fingertip (Maximum sensitivity 200 Hz).	Varies with size and location of stimulator. Pain likely 40 dB above threshold.
Touch (pressure)	Fingertips, 0.04 to 1.1 erg (One erg approx. kinetic energy of 1 mg dropped 1 cm.) "Pressure," 3 gm/mm^2.	Unknown.
Smell	Very sensitive for some substances, e.g., 2×10^{-7} mg/m^3 of vanillin.	Unknown.
Taste	Very sensitive for some substances, e.g., 4×10^{-7} molar concentration of quinine sulfate.	Unknown.
Temperature	15×10^{-5} gm-cal/cm^2/sec. for 3 sec. exposure of 200 cm^2 skin.	22×10^{-3} gm-cal/cm^2/sec. for 3 sec. exposure of 200 cm^2 skin.
Position and movement	0.2–0.7 deg. at 10 deg./min. for joint movement.	Unknown.
Acceleration	0.02 g for linear acceleration 0.08 g for linear deceleration 0.12 deg./sec^2 rotational acceleration for oculogyral illusion (apparent motion or displacement of viewed object).	5 to 8 g positive; 3 to 4 g negative. Disorientation, confusion, vertigo, blackout, or redout.

Fig. B.11. Stimulation-intensity ranges of man's senses (adapted from Mowbray and Gebhard, 1958).

Appendix C
Defining Criteria for Core Performance Areas

The eight core performance areas are defined below in terms of their included core performance elements.

1. Monitoring and Sampling: To maintain a state of readiness or preparation for changes to system status. This is an active process, which requires the operator to continuously sample display data, evaluate it, and detect significant system change.

- Monitor--To keep track of over time
- Scan--To quickly survey displays or other information sources to obtain a general impression
- Check--To quickly sample a specific display (or other information source) value or range to obtain a general impression

Human Limitations--A number of factors produce decrements in monitoring. Infrequent or unpredictable signals are difficult to monitor. The number of missed signals increases steadily as a function of the number of hours worked; this effect becomes especially pronounced beyond about four hours. Differential location of displays interacts with workload to increase monitoring difficulty. The addition of such tasks as problem solving, mental arithmetic, target identification, and other vigilance tasks tends to increase detection time.

2. Sensing: To detect a change in system status; the purposeful acquisition of data from the environment in response to or for the creation of system changes. This includes the detection, discrimination, reception, and recognition of external stimuli.

- Observe--To attend visually to the presence or current status of an object, indication, or event
- Detect--To become aware of the presence or absence of a physical stimulus
- Visual Search--To visually scan a possible set of objects in order to locate a particular object
- Inspect--To examine carefully, or to view closely with critical appraisal
- Read--To examine visual information which is presented symbolically

Human Limitations--Audition is influenced by the signal/noise ratio; vision is influenced by factors such as lighting and glare. Both senses are stressed by increasing time demands and by the number of channels a person must monitor simultaneously. For example, discriminating more than a few channels given a high signal rate (per minute) will increase the error rate significantly.

3. Information Processing: To transform, organize, break down, combine, or operate on input data or signals. This includes such operations as coding, sorting, filtering, ordering, merging, analyzing, and computing.

- Calculate--To determine by mathematical processes

- Interpolate--To determine or estimate intermediate values from two given values

- Compare--To examine the values or characteristics of two or more inputs to establish a relationship between the inputs

Human Limitations--People have difficulty computing rapidly and under stress. This also is true for such tasks as anlysis and coding. Machines generally can process information faster than people and are better at highly repetitive tasks.

4. Interpreting: To construct, derive, translate, or assign meaning to data or signals. Pattern recognition, classification, interpolation, and extrapolation are examples.

- Identify--To recognize the nature of an object or indication according to predetermined characteristics

- Diagnose--To recognize or determine the nature or cause of a condition by consideration of signs or symptoms

- Predict--To postulate a future state of the system or system parameter(s) based upon control actions or system trends

Human Limitations--Although people are much better than machines in pattern recognition and the classification of ambiguous information, there are real limits to human ability to interpret information. Interpretation involving the classification of large amounts of information coming from disparate sources greatly taxes humans. Also, prior experience and emotional states can significantly bias interpretation. Design which integrates information can help greatly, as can training.

5. Decision Making: To select or develop procedural strategies; to decide a time to initiate action; to select among alternatives; to determine a course of action; or to assess the validity of a proposition. Important to the making of decisions is the probablistic estimation of outcomes (contingencies) and their importance (weights).

- Plan--To devise or formulate a program of future or contingency activity

- Choose--To select after consideration of alterantives

- Decide--To come to a conclusion based on available information

Human Limitations--In many cases humans must be the decision makers due to the lack of pre-designated alternatives and unforeseeable contingencies. Where the decision rules are straightforward, machines often are better. This is especially true when large amounts of information must be memorized and integrated. People respond poorly in probablistic assessment of risk, by their oversimplified responses and predictable bias.

6. Memory Information Storage and Retrieval: To retain or to remain aware of information or, conversely, to recall or to bring forth previously acquired information. Short-term memory is the ability to recall information immediately after its presentation; long-term memory refers to the storage of information for recall following a substantial period of time.

- Retain--To store information in short-term memory
- Recall--To retrieve information from short-term memory
- Remember--To retrieve infomation from long-term memory

Human Limitations--Well-learned material often can be recalled after substantial periods of time. However, large amounts of information presented at a high rate may not be recalled even immediately. Prefiltering of information and short delays between information display and response to that information will reduce the interference effects from different informational inputs. Short-term memory is channel-limited to approximately 1.5 sensory modes at a time and to approximately 7 significant items of information stored.

7. Controlling: To adjust and correct for changes in system status, or to adjust for deviations from a prescribed optimum state. Controlling is the movement, manipulation, or adjustment of systems instrumentation via knobs, handles, and other usually manually activated devices, eye-movement detectors, and similar advanced control hardware, or as the result of a verbal signal to another operator [as when a CR operator calls a plant equipment operator (PEO)]. (See also "Communicating"). The major control categories are discrete and analog.

- Actuate--To exert a pushing, turning, or pulling force in the actuation of a discrete control
- Position--To operate a control which has discrete steps
- Adjust--To operate a continuous control
- Type--To operate a keyboard

Human Limitations--People are limited in this area to the degree that controls impose excessive requirements for force, speed, precision, or accuracy. Invariant control sequences usually should be performed automatically rather than manually.

8. Responsing-Communicating: To execute a command, a request for information, or a transfer of information involving two or more persons. The manner of communication may entail face-to-face interaction or messages sent via electronic or writen media.

- Respond--To respond to a request for infomation
- Inform--To impart information
- Request--To ask for information
- Receive--To be given written or verbal information
- Direct--To ask for action
- Record--To document something, as in writing.

Human Limitations--The ability to communicate is affected by environmental conditions (visual, auditory) and by systems design in its impact upon spatial arrangements, need for frequent communication, etc.

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This report describes a general method for allocating control functions to man or machine during nuclear power plant design, or for evaluating their allocation in an existing design.

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