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Proposal to

U. S. Nuclear Regulatory Commission
Washington, D.C.

MODELING COGNITIVE BEHAVIOR OF NUCLEAR POWER PLANT PERSONNEL

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Approved:

D. R. Muss, Manager
Applied Sciences Division
Westinghouse R&D Center

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APPENDICES

1. SUMMARY

The Westinghouse Electric Corporation proposes a three-year program to develop and validate improved methods and techniques of modeling cognitive behavior of nuclear power plant personnel. The methods and techniques developed will be compatible, to the extent possible, with reliability evaluations that use probabilistic risk assessment approaches.

The program will be divided into three phases. This proposal contains a detailed plan for Phase I, and general plans for the second and third phases. The Phase I objectives are:

1. To identify and prioritize selected nuclear power plant personnel jobs, roles, and functions which involve aspects of cognitive behavior that affect safety.

2. To assess the impact of this behavior on other plant personnel, plant safety systems, and overall plant risk.

3. To select one or more approaches for quantitatively and/or qualitatively modeling aspects of the jobs, roles, and functions previously identified.

Phase II involves developing one or two models. Phase III has as its objective field evaluation and validation of the models developed during Phase II.

The program will be carried out by the Human Sciences Department of the Westinghouse R&D Center in Pittsburgh. For the past 12 years, this group has been involved in the study of user-system interface issues for military, industrial, and commercial applications. Their experience includes models of operator cognitive behavior, evaluation of operator aids, principles and concepts to enhance human-computer interaction, and development and evaluation of decision support systems (both AI and Disturbance Analysis Systems).

2. INTRODUCTION AND PROGRAM OBJECTIVES

2.1 INTRODUCTION

The Westinghouse R&D Center proposes a phased three-year program to assess, develop, and evaluate models of the cognitive behavior of nuclear power plant (NPP) personnel. This research will result in the development and validation of improved methods and techniques for modeling human cognitive performance. These methods and techniques will be developed to be compatible, to the extent possible, with NPP reliability evaluations that use probabilistic risk assessment approaches. The results of the proposed effort will be an improved capability to describe the cognitive behavior of NPP personnel in a quantitative form.

The validated model that will result from this three-phase program can be used to analyze and measure cognitive aspects of behavior for the NPP jobs, roles, or functions selected during Phase I. The model will aid in the assessment of human reliability and in the evaluation of changes to NPP human-machine interfaces. The model to be developed during the program will meet these objectives because the Westinghouse team assembled for this program has a unique combination of expertise in cognitive psychology; expertise in applying cognitive psychology to model and evaluate operator decision making; extensive knowledge of nuclear power plant jobs, roles, and functions; and experience with and understanding of human reliability and probablistic risk assessment. The Westinghouse team brings to this project:

1. A large data base of empirical results on operator decision making in both actual and simulated emergencies.[1-4] (An in-depth understanding of how NPP personnel monitor, plan, and decide is an essential ingredient in the assessment, development, validation, and use of models of cognitive aspects of behavior.)

2. A technique for cognitive task analysis (i.e., to identify decision making requirements) developed in the context of NPP operations and applied to a portion of the NPP functions and systems important to safety. This technique is a form of knowledge representation that maps the problem space of goals, subgoals, side effects, functions, and requirements for NPP tasks related to safety.[5]

3. Experience in building and using models of cognitive behavior in process control,[6,7] including a signal detection analysis of the operator's alerted-monitor role,[8] knowledge based data sampling,[9,10] supervisory control,[11] and errors of decision making.[1,12,13]

4. Qualified cognitive psychologists who are also experienced in NPP tasks through studies of operator performance, operator reliability, evaluations of operator aids, NPP control room reviews, and development of NPP data base systems, display systems, decision aids, and disturbance analysis and surveillance systems.

5. Extensive knowledge of ongoing research and the results of research done around the world through active participation in international cooperative programs (e.g., with Risø National Laboratory, Electricite de France, the International Evaluation of Operating Practices Group) and national activities (e.g., the IEEE Subcommittee on Human Factors and Control Facilities, the ANS Technical Group on Human Factors, the two NRC-sponsored Myrtle Beach Workshops, the NRC-sponsored Cognitive Modeling Workshop).

6. Successful management and completion of related programs for the Electric Power Research Institute, The National Science Foundation, and various Westinghouse operating divisions.

2.2 NEED FOR PROGRAM

The need for this cognitive modeling program is well documented. Conclusions from three NRC-sponsored workshops (Myrtle Beach I[53], Myrtle Beach II[54], and the 1982 Boston session on cognitive modeling of nuclear plant control room operators[24]) were that a problem exists because current human reliability assessment methods do not describe NPP

personnel cognitive behavior adequately, and that research is required to develop models that better describe cognitive performance. It is stated in the Human-Reliability Analysis Chapter of the PRA Procedures Guide[46] (NUREG/CR-2300, Vol.1) that "For some operations, cognitive errors are critical (e.g., errors in evaluating display indications). There is very little information on errors of interpretation or decisionmaking (i.e., errors in the thought process)." In addition, the importance of and need for consideration of cognitive factors was documented in a letter from the ACRS to the NRC Commissioners.

2.3 OBJECTIVES AND SCOPE

The proposed program consists of three phases with the following objectives:

Phase I

1. Identify and prioritize selected NPP personnel jobs, roles, and functions which involve aspects of cognitive behavior that affect safety.

2. Assess the impact of cognitive behavior on other plant personnel, plant safety systems, and overall plant risk.

3. Select one or more approaches for quantitatively and/or qualitatively modeling cognitive aspects of the selected jobs, roles, and functions.

Phase II

Develop a maximum of two models for analyzing the quantitative and qualitative aspects of cognitive activities emerging from Phase I research.

Phase III

Conduct field evaluation and validation of the cognitive model(s) developed during Phase II.

Westinghouse will furnish highly qualified personnel, equipment, materials, transportation, and facilities necessary to perform the three-phased program. This proposal contains a detailed plan to perform Phase I of the program. Plans for Phases II and III are presented in

less detail. Detailed plans for the second and third phases will be prepared as part of the Phase I and II efforts, respectively. Phases II and III will be performed, if authorized by the NRC.

3. PROGRAM PLAN

3.1 PHASE I: IDENTIFICATION, ASSESSMENT, AND SELECTION

In Phase I models of cognitive behavior that are relevant to a subset of NPP jobs, roles, and functions important to safety will be identified and assessed, and one or two will be chosen for development in Phase II. Phase I will consist of five tasks, which are described in Sections 3.1.1 to 3.1.5 and are related to time in Figure 3.1.

3.1.1 Task 1: Conduct Meeting to Identify Cognitive Aspects of Behavior that Affect NPP Safety

Objectives: Establish working definitions of the cognitive activities that are important to safe operation of a NPP; establish communication with other completed or ongoing NRC work on cognitive related issues; and focus model identification and assessment on selected portions of NPP jobs, roles, or functions.

Technical Approach: Westinghouse will provide an agenda, coordinate, schedule, and convene a meeting at NRC facilities with NRC personnel and consultants to achieve these objectives. To ensure a focused and productive meeting, Westinghouse will, prior to the meeting, provide participants with a preliminary bibliography of reports on cognitive activities in NPPs, preliminary breakdowns and working definitions of cognitive activities relevant to NPP safety, and a preliminary breakdown of NPP personnel roles and functions. These materials for the meeting will be supplied to the NRC and those designated by the NRC one week prior to the meeting. Table 3.1 contains a preliminary agenda for this meeting.

Task	Months after Start of Contract 2 4 6 8 10 12
1. Conduct Meeting	—Δ
2. Assess Impact of Cognitive Activities on NPP Safety	Δ——Δ
3. Inventory of Models	Δ————————Δ
3.1 Survey Literature	Δ————Δ
3.2 Synthesize Empirical Results on Cognitive Activities in NPP Safety	Δ———Δ
3.3 Decision Analysis to Assess and Select Models to be Pursued in Phases II and III	Δ——————Δ
4. Document and Present Results	Δ————Δ
5. Final Phase II Research Plan	Δ———Δ
Deliverables:	
Status Reports	(Monthly)
Minutes Initial Meeting	Δ
Inventory of Models of Cognitive Activities	Δ
Final Report	Δ
Paper Summarizing Results	(If Requested)
Final Administrative Plan, Phase II	Δ

Figure 3.1 -- Schedule for Phase I.

Table 3.1 -- Preliminary Agenda for Meeting to Identify Cognitive Activities Relevant to NPP Safety

	DAY 1	
8:30 - 8:45	Introduction	L. Hanes (R&D)
8:45 - 9:00	Project Overview	NRC
9:00 - 10:00	Review of Preliminary Breakdown of Cognitive Activities and NPP Personnel Roles and Functions	D. Woods (R&D)
10:00 - 10:15	Break	
10:15 - Noon	Discussion of Candidate NPP Jobs, Roles, and Functions	All
Noon - 12:45	Lunch	
12:45 - 3:00	Discussion of Breakdown and Working Definitions of Cognitive Activities Related to NPP Safety	All
3:00 - 3:15	Break	
3:15 - 5:00	Discussion Continued	All
	DAY 2	
8:30 - 10:00	Selection of NPP Jobs, Roles, Functions to be Focused on in Model Identification/Assessment	All (group consensus technique led by L. Hanes)
10:00 - 10:15	Break	
10:15 - 11:15	Selection of NPP Jobs, Roles, Functions	
11:15 - Noon	Finalize Working Definitions of Cognitive Activities of NPP that Affect Safety	All
Noon - 12:45	Lunch	
12:45 - 3:15	Finalize Working Definitions of Cognitive Activities	All
3:45 - 4:15	Update Bibliography and Points of Contact on Research Related to Cognitive Activities in NPP	All
4:15 - 4:30	Final Comments	D. Woods, NRC
4:30	Adjourn	

Westinghouse will use the nominal group technique (NGT) consensus process to:

- Integrate the attendee's viewpoints
- Select the NPP jobs, roles, and functions to be focused on in model identification/assessment
- Finalize the working definitions of cognitive activities in NPPs that affect safety

Westinghouse personnel utilized the NGT process successfully with one of the groups during the first Myrtle Beach workshop[53] and during the deliberations of a group identifying robotic research priorities in a contract sponsored by the National Service Foundation.[55]

Expected Results: Westinghouse will provide the NRC the minutes of the meeting within one week after the meeting. The minutes will contain the agenda, summaries of the discussions, a bibliography annotated with points of contact on research related to cognitive activities in NPPs, the set of working definitions of cognitive activities important to NPP safety produced during the meeting, and the set of NPP jobs, roles and functions to be focused on during Phase I research as identified in the meeting.

3.1.2 Task 2: Assess the Impact of Cognitive Activities on NPP Safety

Objective: Assess the impact of cognitive activities on each NPP job, role, and function (from Task 1), and categorize and prioritize each NPP job, role, and function in terms of their potential impact on safety.

Technical Approach: The relationship between cognitive activities and NPP jobs, roles, and functions and NPP safety will be categorized and prioritized based on:

- A function based, goal-means analysis of the relevant portion of the NPP
- The roles NPP personnel play in safety (prevent, terminate and mitigate disturbances and roles of process management, equipment operation, test, calibration, and maintenance)

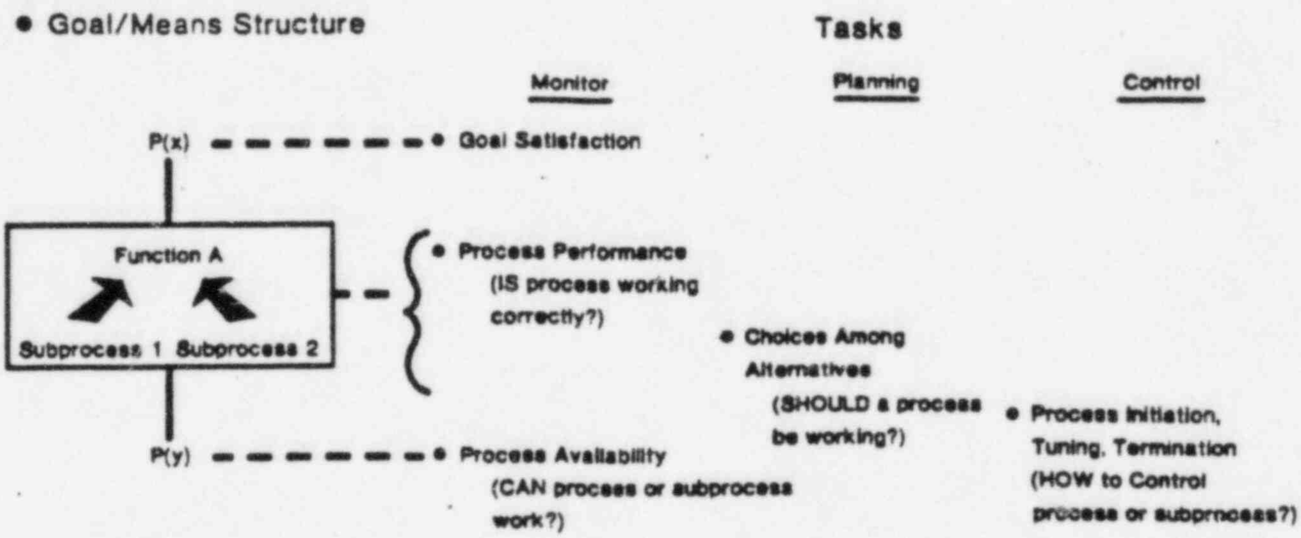

Figure 3.6 -- Structure of the Operator Task Analysis.[5]

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Another aspect is how NPP personnel interact with the process: roles of maintenance, test, calibration, equipment operation, process management. For example, equipment operation refers to direct operation of systems or equipment (the Level 1 controller in the supervisory control structure shown in Figure 3.7). The process management role refers to supervisory control activities that monitor Level 1 control, diagnose problems, coordinate recovery, and plan in cases beyond the procedure base, among other things. These two dimensions of personnel roles will be used to map NPP jobs (from Task 1) onto the goal-means network.

The combination of the function based, goal-means network, the cognitive task analysis and the definitions of operator roles will provide the machinery for assessing the impact of cognitive activities on NPP safety. Westinghouse has developed a goal-means network and a cognitive task analysis for a portion of NPP safety, and will use this as a base for the work in Task 2 as well as for the preliminary structure of cognitive activities and NPP personnel jobs and functions needed for the meeting in Task 1.

Expected Results: Westinghouse will develop a function-based, goal-means network for the portion of the NPP related to the personnel jobs, roles, and functions identified in Task 1. This network will then be used to develop a cognitive task analysis for these jobs, roles, and functions and to categorize and prioritize their role in NPP safety.

3.1.3 Task 3: Identify, Assess, and Select Models of Cognitive Activities

Objective: Identify and assess approaches to modeling cognitive behavior in NPPs for the range of cognitive activities and NPP jobs, roles, and functions identified in Tasks 1 and 2.

Technical Approach: If one thinks of the task of assessing and selecting among alternative models as a problem-to-be-solved, then one can apply the same techniques to this problem as have been used to analyze operator problem solving. Westinghouse has applied decision analysis techniques to better understand how operators make decisions in

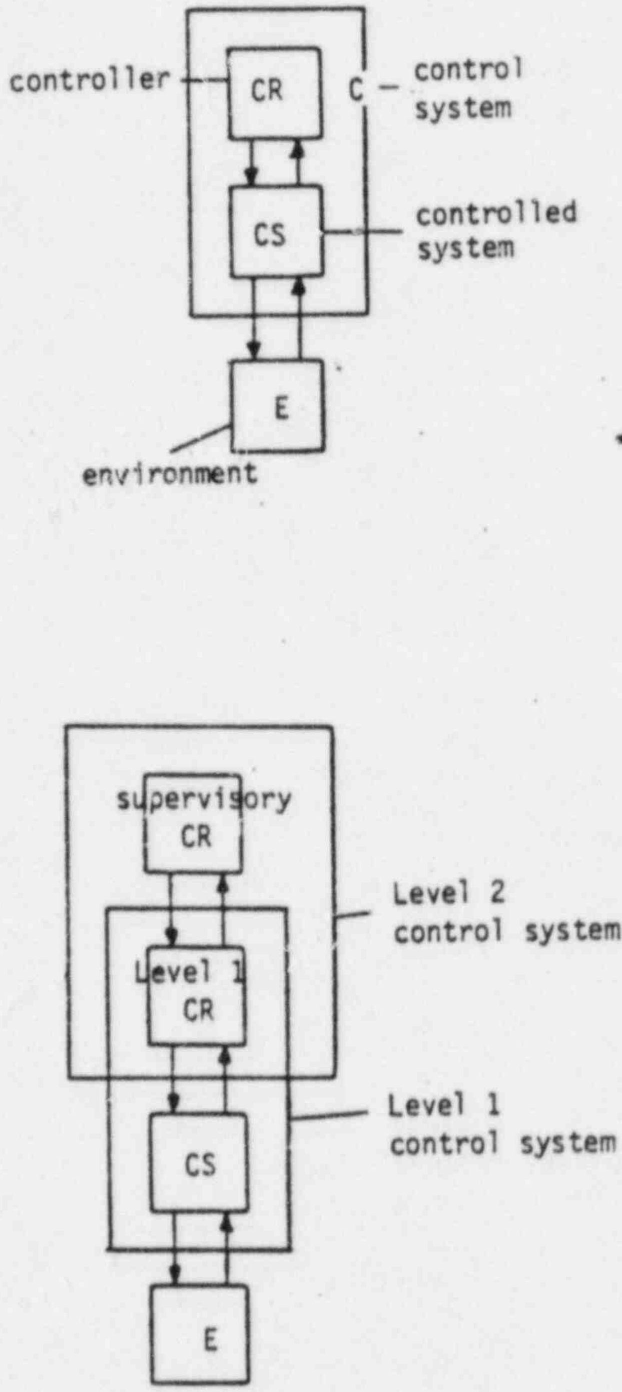

Figure 3.7 -- Basic structures to describe Supervisory Control.

emergencies.[1-4,16] To accomplish the objective of Task 3, Westinghouse will carry out a decision analysis on the decision: choose models of cognitive activities in NPP safety (for the jobs, roles, and functions identified in Tasks 1 and 2) to be developed and evaluated.

Decision analysis is a technique to frame a choice problem so that the decision maker can take into account all available information to more effectively formulate and choose an option that will meet his objectives. In this program, decision analysis will be used to aid a prospective choice (choosing a cost-effective modeling approach for cognitive activities in NPPs) by compiling all of the elements which should be considered, as opposed to the operator decision making studies where it was used to analyze the key elements that went into whatever choices operators had made. This decision analysis will

(1) identify the modeling frameworks, specific models, and modeling tools available for the cognitive activities and NPP jobs, roles and functions specified in Task 1 (Task 3.1);

(2) assess the modeling approaches in terms of the important characteristics of models and the important characteristics for successful application of a model to NPPs (Task 3.3).

In order to assess the important characteristics of models, it is necessary to compare the concepts in and results with different models to empirical data on cognitive activities in NPPs. Task 3.2 will provide this knowledge base (which will also be important in Phase II and III).

3.1.3.1 Task 3.1: Survey Literature on Models of Cognitive Behavior Relevant to NPP Safety

Objective: Survey the literature on models of cognitive activities relevent to the jobs, roles, and functions from Tasks 1 and 2.

Technical Approach: Westinghouse will provide a survey of the literature on models of cognitive behavior relevant to the cognitive activities and NPP jobs, roles, functions identified in Tasks 1 and 2.

Westinghouse is extremely knowledgeable in available modeling approaches because of its own work in models of cognitive behavior[1,8,9,10] and because of participation in workshops and symposia on models of person-machine systems.[7,11,12,19,24] Westinghouse is also extremely familiar with work carried on in related areas such as other process control applications, aerospace, developments in artificial intelligence,[7,25] and developments in models of cognition in general. Westinghouse will search, compile and organize the literature on cognitive models based on this knowledge and experience to provide a broad and up-to-date survey.

Expected Results: An up-to-date bibliography of modeling frameworks, specific models, modeling tools, and model evaluations relevent to NPP jobs, roles, and functions (from Tasks 1 and 2) will be developed and organized around the dimensions of models used in the decision analysis in Task 3.3.

3.1.3.2 Task 3.2: Assess Current Empirical Knowledge on Cognitive Activities in NPPs

Objective: Provide synthesis of current empirical knowledge of cognitive activities in NPP.

Technical Approach: The process of building a model involves an assessment of the behavior the model is meant to address. The cognitive task analysis from Task 2 provides one part of that assessment: the domain-specific decision requirements. The second part consists of the empirical knowledge available on cognitive activities in NPPs and related process control applications. This knowledge base will be used:

- To assess a model's applicability, scope, and validity to the NPP domain
- To aid in the development of specific model in Phase II
- To provide guidance and preliminary data for the evaluation of the model in Phase III

This synthesis of results on cognitive activities does not currently exist although in the last few years there have been studies of operator behavior in NPPs. Westinghouse has begun to develop a unique knowledge base on operator cognitive activities[1] based on the

empirical studies of operator decision making Westinghouse has participated in or conducted[2,3,4,16] and based on studies of decision making from related process industries.[18,19] Westinghouse will further develop this synthesis based on the personnel jobs, roles and functions identified in Task 1, and based on an analysis of other studies of operator behavior (e.g., 21,22,23) to identify results on cognitive activities.

Expected Results: Westinghouse will provide a synthesis of empirical knowledge of cognitive activities in NPPs for the range of jobs, roles and functions identified in Task 1. This knowledge base will be used in Task 3.3 of Phase I and in Phase II and III.

3.1.3.3 Task 3.3: Decision Analysis: Inventory of Approaches to Modeling Cognitive Behavior in NPPs

Objective: Assess alternative approaches to modeling cognitive activities.

Technical Approach: Westinghouse will assess models of cognitive activities as applied to NPPs through a decision analysis approach. Decision analysis is a technique to frame a choice problem so that the decision maker can more effectively choose an option to meet his objectives. Decision analysis will identify the important characteristics of models with respect to successful application of the model to NPPs; it results in a broader, more in-depth formulation and analysis of alternatives with respect to NRC objectives.

The problem of selecting a model of cognitive activities for development and application to NPPs is a multi-dimensional problem with tradeoffs (breadth of coverage versus specificity of predictions), constraints (is the empirical data needed available?), and post-conditions (e.g., complexity of implementation). Decision analysis handles this complexity by

- Identification of the critical dimensions underlying the choice
- Analysis of alternatives in terms of their position in this multidimensional space.

The selection process, then, involves not only the position of a given model in this space, but also the judged relationship between the dimensions themselves and the objective of successful application of the model to NPP safety.

To chart and illustrate how the decision analysis of models of cognitive behavior will proceed, we will first define the term model, then describe some of the important dimensions of models (Table 3.2), and finally analyze some examples of models or classes of models (a set of models that use the same basic concepts) in terms of the dimensions.

What is a model?

1. Models contain concepts and relations among concepts that represent (but do not duplicate) some aspect of the situation of interest. The concepts in a model specify what is really important in producing and controlling behavior in the situation of interest. The concepts suggest what to look at about the situation and how to describe the situation. For example, is a bird more like a gnat or a 747? A model of how flight is possible (a description of functional characteristics) shows that birds and jets both fly based on the concept of lift provided by an airfoil, while a gnat treads air in a turbulent regime.

2. Since models are representations, they carry implicit or explicit assumptions about the situation of interest. This means models vary in scope and applicability to real world tasks.

3. Models can also have some machinery to generate specific and reproducible outputs given some inputs.

These tools can be mathematical, Monte Carlo simulation, and, with the development of AI programming languages, effective procedures. There is an interaction between modeling tools and model concepts/relations in that certain tools may be most appropriate for certain kinds or classes of models and certain concepts may naturally suggest certain kinds of tools.

There are two sets of dimensions to models: (1) characteristics of models themselves (Table 3.2) and (2) important factors for successful application of the models (Table 3.3).

Table 3.2 -- Dimensions of Models*

1. FORMAL-CONCEPTUAL:

Formal models have well specified concepts, relations and machinery to generate model output (e.g., Refs. 8,28,29,30); traditionally, some form of mathematical expression, but with advances in symbolic programming, models also can be expressed as effective procedures.

Conceptual models lack a formal expression which generates a subjective component in the application of the model (e.g., 9,10,34,35). While formalized models are more highly valued in mature sciences; conceptual models by themselves can be extremely useful to identify important factors and general effects, to classify situations, and to provide a framework to apply several formal but narrow scope models to real world situations.

Interactions: This dimension generally trades off with scope and with applicability (formal models may carry simplifying assumptions which can affect the model's applicability to real-world situations).

2. BROAD-NARROW SCOPE:

The range of tasks covered by a model.

Interactions: Often, the broader the coverage of a model, the less formal the expression of the model; this tradeoff is often overcome through the use of a framework conceptual model that holds or structures a variety of (possibly heterogeneous) narrower but more formal models for pieces of the framework. For example, Pew and Baron[17] use optimal control theory as framework to integrate several psychological models of cognitive activities (e.g., goal setting) together and to the process being controlled. Narrow scope models tend to have narrower applicability.

3. APPLICABILITY:

The degree to which model assumptions and concepts match the critical characteristics of the situation-to-be-modeled. For example, most models of choice were developed on well formulated, time bound, finite tasks whereas most real world decision problems have a history, a future (decision horizon), are not well-formulated, require information seeking, etc. As a result, models of choice have limited applicability to dynamic decision making situations like control room emergencies.

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*This is not meant to be an exhaustive list, but to illustrate some of the dimensions to be used in the decision analysis.

Interactions: Correlated with scope; more relevant to causal, rather than correlational, models since the latter's only claim is that model output is sufficiently correlated with behavior.

4. CASUAL-CORRELATIONAL:

Casual models attempt to model the process as well as the outcome; correlational models are only concerned with outcome, if model outputs match human outputs sufficiently then the model is acceptable. One classic example of correlational models is readability indices which make no claim to be model of how people read but only to capture an empirical correlation between characteristics of the material to be read and reading performance.

Interactions: Correlational models are not prescriptive; applicability may not be relevant to correlational models.

5. DESCRIPTIVE-PRESCRIPTIVE (NORMATIVE OR IDEAL):

Prescriptive models specify how tasks should be done; descriptive models codify what people actually do. A classic modeling approach is to begin with a normative model (e.g., expected utility theory),[26] to add descriptions of how people deviate from this standard,[27] and finally to move from description to explanation and prediction through models that address the mechanisms underlying human performance (e.g., psychological decision theory).[28] Another example of this approach is occurring with models of operator data sampling where models for optimal data sampling in manual control were adapted to describe more complex tasks and human deviations[29,30] and finally to models that include the psychological mechanisms underlying human attention.[10,31]

Interactions: Prescriptive models are usually formal, model the task environment, and carry assumptions which can constrain applicability; descriptive models tend to be models of the person (psychological).

6. MODEL OF HUMAN PERFORMANCE (PSYCHOLOGICAL MODELS) OR TASK ENVIRONMENT:
Models can focus on what people do or on what the task demands of people. While modeling approaches may start from one or the other direction, these are really two sides of the same coin. Task factors constrain human performance models and, to be useful, task models must incorporate human deviations. Often, both points of view are needed for successful modeling.

Interactions: Models of task environment are prescriptive and formal; their applicability may be constrained by assumptions.

7. DESCRIPTION-EXPLANATION-PREDICTION:

Descriptive models codify what people do; explanatory models express how or why, i.e., mechanisms; predictive models predict outcomes in new situations.

Interactions: Descriptive models may not explain or predict; explanatory models can describe and predict; correlational models predict without explanation or description. Since explanatory models contain mechanisms that underlie performance, they are psychological, can potentially be formal, and can measure process as well as outcome (e.g., not just time to detection but did operator sample relevant data).

8. BOTTOM UP-TOP DOWN:

In bottom up approaches to modeling human performance measures on simple behavioral elements are combined to produce an assessment of the performance of the whole; examples are traditional human reliability approaches and the kinds of models that can be built with network tools. The problem is what are the units of behavior to be measured and combined. Top down approaches attempt to model larger behavioral units.

9. INCOMPETENCE - COMPETENCE:

Modeling human performance can focus on competence (what makes for good performance) or an incompetence (what problems occur in performance). However, these are basically complementary starting points because a taxonomy of errors implicitly or explicitly supposes a model of human behavior in the task environment. Conversely, models of competence can be elaborated to address failure modes.

10. VALIDITY:

All of these dimensions in some way relate model contents to empirical knowledge on human behavior in the situation of interest. Thus, a critical factor in the assessment is the empirical knowledge base on cognitive activities and the ability of a particular model to capture the relevant empirical results. As a result, an important part of the assessment is a synthesis of empirical results on cognitive activities in NPPs.

To illustrate how these dimensions work in the decision analysis consider one class of models -- multilevel views of cognitive processing (Refs. 32 to 37) are examples of this class.

The key elements of this view are:

- Human processing of information is organized at different levels which operate simultaneously over different time spans.

- Some (presumably "higher") levels modify or control the operations of others.
- Lower levels are capable of independent function.

The result is that there is a multi-level (not necessarily hierarchical) architecture of cognitive processes. Lower level processes, which might be characterized as more ballistic or parameter driven behavior modes, bring efficiencies to behavior (e.g., sterotypical jumps in Rasmussen's step ladder model) but operate only over a limited range of situations. This tradeoff is balanced by other layers of processing, in the multi-level view, which monitor and modify the application of the lower level routines with respect to error correction (are skilled routines proceeding correctly), goal achievement/setting (are skilled routines achieving the desired effects), and responses to novel situations (which includes the ability to distinguish novel from stereotypical situations). If only the upper levels were available, performance would be slow, awkward and demanding as when we learn a new skill. On the other hand, if only lower levels were available, performance would be effective only when the novel or unexpected do not occur. Cognitive architectures that consist of multiple levels combine the advantages of these two kinds of processing while minimizing the disadvantages. Empirical data[1] show that many operational problems are related to a lack of feedback on the success or non-success of recovery actions. From the multi-level view, this is due to lower level routines running on the absence of higher level control based on monitoring changes in process state and goal achievement. Norman and Reason have developed taxonomic models that classify the conditions for failures in lower level skilled routines.[36,37] Breakdowns in executive processes lead to:

- coordination failures (goal or structural coordination)
- errors of omission -- failing to correct/adjust lower level activities

- timing errors -- doing the right thing at the wrong time
- errors of the third kind -- solving the wrong problem
- attention failures -- e.g., disintegration of the visual field, cognitive tunnel vision, navigation problems in display networks (attention failures are one factor that produce human performance problems whose solution seems obvious to hindsight or outside observers).

This class of models is conceptual; it integrates and codifies a large body of knowledge that addresses a broad range of cognitive activities (wide scope, high applicability, high validity). It is a model of human behavior and the underlying mechanisms that produce behavior (psychological model). It directly addresses the kinds of failures that occur in human cognitive processing (addresses incompetence as well as competence) and the mechanisms that produce these failures. Figure 3.8 is an example of one type of error from this class of models.

This class of models has been used to describe performance, and to explain how outcomes were produced,[1-4] and it could be used to predict outcomes (if condition set X exists, then a mode error is "relatively" likely). However, the weakness is the lack of formal specification which makes application of this class of models open ended. As a conceptual model, it can be used to describe NPP personnel performance in cognitive terms and could be deployed as a set of situation templates and factors to be considered during human reliability assessment much as performance shaping factors are used in the THERP approach. It can also function as a framework model to structure more formal models that only cover a narrow scope of cognitive activities. Finally, models from this class (at least some versions and perhaps over a more restricted range of cognitive activities, e.g., slips) can be formalized. For example, Norman's[36] and Reason's mechanisms underlying slips can be parameterized[40] or formalized via AI tools,[41,42] and Broadbent[33] used a specific version to model control of a simulated transportation system.

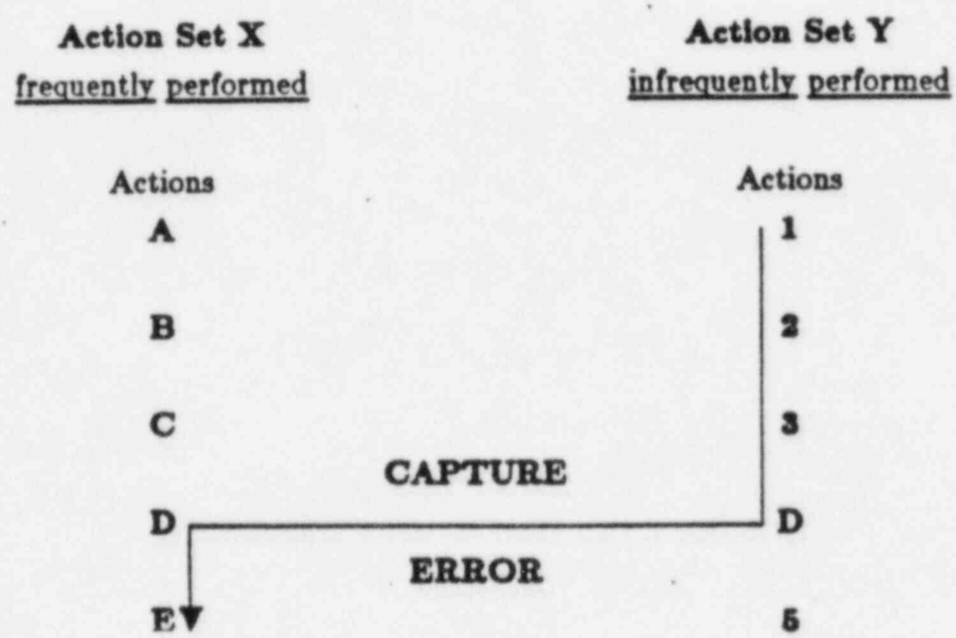

Figure 3.8 -- Illustration of one human error category: capture error (a highly practiced behavioral routine inadvertently takes control from a less established sequence).

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The second set of dimensions apply to factors important for successful use of a model to analyze the contribution of cognitive activities to NPP safety. Table 3.3 contains some of these factors.

It is important to note that, while a successful modeling approach needs to be both accurate and practical, the useability factors are logically secondary to the dimensions of models. If a model is inapplicable or too narrow in scope, questions of useability are moot. The useability factors are a means to perform a finer breakdown of modeling approaches that seem to be equivalent to terms of their potential to accurately predict performance.

The result of the decision analysis along these two sets of dimensions will constitute an inventory of available modeling approaches. Some approaches may be rejected because of their position on some model dimensions, e.g., little applicability or too narrow a scope. Others may be eliminated because the dimensions that characterize these models are judged to be of low priority with respect to producing a successful model for NPP safety. Still others may be rejected on useability factors where cost, scale of effort, special resources, or other factors raise questions about practical feasibility.

To take an example, if the decision analysis reveals that a wide scope, highly applicable, formal model is desirable but that all applicable, formal available models are narrow in scope, then the result might be to develop one type of framework conceptual model that can integrate more formal but narrow scope models and to develop one example of the formal, narrow scope models.

Expected Results: Westinghouse will produce a written inventory of models potentially relevent to cognitive activities in NPP safety based on decision analysis techniques. The inventory will document the models considered in the decision analysis, the dimensions used to characterize each model, the analysis of each model in terms of these dimensions, and the results in terms of models which would or should be pursued in Phases II and III.

Table 3.3 -- Factors Important for Successful Use of a Model

1. Type of Output:

   Description -- Highlight important factors; define the units of behavior whose quality should be determined

   Explanation -- How or why an outcome was produced, e.g., what factors affect diagnosis time distributions or how does data sampling pattern relate to quality of diagnosis

   Prediction -- Given appropriate specification of a situation, what will be the behavior or outcome.

2. Measurement Scale: nominal, ordinal, interval, ratio.

3. Expandability: A model, model class, or modeling framework may be developed and evaluated on only a small range of the cognitive tasks of importance to NPP safety. Can the scope or range of applicability of the model be expanded if the narrower usage is successful?

4. Complexity of Implementation: The resources required for use of a model varies from mathematical implementations in equation,[8,17,30] to a statistical implementation (e.g., Monte Carlo simulation), to AI implementations, to strictly conceptual models.

5. Transfer of Technology: How easily can others apply the model; what tools, expertise, documentation is needed or can be provided to enable or facilitate broad use of the model.

6. Ready Useability of Output: For example, accurate measures of the quality of data sampling behavior may be easily used to evaluate new displays but harder to use to generate reliability numbers on tradiational descriptions of operator tasks.

7. Accessibility of Data Required as Input: Application of many models requires a task analysis.[17] Is the appropriate kind of task analysis for a particular model easily available or easily generated? Other kinds of input data could take the form of error data banks which may be difficult to create or translate from existing data banks. Other models may require information about cognitive activities in NPPs (both empirical and nomative, e.g., how complex or difficult is a given decision or measures of operator workload for samples of the tasks being modeled).

8. Relationship to other (i.e., noncognitive), existing techniques to assess the quality of human performance in NPPs (e.g., THERP, SHARP).

3.1.4 Task 4: Document and Present Results of Phase I Research

Objective: Prepare final written report of Phase I results and formal presentations of these results as directed by NRC.

Technical Approach: Westinghouse will prepare and submit a complete draft of the final report on Phase I research results no later than eleven months after start of the contract and the final report prior to the end of the contract. The final report will include the

- Set of NPP jobs, roles, functions and the working definitions of cognitive activities important to NPP safety from Task 1
- Assessment of the impact of cognitive activities on NPP safety including the goal-means network and cognitive task analysis from Task 2
- Bibliography on modeling cognitive activities in NPP
- Synthesis of empirical results on cognitive activities in NPP safety
- Decision analysis based assessment of alternative modeling approaches and the written inventory of models
- Models selected based on the results of the decision analysis

Expected Results: Complete draft of final report will be submitted for NRC review no latter than eleven months after the start of the contract. The final report will be submitted to the NRC no latter than twelve months after the start of the contract.

The report will be formatted in accordance with the requirements of NRC Manual Chapter 3202.

3.1.5 Task 5: Final Plan for Phase II Research

Objective: Prepare final administrative and technical plan for the development of models in Phase II.

Technical Approach: Based on the results of Phase I research, Westinghouse will modify the Phase II research plan presented in this

proposal to take account of the specific details of the types of models chosen for development in Phase II.

Expected Results: Revised Phase II research and administration plan will be submitted to the NRC no later than ten months after the start of the contract.

3.2 PHASE II: MODEL DEVELOPMENT

Phase II will consist of three tasks. Sections 3.2.1 to 3.2.3 describe the tasks and Figure 3.9 relates them to time.

3.2.1 Task 1: Development of Models

Objective: Develop maximum of two models to describe and predict cognitive behavior in selected NPP jobs, roles, and functions important to safety.

Technical Approach: Development of a model involves four steps:

1. Specification of concepts and relations that will describe, explain, and predict behavior
2. Formalization of these concepts and relations (e.g., equations, simulation, effective procedure)
3. Application of the model to the NPP domain (e.g., task analysis, empirically based parameter estimation)
4. Specification of how the model generates descriptions, explanations, predictions

The relative amount of effort devoted to each area varies depending on the particular models chosen for development. If a conceptual model is chosen, then formalization will be a major task. If a formal model from another domain is chosen, then application of the model to the NPP will be a major task. In any case, each of these four steps is critical to the successful development, evaluation, and eventual use of the model.

Westinghouse has developed conceptual and formal models of cognitive activities in NPPs[1,8,9,10] and has experience using these models to analyze operator performance,[1,3] to assess modifications to existing interface systems,[2] and to measure human error.[12,13]

Expected Results: See subtasks.

Task	Months after Start of Phase II Contract 2 4 6 8 10 12
1. Develop Model	Δ————————————Δ
1.1 Model Concepts/Relations	Δ——Δ
1.2 Formalize Model	Δ————Δ
1.3 Apply Model to NPP Domain	Δ—————Δ
1.4 Implement Model	Δ———Δ
2. Document and Present Results	Δ——Δ
3. Finalize Phase III Research Plan	Δ—Δ
Deliverables:	
Status Reports	(Monthly)
Final Report	Δ
Paper Summarizing Results	(If Requested)
Final Administrative Plan, Phase III	Δ

Figure 3.9 -- Schedule for Phase II.

3.2.1.1 Task 1.1: Model Concepts and Relations

Objective: Specify explicity the concepts and relations needed to describe, explain, and predict cognitive behavior.

Technical Approach: Westinghouse will specify the concepts and relations used to model cognitive behavior. While the modeling approaches chosen for Phase II will already contain concepts and relations, it is important to clearly specify what they are. Furthermore, they may need to be specified in more detail and to be scrutinized in light of the current empirical knowledge base on cognitive activities in NPPs (from Task 3.2, Phase 1).

Expected Results: Specification of the concepts and relations to be used to describe, explain, and predict cognitive activities in the selected areas of NPP safety.

3.2.1.2 Task 1.2: Formalization of Model

Objective: Formalize the concepts and relations so that the model will be able to generate specific descriptions, explanations, and predictions.

Technical Approach: Westinghouse will specify how the concepts and relations operate formally to produce behavior. The techniques for formalization include mathematical models, Monte Carlo simulation, and effective procedures.

With effective procedures, the concepts and relations in the model can be made computable through symbol manipulation procedures in addition to the numeric manipulation possible with more familiar mathematical machinery (effective procedures can be implemented via AI programming languages).

Einhorn and Hogarth[43] provide an outstanding example of how concepts about what are the important factors in cognitive activities (in this case, diagnostic inference) can be transformed into a formal (in this case, parameterized) model.

To take a simple example, suppose the concept of field of attention is applied to operator information gathering. The concept

says that there is a distribution of attention across the field of potentially viewable data and identifies factors that effect whether available data is in the current field of attention. The concept is based on an analogy to a spotlight moving across a spatial field. Formalizing the concept requires specification of exactly how attention varies over the field of potentially available data, i.e., what is the function relating level of attention with distance (if the edge of the spotlight is sharp, then the function takes values of 1 or 0; if the edge of the spotlight is blurred, then the function decreases gradually to zero through the transition zone). Similarly, formalization requires specification of how to measure concepts, e.g., is distance measured as physical distance around a conventional control board, as the number of key-presses or intermediate displays between data points in a computer-based display system, or as psychological distance in a normative or descriptive mental model of the portion of the NPP relevent to the current event.

Models of cognitive activities can also be formalized as effective procedures (which in turn can be implemented in AI programming languages). For example, the conceptual model of cognition underlying Norman's[36,40] and Reason's[37] taxnomic model of human error can be formalized as an effective procedure consisting of schemata and activation rules. The schemata are units of knowledge about the NPP and about control of the NPP; schemata can be activated by data (e.g., a detected change in plant state) or by knowledge (e.g., if the operator knows the event is a tube rupture, then he should closely monitor isolation of the faulted steam generator especially with regard to radiation releases through that steam generator's relief valves). Figure 3.10 contains an example of using this model to analyze how knowledge structures (schemata) are activated, what knowledge structures are activated, and how the activated knowledge structures control observaton and action.

Expected Results. Formal description of the concepts and relations from Task 1.1.

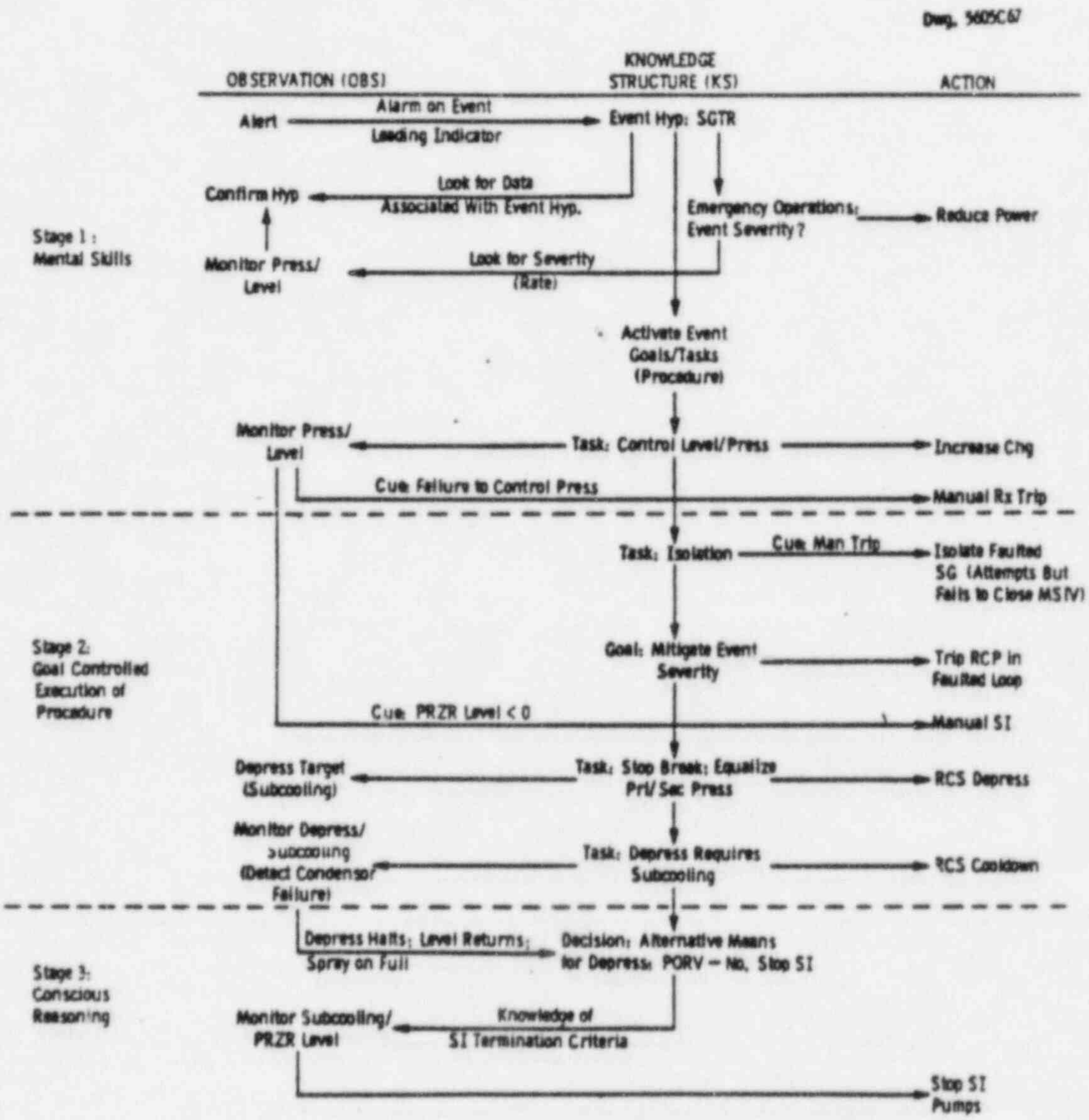

Figure 3.10 -- Decision flowchart of crew response in a simulated emergency (steam generator tube rupture). The format was developed to map how knowledge structures are activated and how they control observation and action.[1]

3.2.1.3 Task 1.3: Application of Model to the NPP Domain

Objective: Apply the model to the relevent aspects of the NPP domain.

Technical Approach: The formal description of the conceptual relations constitutes a model. This task and the next are needed so that this model (from Tasks 1.1 and 1.2) can generate descriptions, explanations, and predictions in the NPP domain. Application of a model to the NPP domain can require (a) a form of description of the relevent NPP tasks (i.e., some form of task analysis) and (b) empirical results, for example, to estimate parameters.

To apply the GOMS model (goals, operators, methods, and selection rules)[44] to the NPP requires an analysis of goals and means for NPP tasks. Note that the goal-means network and the resulting decision requirements from Task 2 of Phase 1 provides this type of analysis (Figure 3.6).

The schema model underlying Norman's[36,40] and Reason's[37] work on errors requires an analysis of the relevent knowledge structures for the NPP job, role, or function under consideration. One source of the relevent knowledge structures is the goal-means network (from Task 2 of Phase 1). Another source is empirical results (from Task 3.2 of Phase 1) on what knowledge structures are active during actual NPP tasks[1,3] (see Figure 3.10 for an example of the knowledge structures active during one simulated emergency).

Another aspect of application is the tradeoff between the formal, applicable dimensions and the scope dimension of models. In general, formal and applicable models have narrow scope. Since building a useful model of complex real-world tasks like NPP safety generally requires a wide scope, there is a problem. Most modeling efforts have tackled this problem by using a modeling framework that integrates narrow scope, heterogeneous, formal models. The Pew/Baron approach to supervising control[17] uses optimal control theory as a framework to integrate diverse models of cognitive activities (e.g., goal setting). Other potential model frameworks are schemata[36,37,40-42] production

systems[44] and the multilevel view.[32-37] One strategy, then, is to develop a wide-scope, framework model and a narrow-scope formal model that is compatable with the framework model.

Westinghouse will use task analysis and the empirical knowledge base, as appropriate to the specific models under consideration, to apply the models to the relevent aspects of NPPs.

Expected Results: A specification of the formal model (from Tasks 1.1 and 1.2) as appropriate for its application to describe, explain and predict the selected cognitive activities for the selected NPP jobs, roles, and functions.

3.2.1.4 Task 1.4: Modeling Tools and Model Implementation

Objectives: Set up the machinery by which data can be input to the model and by which the formal concepts and relations can be used to generate output.

Technical Approach: Westinghouse will implement the model in a form that can generate output (descriptions, explanations, predictions) from a set of input. This machinery can take the form of hand calculations, computerization, computer simulation (e.g., Monte Carlo techniques), or AI programming languages (for effective procedures).

For example, the schema-based class of models can be implemented through blackboard architecture AI programming systems.[41] In fact, this type of AI system architecture was designed explicitly to correspond to the model of data- and concept-driven activation of knowledge structures (schemata).[42,45] This approach is therefore a robust, effective tool for formal expression of these types of concepts.

The implementation of the models must also provide mechanisms to tune and change model parameters and values. Tuning model parameters will be needed to set up the model in the generation of specific predictions in specific situations; changing model parameters is needed to use the model to assess the effects of changes in the human-machine system, e.g., level of skill of the operator or different operator mental models.

Expected Results: An implemented version of the formal model adapted to the NPP domain that is capable of generating model output and capable of being modified to generate output under different conditions.

3.2.2 Task 2: Document and Present Results of Phase II Research

Objective: Prepare final written report of Phse II results and formal presentations of these results as directed by NRC.

Technical Approach: Westinghouse will prepare and submit a complete draft of the final report on Phase II research results no latter than eleven months and the final report no latter than twelve months after the effective date of the Phase II contract. The final report will include the (a) model concepts and relationships; (b) formalization of the model; (c) application of the model to the NPP domain, i.e., the task analysis and/or empirical data used to apply the model to NPPs; and (d) the implementation of the model, i.e., how model output is generated. The report will be formatted in accordance with the requirements of NRC Manual Chapter 3202.

Expected Results: A complete draft of final report will be submitted for NRC review no later than eleven months and the final report will be submitted to the NRC no latter than twelve months after the effective date of the contract for Phase II.

3.2.3 Task 3: Final Plan for Phase III Research

Objective: Prepare final administrative and technical plan for the development of models in Phase III.

Technical Approach: Westinghouse will modify the Phase II research plan continued in this proposal to take account of the specific details of the models developed in Phase II.

Expected Results: Revised Phase III research and administration plan will be submitted to the NRC not later than ten months after the effective date of the contract for Phase II.

3.3 PHASE III: MODEL EVALUATION AND VALIDATION

3.3.1 Task 1: Collection and Analysis of Data

Objective: The purpose of Task 1 is to collect and analyze empirical data to provide a rigorous evaluation/validation of the cognitive model developed during Phase II.

Technical Approach: There are a number of different criteria that can be used in evaluating models. These criteria fall into two classes. The first involves the adequacy of the model as a predictive tool. This includes whether the model generates testable predictions, and the accuracy of the predictions it makes. A second class of criteria relates to the general useability of the model, such as degree of technical expertise required to understand or apply the technique, accessability of data required as input, ready useability of output, etc. While both represent important criteria in evaluating a model, adequacy of predictions is of primary concern. Consequently Phase III will focus primarily on providing empirical evaluation of the predictive adequacy of the model developed in Phase II.

Once model predictions have been validated, useability criteria will be addressed. Consideration will be given to how the output of the model can aid in the assessment of human reliability and in the evaluation of changes to NPP human-machine interfaces.

Westinghouse is highly skilled at the design, conduct, analysis and interpretation of empirical studies of human performance in nuclear power plants. These skills have been developed and honed into efficient forms through evaluations of operator aids,[2] studies of operator performance,[2,3,16] and improved methodologies.[38,39] Westinghouse has control room simulators, an engineering working model for control rooms (a reconfigurable, computer-based test facility for new concepts in control room design hooked to the most advanced available nuclear power plant simulation programs), and a pool of operator and test and calibration instructors as resources to construct efficient and meaningful empirical assessments.

While the specific form of the empirical test of the model will depend on the nature of the model selected, six tasks can be identified. These are:

1.1 Question Formulation: Identifying the major factors that the model predicts should produce observable differences.

1.2 Test Case Selection: Identifying/constructing test situations that fit the assumptions of the model and vary systematically along dimensions identified in Task 1.1 as leading to differences in model prediction.

1.3 Establishing Specific Model Predictions for the Test Cases: Computing specific model predictions based on the particulars of the test cases.

1.4 Performing An Empirical Study: Collecting empirical data on performance in the test cases.

1.5 Analyzing the Results: Performing data reduction and analysis examining performance and the background context, in relation to model predictions.

1.6 Evaluating the Model in Light of Results: Evaluating the degree of match between model predictions and performance, establishing the limitations of model applicability, identifying model refinements that could increase its accuracy, and assessing the useability of the model for nuclear power plant safety analyses.

Each of these tasks, and the different forms they might take depending on model characteristics are described below. The delineation of tasks is not intended to imply a strict linear progression culminating in the performance and analysis of one large empirical study. Depending on the model, Phase III may involve one or more iterations through these tasks, resulting in each case in refinements in model predictions and test. Figure 3.11 gives the schedule for Phase III.

3.3.1.1 Task 1.1: Question Formulation

Objective: To determine the classes of empirical predictions the model makes.

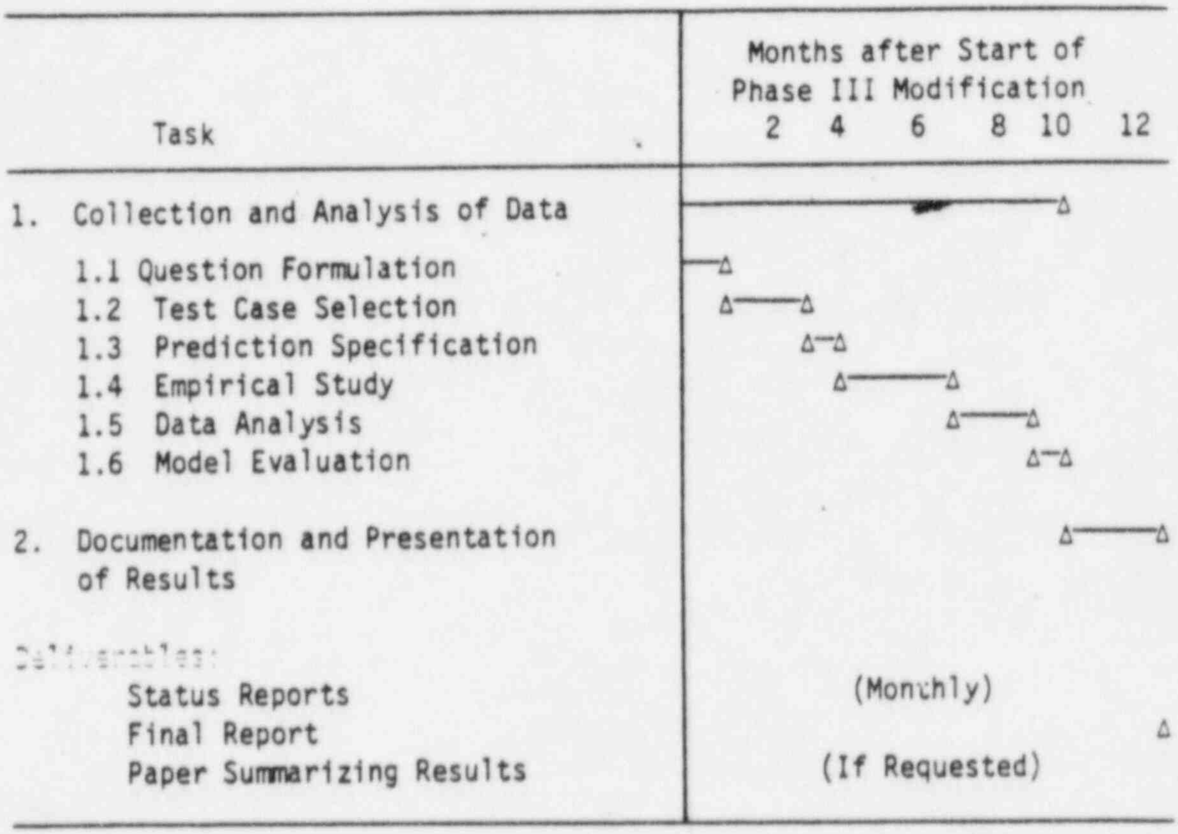

Figure 3.11 -- Schedule for Phase III.

Technical Approach: This involves establishing what situations meet the underlying assumptions of the model, and determining what factors would be expected to lead to different model predictions. For example, most prescriptive models have highly constrained assumptions of applicability. Optimal sampling models[29] may only apply for highly experienced operators under ideal plant conditions. Performance may be expected to degrade as the assumptions are weakened (e.g., less experienced operators, failed indicators).

Factors that would be expected to alter (not necessarily degrade) performance can be obtained from descriptive models that attempt to model psychological processes. These would include task structure variables. For example attentional models might predict that stimulus intensity and distance of stimulus from focus of attention would affect data sampling. Similarly predictions regarding psychological variables could be derived. For example schema models[40,47] would predict that differences in mental models of the plant (e.g., different functional goal hierarchies) or differences in interpretation of a situation would lead to different sampling behavior.

In addition to establishing factors that predict differences across tasks or characteristics of individuals, parameters predicted to remain constant across situations would also be identified. For example, an attentional model may predict that the number of elements sampled from a display remains constant, while the particular configuration of items sampled varies with task goal.

Expected Results: Specification of the empirical predictions made by the model.

3.3.1.2 Task 1.2: Test Case Selection

Objective: To select/design test situations that fit the assumptions of the model and vary systematically along dimensions identified in Task 1.1 as leading to differences in model prediction.

Technical Approach: Particular test events will be chosen in order to create decision situations that accurately represent applicable

cases where the model makes specific predictions. For example if a model posits a relationship between functional field of view and effectiveness of monitoring behavior (i.e., error identification and correction), then events can be developed that measure/test this relationship. It might be studied by simulating operator errors as well as plant malfunctions, perhaps by timing instrumentation or component malfunctions to occur just after a relevant operator action. The test might then measure how supervisors detect and correct the simulated execution errors under different display conditions that affect their field of view. The relation between field of view and monitoring behavior could be mapped out in detail by varying the number and variety of data sources that would have to be integrated for correct state identification.

One advantage of this approach to test event selection is that the classification of problems provides a mechanism to generalize results acrosss events. This is because the decision situations in the test can occur in many particular events, including events that are not part of the test bed. In other words, this approach mitigates against the completeness problem in event selection.

In constructing the test cases a mixed fidelity/focused task approach will be taken. The mixed fidelity or focused task approach to evaluation design is based on the recognition that realistic simulation of all aspects of human performance in complex systems is impractical if not impossible.[11] Instead, the critical features of the work environment with respect to evaluation goals must be identified. It is these critical features, as defined by the concepts or problems guiding the evaluation, that require high fidelity simulation; low fidelity can suffice for other aspects. Furthermore, some low fidelity elements may be deliberately introduced in order to create the problems of interest. For example, to study the effect of stress on user performance, low fidelity features (e.g., time pressure) may be introduced in order to produce (i.e., simulate) the feature of interest in the actual work environment (stress).

When evaluations are based on full scale simulation, the evaluator replicates as much as possible of the actual work envirorment, asks users to behave as if they are in the real system, and then waits for the operational problems of interest to occur. While this can be appropriate for some research goals, such naturalistic observation is inefficient (i.e., expensive, time consuming, and caplable of only weak tests of evaluation objectives). Using mixed fidelity simulation, the evaluator can create the situations of interest by how he selects and constrains the task.

By using mixed fidelity simulation, the evaluator can create more controlled situations that allow for greater precision in the measurement of behaviors of interest. For example one technique for studying information acquisition strategies (e.g., for plant state identification) is to use a "piecemeal" presentation technique, where the subject is presented information sequentially as he requests it. While this represents low fidelity modeling of how operators are normally presented information, it has been successfully used to provide precise information about plant operator's diagnostic strategies.[48,49]

These focused task results can then be confirmed through converging measures of performance derived from a small number of full scale scenarios or from retrospective analyses of performance in actual incidents.[1]

Expected Results: Description of test cases and how they were selected.

3.3.1.3 Task 1.3: Prediction Specification

Objective: Determine precise model predictions for the specific test cases identified in Task 1.2. This may include fine tuning the model based on collection or application of some preliminary empirical data.

Technical Approach: The extent of this task will depend on the computational machinery associated with the model being evaluated. The work involved in this subtask will be most extensive for formal models

with mathematical or AI mechanisms for generating precise predictions. For example, mathematical models of operator behavior (e.g., optimal control model) may involve input of detailed descriptions of plant state parameters, instrument and display information, and potential disturbances required to perform a closed-loop system analysis. In addition, Monte Carlo simulations may be required to generate error rate and response time predictions.[50] Models based on Artificial Intelligence techniques, would require developing knowledge representations describing plant states, and/or the operator's mental model of the plant.[41]

As part of this task empirical "pilot" data may be collected to "fine tune" the predictions of the model. For example, empirical data may need to be collected to define the values of mathematical model parameters such as size of field of attention, or similarity between plant state and classic patterns for transients (e.g., a schema for a steamline break).

Expected Results: Specification of model predictions for the test cases identified in Task 1.2.

3.3.1.4 Task 1.4: Empirical Study

Objectives: Perform an empirical study to provide a rigorous test of the validity of the model predictions.

Technical Approach: While the most appropriate form of empirical study will depend on the particular nature of the model to be tested, it is expected that a controlled study that tests operator performance under simulated conditions will enable collection of data that can provide the strongest test of the model predictions. Controlled simulation conditions enable precise control of the test situation thus allowing multiple replications of the same event. In this way a large data base on performance can be accumulated that provides information on distribution characteristics of performance (e.g., probability of error; distribution of response time) that can be compared to specific distribution predictions of the model (e.g.,

theoretical curves or Monte Carlo results). In addition a controlled simulation environment allows precise manipulation and recording of plant state information that can be used in evaluating the context of specific operator action. Precise measurements of operator actions, and the decision processes behind those actions can also be recorded.

A decision analysis methodology will be employed for data collection and analysis. This method captures not only the details of plant behavior and operator actions (<u>what</u> happened <u>when</u>) but also the context behind the specific behavior (<u>how</u> or <u>why</u> it happened). It has been developed and refined through several recent investigations of operator performance in nuclear power plant control rooms.[1,2,3,16]

A key to the method is the collection of multiple sources of data: a computer record of plant parameter behavior and operator actions, an observer's log of the background for operator actions, and audio-video recording of crew activities. Other sources of data such as eye movement recordings may also be used to provide information about operator information sampling strategies, and decision processes.

An integral aspect of decision analysis methodology is the recognition that process measures of performance are a critical to evaluation. It is not enough to only record the outcome of a given test situation (e.g., performance time; error rate), how the user reaches the outcome provides critical insight into the factors that contribute to successful or unsuccessful human performance. For example analysis of glance duration, amount of information obtained in each glance and transition path, provide information about the operator's cognitive state (i.e., activated schemas) and information sampling strategies.[9,10,51]

Table 3.4 contains an example of outcome and process performance criteria for one operational task in one process control event (simulated nuclear power plant emergency). Data from an unpublished study that included this task[16] illustrates the importance of process measures of performance. In some cases there were no outcome measure violations, but performance was rated only reluctantly acceptable

because some process measure was violated (5 out of 15 cases). In one case (out of 15), there was an outcome measure violation (less than 15 degrees subcooling). Here, the process measures provide insight as to why the outcome failure occurred. In this case, the crew failed to monitor the goal of the task (subcooling) so that, when the event deviated from expected course, the crew failed to detectand correct the deviation for 14 minutes.

Table 3.4 -- Outcome and Process Performance Criteria (Cooldown Task During Steam Generator Tube Rupture)

Outcome Measures:

- Greater than 50 deg subcooling
- Greater than 0 deg subcooling

Process Measures (examples):

- Timely initiation of cooldown
- Select correct target
- Monitor subcooling
- Stop cooldown at target

Tracing the decision process requires trained observers (both domain experts and human performance experts) to produce protocols that describe user decision activities. Other inputs to decision protocols can be information search measures (e.g., eye track records) and, for single user part-task tests, thinking aloud records. These protocols can then be analyzed in terms of the classification of decision situations of interest.

As a result of extensive experience conducting empirical evaluation studies procedures have been developed to efficiently codify the decision process an operator goes through in solving a problem. The computer and observer records are streamlined and focused to capture the

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data of interest. The computer summary provides critical plant parameters and important operator actions as a function of time. The observer's log is a pre-formulated decision flowsheet customized for the event and designed to capture those aspects of control room activity that did not appear on the computer record. The focus is on the background for operator actions (e.g., when did they diagnose the problem, what were their intermediate hypotheses, how did the crew work together) including the diagnosis process, planning strategies, and control action sequences.

Westinghouse has outstanding facilities for controlled data collection on power plant control room operations. In addition to the availability of nuclear power plant training simulators that model current power plant control rooms, Westinghouse has developed an Engineering Working Model (EWM) that is designed to test innovative concepts for advanced control rooms. The EWM includes reconfigurable CRTs and flat-panel display arrangements to accomodate simulation of various control and presentation layouts. It also includes a power plant simulator for realistic modeling of transient conditions and realistic response to operator action.

An additional resource available is a pool of operator and test and calibration training instructors that can provide operations expertise. The instructors can contribute as expert consultants in designing test cases; they can serve as expert observers in monitoring and interpreting crew performance as part of the empirical evaluation; and they can serve as a subject pool for evaluating expert decision performance.

In the case that the data will be collected at a utility site and/or that NPP personnel will be employed as part of the evaluation study, Westinghouse will submit one copy of a written statement of need and justification to the NRC Project Officer for his written approval, and one copy to the NRC Contracting Officer. If the Project Officer determines it appropriate, Westinghouse shall also submit a written request through the NRC Project Officer, to the Office of Management and Budget (OMB) for OMB's clearance.

Expected Results: A rich set of empirical data on operator performance ready for data reduction and analysis that addresses the validity and useability of the model.

3.3.1.5 Task 1.5: Data Analysis

Objective: Providing a compact presentation of the results of the study in relation to model prediction.

Technical Approach: The concepts and units of the model will provide the framework for analysis of operator performance in the evaluation study. For example if the model relates errors in performance to properties of action classes (e.g., how well learned it is, similarities to other actions) and properties of the triggering situation (e.g., familiarity, similarity to other situations that call for different actions) then performance would be analyzed with regards to those categories.

The intent of the analyses will be to elucidate the conditions under which the predictions of the model are most accurate and where they fall short. In addition to measures of overall model accuracy, primary emphasis will be placed on providing a fine grained analysis of operator action in relation to background conditions.

The results will include descriptive statistics summarizing the process and outcome measures collected as they relate to the classes of performance relevant to the model. This will include analyses of: (1) operator performance times, (2) error (or near error) occurences, (3) process measures (e.g., eye tracking results), (4) detailed analysis of the background behind operator actions and problems.

Statistical analyses of the accuracy of prediction of the model will also be computed as appropriate. In cases where the model makes clear predictions of differences in performance among classes of events (e.g., that errors will more often occur for infrequent action classes that have overlapping properties with highly practiced action sequences than those that do not) then statistical tests of the predictions will be performed.

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If the model predicts probability of success in diagnosis or state identification, then diagnostic accuracy will be computed based on a formal accuracy analysis.[52]

Goodness-of-fit tests will be performed for model predictions that take the form of precise mathematical relationships. For example, models that specify particular functions relating variables such as degree of similarity to familiar situations (well established schemas) and probability of "capture" errors, or models that specify particular error or response time distribution forms.

Expected Results: A complete presentation of raw data and summary statistics describing operator performance in the study as it relates to the adequacy of model predictions.

3.3.1.6 Task 1.6: Evaluation

Obective: The purpose is to employ the results of the study to evaluate the predictive adequacy and useability of the model. This includes establishing the limitations of model applicability, identifying refinements that could improve model accuracy, and establishing how the model can interface with, and contribute to the assessment of human reliability.

Technical Approach: The results will be used to evaluate the usefulness of the model as a predictive tool. The extent to which the model accounts for the results of the study will be evaluated. This includes not only whether the predictions of the model are accurate, but also the completeness of the model in accounting for observed performance. For example, optimal sampling models may acccurately predict rate of sampling but provide no insight into other aspects of sampling behavior such as what can be expected to be sampled, or what the data-acquisition time for any given sample can be expected to be. In areas where the model falls short, potential additions/modifications to extend its depth (i.e., completeness in accounting for observed performance) or its range of applicability (i.e., the range of situations it handles) will be considered. The results of the analysis

will be employed to reassess and specify the usefulness and range of applicability of the model.

Once accuracy of model predictions have been validated, the useability of the model as input to nuclear power plant safety analysis will be evaluated. A model may contribute to safety analyses in a variety of ways. For example, depending on the characteristics of the model, it may be used to assess the safety impact of proposed changes to man-machine interfaces prior to implementation (e.g., through simulation); alternatively (or in addition) it may generate human reliability estimates than can feed directly into propabilistic risk assessment methodologies. How readily and reliably the output of the model can be used for safety evaluation will be specified.

Expected Results: Evaluation of the adequacy of the model as a predictive tool. Included will be a reevaluation of the range of applicability of the model, identification of possible refinements to increase model accuracy and scope of applicability, and reassessment of the useability of the model as input to power plant safety analysis.

3.3.1.7 Expected Results for Task 1, Phase III

The results of the empirical study are expected to provide a rigid test of model validity/useability. The study should generate information on the usefulness of the model in predicting performance, and its range of applicability. Information on how readily and reliably the output of the model can be used for safety evaluation, including probabilistic risk assessment methodologies will be provided. In addition, the results are expected to provide the basis for further model refinements, and significantly extend the empirical database on operator performance.

3.3.2 Task 2: Document and Presentation of Results

Objective: The purpose of this task is: (1) to prepare a written report of Phase III results and (2) to make formal presentations of these results as directed by the NRC Project Officer.

Technical Approach: Westinghouse will prepare and submit a completed draft of the final report on Phase III research results no later than eleven months, and the final report no later than twelve months after the effective date of the contract modification for this optional Phase III.

The final report will include descriptions of:

- The major factors predicted by the model to affect performance.
- The test cases employed in the study and the bases for their selection.
- Model predictions as they apply to the test cases.
- The methodology employed in the empirical study.
- All raw data and statistical summaries of the results of the study.
- The implications of the study results for the usefulness and range of applicability of the model(s).
- How the output of the model can interface with and contribute to nuclear power plant human reliability assessments.

Expected Results: A complete draft of the final report no later than eleven months, and a final report within twelve months of the effective date of the contract modification for this optional Phase III.

4. SCHEDULE AND DELIVERABLES

The schedules for each phase of the program are given in Figures 3.1, 3.9, and 3.11. These figures also show the project deliverables. The following listing gives the deliverables for the three phases.

PHASE I

- Minutes of Initial Meeting (Task 1)
- Results of Assessment of Impact of Cognitive Activities on NPP Safety (Task 2)
- Inventory of Model Approaches (Task 3)
- Final Report, prepared in accordance with NRC Manual Chapter 3202 (Task 4)
- Paper Summarizing Phase I Research and Results (if requested, Task 4)
- Final Administrative Plan for Phase II (Task 5).

PHASE II

- Final Report, prepared in accordance with NRC Manual Chapter 3203 (Task 2)
- Paper Summarizing Phase II Research and Results (if requested, Task 2)
- Final Administrative Plan for Phase III (Task 3).

PHASE III

- Final Report, prepared in accordance with NRC Manual Chapter 3203 (Task 2)
- Paper Summarizing Phase III Research and Results (if requested, Task 2).

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5. POTENTIAL PROBLEM AREAS

Westinghouse foresees no potential problem areas in accomplishing the objectives and tasks in the program.

6. PROGRAM MANAGEMENT, PERSONNEL, AND RESOURCES

6.1 PROGRAM MANAGEMENT AND PERSONNEL

The proposed program will be carried out at the Westinghouse R&D Center by the Applied Sciences Division, Dr. D. R. Muss, Manager. (See Figure 6.1.) Management responsibility for the program will be assumed by the Human Sciences Department, Dr. L. F. Hanes, Manager.

The project organization is shown in Figure 6.2. The Program Manager will be Dr. Hanes. Dr. Hanes has over 25 years of management and research experience in applied behavioral science, human factors, and training programs. For the past 12 years, Dr. Hanes has been managing a growing group of human factors professionals in the study of user-system interface issues for military, industrial, and commercial applications. Since joining Westinghouse, he has managed contract programs for the National Science Foundation and the Electric Power Research Institute (EPRI). In addition, he has managed many subcontracts at the R&D Center for which the prime contract was held by a Westinghouse division. Funding agencies for these projects included the U.S. Air Force, Department of Energy, EPRI, and Department of Justice. His direction of the project assures full management support to achieve the goals of this program.

The Principal Investigator for this program will be Dr. D. D. Woods, Senior Engineer in the Human Sciences Department. Dr. Woods received his Ph.D. in Cognitive Psycholoy from Purdue University and his research focuses on applying knowledge from cognitive science to model, develop, and evaluate person-machine systems in process control applications. Major research projects related to nuclear power plants have included studies of operator decision making in nuclear power plants for both simulated and actual emergencies (5 actual and 99 simulated emergencies in four separate studies), models of operator

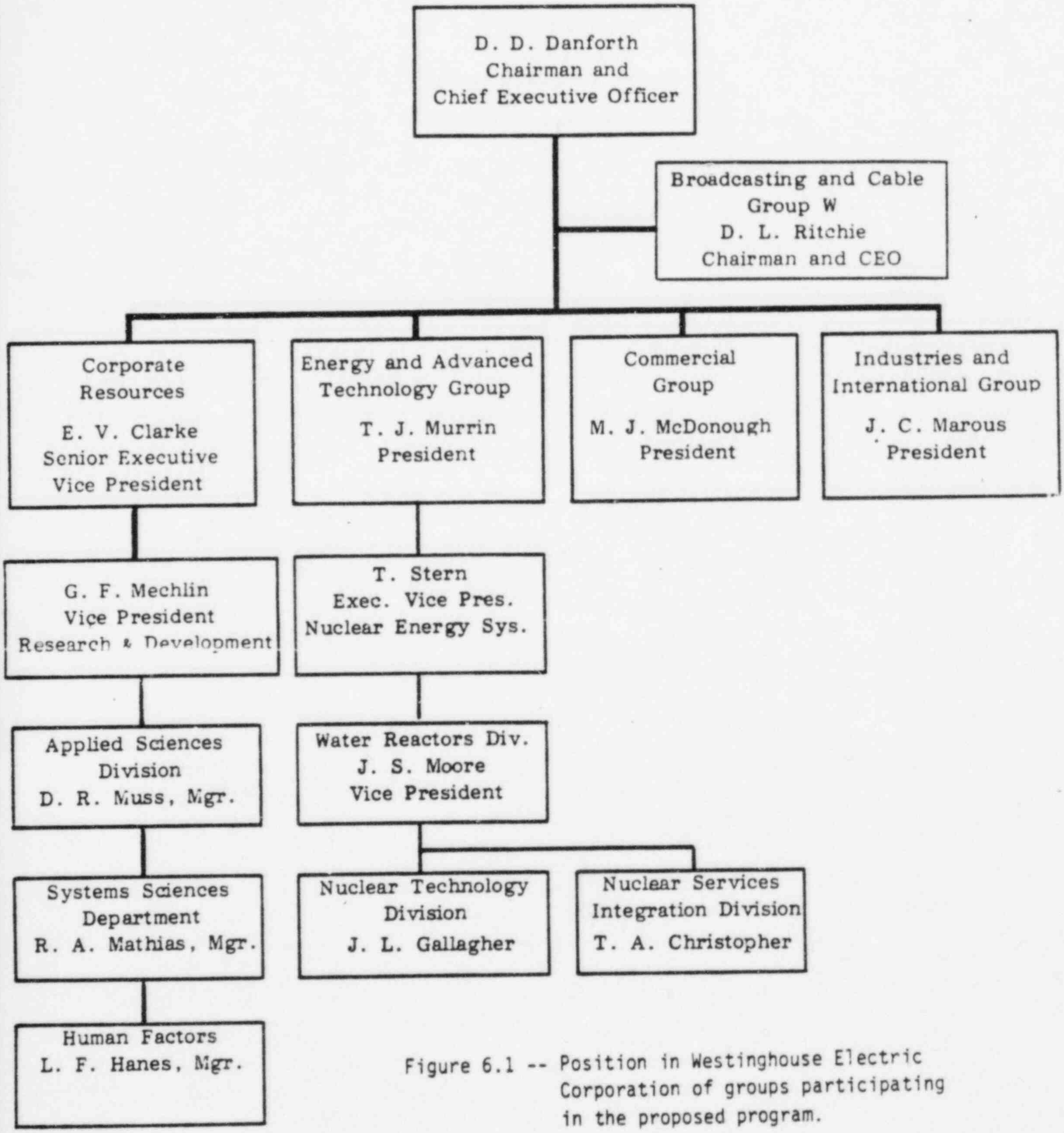

Figure 6.1 -- Position in Westinghouse Electric Corporation of groups participating in the proposed program.

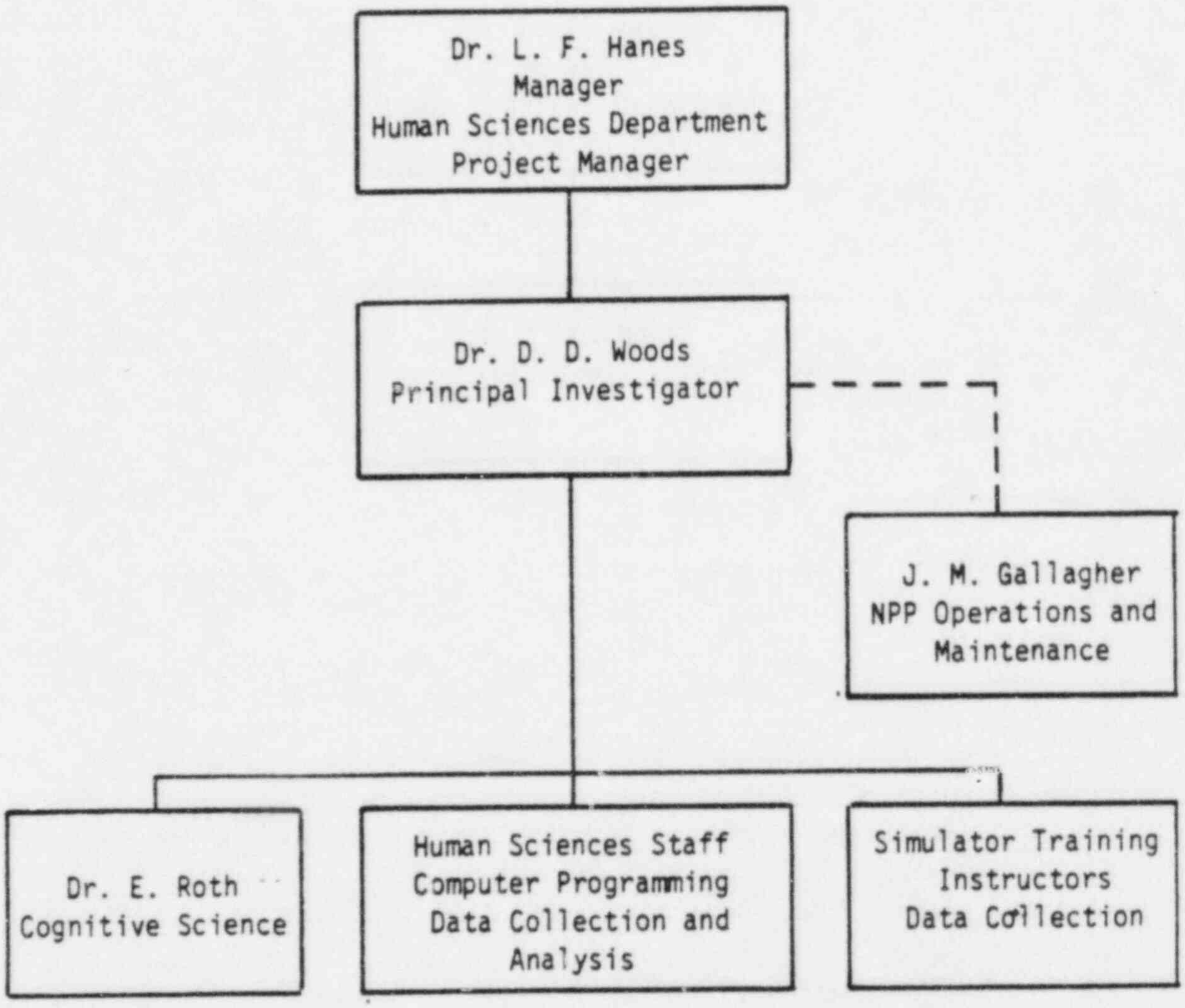

Figure 6.2 -- Program organization.

cognitive behavior (signal detection analysis of operator's alerted-monitor role, supervisory control, knowledge-driven data sampling), principles and concepts to enhance human-computer interaction (including visual momentum, advanced pattern recognition displays, techniques to display data in context, and advanced alarm management techniques), development of a technique to determine the operator's decision-making requirements in power plants (Cognitive Task Analysis), evaluation of operator aids (Safety Panel Evaluation Project), and development and evaluation of decision support systems (both AI and Disturbance Analysis Systems).

Dr. Woods has been principal investigator on research projects funded by EPRI (Safety Panel Evaluation Project) and internally funded projects. He has a unique combination of knowledge and experience with nuclear power plant person-machine systems and emergency operations, as well as formal training and scientific research in cognitive psychology.

Dr. E. Roth, Senior Engineer in Human Sciences, will contribute to the program. Dr. Roth received her Ph.D. from the University of Illinois in Cognitive Psychology. Her basic research concerns how people represent and organize their knowledge of a domain, and the effects of knowledge representation on cognitive processes (e.g., problem solving, decision making).

Dr. Roth has participated in a study of nuclear power plant operator decision making during simulated emergencies (60 simulated emergencies), in the design of an information system to support nuclear power plant operations staff in tracking and assessing the impact of changes in plant component status on technical specifications and safety system operability, and in the design and evaluation of computer-based training aids for nuclear power plant operations and maintenance staff. Dr. Roth has also worked extensively in the design and evaluation of user interfaces for AI systems (e.g., expert systems, natural language interfaces).

Mr. J. M. Gallagher, Consulting Engineer in the Westinghouse Nuclear Technology Division, will provide support in Task 2 of Phase I:

assessment of the impact of cognitive behavior on NPP safety. Mr. Gallagher has more than 25 years of experience in NPP controls and instrumentation. He was principal investigator on the EPRI-sponsored scoping and feasibility study for disturbance analysis and surveillance systems; he is currently leading Westinghouse's continuing efforts in this area. He was a participant in the workshop on modeling of the cognitive behavior of NPP operators.

During Phase III of the program, other members of the staff of the Human Sciences Department will provide support in computer programming, data collection, and data analysis. In addition, training instructors from the Westinghouse Nuclear Services Integration Division will be utilized to aid in any data collection needed in Phase III.

6.2 KEY PERSONNEL

The key personnel for this program are Drs. D. D. Woods and L. F. Hanes. This program will be Dr. Woods' primary assignment. Although he will be assigned other projects in related areas, this program will have first priority on his time. Dr. Hanes has approximately 50 percent of his time committed to other programs during the period of this program. Since his proposed level of participation in the program is between 15 and 20 percent, no conflict will exist.

Table 6.1 presents the personnel and consultant resources to be applied to the program by Phase and Task. Computing support is planned for Task 1 in both Phases II and 111.

6.2.1 Consultants

Westinghouse expects to engage consultants in Phases II and III of the program. The consultants will be experts in the particular model chosen in Phase I. The consultants will act to advise Drs. Woods, Hanes, and Roth in the development of a specific model and in the generation of model predictions. The particular consultants cannot be identified at this time since the selection will depend on the particular model chosen in Phase I.

Table 6.1 -- Resources Planned for the Program (Entries in Table are Person-Hours)

	Tasks in Phase I						Tasks in Phase II				Tasks in Phase III		
Resources	1	2	3	4	5	Total	1	2	3	Total	1	2	Total
L. F. Hanes	50	60	80	70	40	300	155	80	50	285	150	100	250
D. D. Woods	60	118	680	70	40	968	1009	140	60	1209	1305	150	1455
E. Roth	20	30	420	80		550	699	80	40	819	850	150	1000
J. M. Gallagher		173				173							
Human Sciences Personnel											1100		1100
Training Instructors											240		240
Consultants							600			600	240		240
Total	130	381	1180	220	80	1991	2463	300	150	2913	3885	400	4285

Table 6.2 -- Expected Travel (Between Pittsburgh and Washington) for Meetings

Task	Scheduled	At NRC Request
Phase I		
Task 1	1	
Task 2	1	
Task 4		2
Task 5	1	
Phase II		
Task 1	1	
Task 2	1	2
Task 3	1	
Phase III		
Task 1	1	
Task 2	1	2

6.2.2 Travel

The trips identified in Table 6.2 are anticipated. Other trips may be necessary for data collection in Phase III, Task 1. Travel by Westinghouse personnel is included in the overhead charges. Even so, prior to any trip taken during the period of performance under this contract, Westinghouse will obtain verbal or written approval of the NRC Project Officer.

6.3 BACKGROUND OF PROFESSIONAL PERSONNEL

Information on the experience, educational background, and publications of program personnel is given in the following pages.

7. RELEVANT EXPERIENCE, CAPABILITIES, AND FACILITIES

7.1 RELATED EXPERIENCE

The Westinghouse Human Sciences Department has performed many programs that relate directly to the proposed effort. The experience gained in accomplishing these projects by personnel identified in this proposal provides the foundation to successfully perform the proposed work tasks.

7.1.1 Advanced Control Room

This program is a four year effort to develop, test and validate a conceptual design for an Advanced Control Room (currently in second year). The design is based on a goal-means network knowledge representation that was derived from a function based analysis of NPP safety and availability and on a cognitive task analysis. The design explicitly addresses how to improve and make more reliable operator monitoring, planning, decision-making, and execution. The conceptual design will be implemented and tested in 1985 and 1986 on the Engineering Working Model to determine the improvements in operator performance, plant availability and safety.

7.1.2 Disturbance Analysis and Surveillance System Scoping and Feasibility Study

This project, sponsored by Electrical Power Research Institute, had two objectives:

- To establish the scope of the disturbance analysis and surveillance system (DASS) for a plant-wide availability and safety application,

- To establish the appropriate engineering and design methods for creating the plant-specific models.

The first objective required the identification of operational crew needs under disturbance situations, the development of critical safety and availability requirements, and the conceptualization of functions to be performed by DASS. The second objective required the formulation of the DASS engineering process and the associated engineering costs, and the translation of the DASS concept into a computer system structure with an estimate of the hardware and software costs.

The identification of operational crew needs was accomplished by characterizing the operational crew in terms of the "systems manager" role and "maintenance" role, and relating these roles to a model for human data processing. This model characterizes the operator behavior in three levels of increasing complexity with respect to the decision-making process, and facilitates the identification of various resources for decision-making aids as they relate to these three levels of complexity of human data processing.

This model shows that the principal use of DASS is to provide support to the operator when he is acting in the systems manager role. Support to the operator in the maintenance role is provided more from the aspect of information coordination than in the form of unique DASS functions.

To support the systems manager role for the control room operators, a top-down structure of plant functions and systems was developed around the concept of the critical plant functions. This structure is organized from the point of view of the operator's overall objectives in satisfying the needs of plant availability and public safety:

- To maximize the plant's capacity factor
- To prevent radioactive release.

The operators' responsibilities then are to maintain the process parameters which drive the plant's control loops within their required limits as specified by the technical specifications, the operating instructions, and so forth. To do this, the plant is designed with systems which have certain designed functions which support and can alter those process parameters and equipment and components which support and make up the plant's systems.

This hierarchy forms the basis for constructing the interface between the plant and the operator for diagnosing problems and suggesting means for overcoming them.

Using this hierarchy, a set of 14 DASS functions was formed which outline the tasks that a DASS can do to support this interface. The tasks have been arranged in their perceived order of importance to the operator in aiding his decision-making activities relative to plant availability and public safety. In essence, the philosophy is that preventing disturbances from occurring in his most important activity, followed by terminating them, followed by mitigating their consequences.

These DASS functions are modular in the sense that once certain basic (overhead) functions have been implemented, each remaining function can stand on its own, in terms of both the engineering effort required as well as the perceived benefit to the operator. This was done intentionally, to allow a phased implementation of a DASS and to minimize the effort required to make future changes to the functions initially implemented.

7.1.3 Westinghouse-Framatome-CEA-EDF Disturbance Analysis and Surveillance System: Functional Design

This joint program, completed in 1984, specifies the functional design for a Disturbance Analysis and Surveillance System. Follow on efforts will develop a breadboard implementation for testing to determine the benefits provided by the system. The design is based on a goal-means representation of a set of NPP functions involved in safety

and availability and on knowledge of successful strategies for human monitoring, diagnosis planning, and fault management.

7.1.4 Operator Action Program

Westinghouse participated in a joint program with Commissariat l'Energie Atomique, Electricite de France, and Framatome to measure and evaluate operator response during simulated accident conditions. Data on operator response during emergencies was collected at the Zion, Illinois and Bugey, France training simulators. A decision analysis methodology was employed to capture not only the details of plant behavior and operator actions (what happened when), but also the context behind specific behavior (how and why it happened). Structured protocols detailing the background for operator action, including underlying cognitive states and processes (e.g., when did they diagnose the problem, what were their intermediate hypotheses, what plans and strategies were developed, how did the crew work together) were obtained, allowing identification of the sources of operator problems when they occurred. This work served to expand the empirical data base on operator decision making.

7.1.5 Operator Decision Behavior During the Steam Generator Tube Rupture at the Ginna Nuclear Power Station

A method called decision analysis was applied in order to describe and better understand operator behavior during the steam generator tube rupture event (SGTR) at the Ginna nuclear power station. The purpose of the analysis was to better understand how operators perform in emergencies. The decision analysis method is built on a simple conceptual framework that describes the decision making process in terms of four decision stages: detection, interpretation, control, feedback. This conceptual framework was used to produce a timeline of crew decision behavior, decision flowcharts which highlight the major components of the decision process, and worksheets which probe important decisions in greater depth. A major result of the

retrospective analysis of the Ginna event is that support for operator knowledge based behavior is required in emergency operations.

7.1.6 An Evaluation of Safety Parameter Display Concepts

In this project, sponsored by Electric Power Research Institute, two experimental concepts for a Safety Parameters Display System (SPDS) were evaluated to assess benefits and potential problems associated with the SPDS concept and its integration into control room operations. Participants were licensed utility operators undergoing retraining on a nuclear power plant simulator. Both quantitative and qualitative data were collected and analyzed on crew response to seven simualted accident conditions.

Data on operator decisions and actions were organized into timelines. Analysis of the timelines and observations collected during testing provided important insights about the potential impact of the SPDS concept on control room operations. The study demonstrated that 1) the safety panel prototypes can provide access to information needed during crew decision-making, but attention must be given to the more general requirements of the crew and to the integration of the panels with procedures, training, and coventional control room instrumentation; 2) the key decision analysis method developed for this project is a useful evaluation tool; and 3) a training simulator can be used during a normal training program to evaluate safety panel concepts.

7.1.7 EPRI Display Guidebook

The Westinghouse Human Sciences Department recently began a contract from the Electrical Power Research Institute to develop a handbook to provide guidance in the optimal design of displays for electrical system control centers. The project will develop a handbook based not only on the traditional human factors display design rules, but also provide a set of general design principles which will allow the guidebook user to deal with design problems which are beyond the limits of the normal design rules.

7.1.8 EPRI Heat Stress Management

The Electric Power Research Institute is sponsoring a project with the Human Sciences Department of the Westinghouse Research and Development Center entitled "A Program for Preventing and Mitigating Heat Stress for Nuclear Power Plant Workers" (RP2166-5). The objective of the project is to provide nuclear utilities with an integrated approach to heat stress management that can be adapted to each particular facility. The emphasis is on measurement and evaluation of environment conditions, and identification of countermeasures to mitigate the effects of heat stress. The output of the project is a handbook on heat stress management.

7.2 WESTINGHOUSE EXPERIENCE IN THE ANALYSIS OF REGULATORY SYSTEMS

The Human Sciences section of the Westinghouse R&D Center has not participated directly in U.S. Nuclear Regulatory Commission sponsored research. It has considerable experience in the modeling, design and evaluation of the person-machine component in nuclear power plant systems. Section 7.1 contains descriptions of some of these projects.

7.3 WESTINGHOUSE R&D CENTER FACILITIES

As one of the select handful of industrial research and development organizations in the world, the Westinghouse R&D Center has figured prominently in the technological accomplishments of the nation and of the world. In so doing, the Center's scope of activity has steadily broadened to touch on every. major discipline that bears upon its five strategic technical areas (see chart on next page).

The Center's outstanding staff of scientists, engineers, and support people continue to focus on two major objectives:

1. To understand scientific phenomena, and

Physical & Biological Sciences	Materials	Electronics	Engineered Systems	Information Sciences
Biological and Environmental	Metallurgy	Data Acquisition and Processing	Experimental Engineering Science	Mathematics
Ionized Gas and Thin Film Technology	Reactor Materials	Integrated Circuits	Electromechanical Systems	Artificial Intelligence
Low-Temperature Technology	Chemical Technology	Power Electronics	Engineering Services	Computer Aided Engineering
Surface and Solid State Phenomena	Ceramics	Electronic Systems	Directed Beam Systems	Human and Business Sciences
	Crystals		Advanced Energy Systems	
	Organic Materials			

The Westinghouse R&D Center's staff strives for excellence in five strategic technical areas to meet the needs of its customers.

2. To transform that understanding into advanced technologies for use in creating new products and processes, improved materials, and more-sophisticated systems.

Through successful pursuit of these goals, the R&D Center's staff members have earned international renown for their pioneering and engineering achievements. They have, for example, led the way in the study of the physics of semiconductors, in the refinement and application of laser systems, in the miniaturization of electronic components for defense applications, and in superconductivity and ion implantation. More recently, they have undertaken major programs in artificial intelligence (AI) for application in expert systems, speech recognition and synthesis, and intelligent, adaptive control systems.

Geographically, the eight buildings of the R&D Center nestle on a 150-acre site in a residential suburb 12 miles east of downtown Pittsburgh. Here nearly 700 chemists, physicists, electrical engineers,

metallurgists, computer technologists and others combine their talents to synergistically keep pace with, and often to set the pace for, today's explosive technological growth.

One of the most important roles of the Center's staff is to respond to the needs of the Corporation's operating divisions. Generally, this means applying the technology available at the Center to a specific need of the division. This would include, for example, the Process Diagnostic System, a Westinghouse-proprietary software program, being used as a diagnostic tool for water-chemistry problems and representing a valuable new AI asset for the entire Corporation.

Another role of the Center, as the Corporation's central R&D organization, is to provide access to those tools and expertise that would be too expensive for any one operating division to acquire, such as the $5-million semiconductor processing facility and the $3-million materials characterization laboratory.

The third major role of the R&D Center is to transfer technology from the Center to an existing operating division or to form the basis for an entirely new operation. A recent example would be the Plasma Center located at Waltz Mill, Pennsylvania, that was formed in 1983 as part of the Corporation's Applied Products Division.

To perform successfully in these three major roles the technical staff at the R&D Center needs to anticipate the often tortuous technology paths of the future, so that the latest technology can be applied to the needs of the operating divisions as required.

Closely related to that anticipatory role is the need to look even further down the technology road to identify important new fields of endeavor, which may involve the aggressive pursuit of opportunities that require totally new business approaches for Westinghouse as a corporation.

The Center's staff also performs considerable research and development for outside agencies.

Approximately 40 percent of the total staff of 1700 at the Center are professional scientists and engineers, including more than

500 with advanced degrees. At their disposal are the finest equipment and facilities available, including a fully equipped Computer Center, which houses the Center's Sperry 1100/81A Computer. Remote stations provide the entire staff with direct access to the main computer at any time, assured of a printout within 3 minutes after the program has been submitted.

The R&D Center library maintains a collection that exceeds 70,000 volumes of technical books and bound periodicals. It subscribes to 1000 scientific journals and provides an extensive collection of bibliographic tools for literature searches.

Enhancing the intellectual stimulation at the R&D Center are numerous conference rooms and a 250-seat auditorium, where members of the Center's staff attend frequent symposia featuring prominent industrial and academic researchers from throughout the world.

Outstanding staff, the finest facilities, and top-caliber management -- all carefully selected to ensure that the Westinghouse R&D Center will continue to play a key role in the understanding of scientific phenomena and the application of that understanding to advanced technologies for use throughout the world.

7.4 LIBRARY AND LITERATURE SURVEY FACILITIES

The Westinghouse R&D Center has one of the finest private technical literature collections in the nation, and it is open 24 hours a day to employees. This collection comprises some 70,000 volumes, plus subscriptions to over 1000 scientific and technical journals.

The library maintains a cumulative collection of many of the worlds leading abstract journals, including Engineering Index, Applied Science and Technology, Computer and Control Abstracts, Dissertation Abstracts, Electrical Engineering Abstracts, Mathematical Reviews, and Research Abstracts. The professional staff of the library are both scientifically qualified and experienced in the use of all databases to which we have access. They are also equipped to handle the acquisition of all references needed for review. For performing literature reviews,

the library has on-line access to numerous computer-based databases, including:

- DIALOG (Lockheed Information Retrieval System) which supports automated searching of more than 40 specific databases such as the National Technical Information Service, Psychological Abstracts, and Dissertation Abstracts.
- BRS (Bibliographic Retrieval Services) which supports similar access to many of those listed for DIALOG, plus additional databases.
- SDC (Systems Development Corporation) which supports similar access to an additional 50 databases, including the Smithsonian Science Information Exchange and the Derwent World Patents Index.
- Defense Technical Information Center (DTIC), which contains two major databases of interest: (1) the Work Unit Assignment Summary (DD Form 1498) database which documents current DOD-sponsored research projects even prior to report production, and (2) the Technical Reports (DD Form 1343) database which covers classified technical reports in addition to those normally available through unclassified channels such as NTIS.
- NASA-International Aerospace Abstracts. There are several potentially-relevant off-site library collections in the immediate vicinity:

  Carnegie Public Library, Science-Technology Division. This excellent collection serves as a regional scientific and technical literature center; it is also a depository for government documents.

  Carnegie-Mellon University, including the Engineering and Science Library and the Mellon Institute Library.

  University of Pittsburgh, with a complex of over 30 libraries.

7.5 HUMAN FACTORS LABORATORY

The Human Sciences Department at the R&D Center operates a Human Factors Laboratory for the controlled measurement and evaluation of system/user performance tradeoffs. The laboratory consists of three reconfigurable experiment bays, an experiment control room, and an equipment development facility for constructing or modifying experimental apparatus (see Figure 7.1).

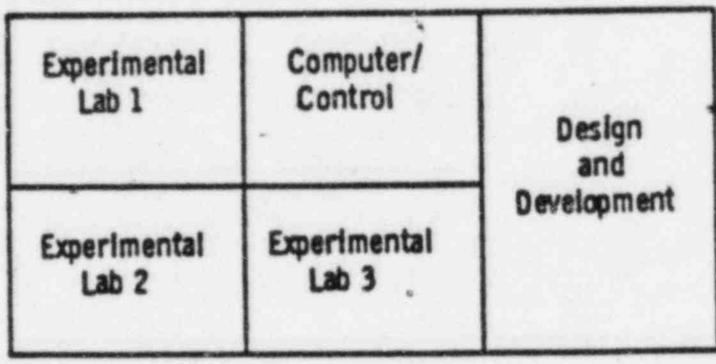

Figure 7.1 -- Functional layout of the R&D Human Factors Laboratory.

The laboratory is equipped with a comprehensive suite of equipment for real-time capture of data for analysis of both human and system performance. Central to this facility is a Data General S130 with 256 Kb of main memory, 10 Mb of disk storage, and a tape drive. The system is equipped with a real-time clock and can receive or transmit on up to 8 channels of analog or digital data.

Several types of measurement equipment may be used independently or interfaced with the computer. These include equipment for multi-channel video recording, 3-channel FM-microphone audio recording, microvolt-level signal analysis (using EEG, EKG, or EMG input), and several types of physiological measurement (e.g., heart rate, respiration rate, oxygen uptake, and GSR). The laboratory also has a high-resolution color graphic display system with preprocessor and joystick control for generating complex raster or vector video stimuli for studying numerous issues in user-system interaction.

In addition, the Human Sciences Department owns portable eye tracking equipment (NAC EYE Mart Recorder Model 4) which has been enhanced by the addition of a digitizer that generates X-Y coordinates for eye position, and software to analyze the data allows much more rapid data reduction and analysis than is generally possible.

7.6 ARTIFICIAL INTELLIGENCE LABORATORY

Research in artificial intelligence (AI) requires a specialized computing environment, a "system-builder's workbench" of integrated, powerful hardware and software tools that are needed to productively assemble and test complex systems.

The Westinghouse R&D Center has such a facility, the Artificial Intelligence Laboratory. The purpose of this laboratory is to support large-scale, in-house development of a variety of applied AI systems. The laboratory currently consists of three computer systems:

1. Symbolics 3600 "Lisp Machine" (based on a microcoded version of the LISP artificial intelligence language)
2. VAX 11/730 super minicomputer which supports several AI development languages, including:
   - Carnegie-Mellon Lisp (Franz Lisp Plus)
   - OPS 5
   - SRL (Schema Representation Language)
3. Two Three Rivers PERQ advanced personal computers with high-resolution, bit-mapped CRT displays; these support extensive database and interface software (Knowledge Management System by Information Technologies) in addition to Common Lisp developed as part of the Carnegie-Mellon University SPICE project.

In addition, a number of AI software development tools are available for the four 11/780 Vaxes. This includes Franz Lisp, OPS5 (a production system language), SRL (schema representation language), DYPAR (a natural language interface), as well as several expert system "shells".

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Appendix A

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Some Results On Operator Performance In Emergency Events

D.D. Woods

In Ergonomic Problems in Process Operations,

Institution of Chemical Engineers, in press

Human Sciences

Westinghouse Research and Development Center

SOME RESULTS ON OPERATOR PERFORMANCE IN EMERGENCY EVENTS

D. D. Woods*

This paper synthesizes results from several studies of operator performance in simulated power plant emergencies and from retrospective analyses of operator performance in five actual power plant critical incidents. This synthesis is feasible because all of these studies used process tracing techniques and a common perspective on decision making as the basis for their analysis of operator performance. The paper focuses on two areas: operator's ability to detect and correct errors and how operators utilize procedures. The results in these areas are assessed in terms of their implications for concepts and models relevant to operator performance and in terms of their implications for man-machine system improvements.

INTRODUCTION

Understanding how operators perform during emergency events is critical to the design and evaluation of person-machine systems in process control applications. This paper examines a data base on operator performance in nuclear power plant emergencies with respect to two issues[1]: what is the operator/crew's ability to detect and correct their errors and how are procedures utilized during emergencies? The data on these questions are assessed in terms of their implications for models of operator performance and for person-machine system improvements.

A data base on operator performance in emergencies now exists through a series of studies of simulated and actual nuclear power plant critical incidents. The data base includes:

a. Woods, Wise & Hanes (1) — a study of the performance of experienced operators in simulated emergency events (including multiple failure events) with and without a computerized operator aid (39 scenarios from 8 crews in 7 events);

b. Woods & Roth (2) — a study of the performance of experienced operators in simulated emergency events (15 crews in 4 events);

c. Pew, Miller & Feehrer (3) — a retrospective analysis of operator decision-making in four actual power plant critical incidents;

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*Westinghouse Research & Development Center, Pittsburgh, PA 15235 USA

[1]The results described in this paper represent a portion of a more complete assessment of this data base.

d. Woods (4) — a retrospective analysis of operator decision-making in one actual power plant emergency event (an additional facility to support emergency operations, Technical Support Center, was active during this incident).

A synthesis of results across these studies is feasible because they all used a process tracing methodology and a common perspective on decision-making [cf., Rasmussen (5)] to analyze operator performance. Operator behavior was analyzed with respect to categories of monitoring plant data, interpretation of this data (knowledge or belief state, intention, expectation, recovery strategy), the resulting control actions, and feedback on the results of recovery actions. These concepts were used to chart, not just what actions the crews took, but also the decision process and context that led to the actions. Figure 1 is an example of the flowchart format used in (1) and (4) to summarize the results of the decision process analysis. In each study, critical decisions identified in these protocols were subjected to a more detailed analysis based on the particular objectives of that study. The results reported here are based on a review of the decision making data base represented by this set of studies.

OPERATOR'S ABILITY TO DETECT AND CORRECT ERRORS

Results on the Detection and Correction of Operational Problems

In general, the operators in these studies performed well. Recovery actions were prompt, there were relatively few operational problems, and those that did occur were usually of little consequence to the final outcome. With respect to the operational problems that did occur, the crews rarely had any difficulties with the initial state identification following the onset of the emergency. In general, when operational problems did occur, it was because operator state identification and control activities gradually became decoupled from actual process state as a function of execution problems or the unexpected. This result suggests an analysis of what happened following the occurrence of some operational problem.

The data in Tables 1 and 2 show that when a crew misidentified plant state or had action execution difficulties, they generally failed to correct their understanding of plant state or to identify execution problems within the duration of the test events[2]. For those problems that were corrected, a relatively long time period elapsed: 4 of the 10 corrected execution problems in Table 1 were detected almost immediately (average of 1:15) but the other 6 took an average of 6:46). Some operational problems were corrected through the intervention of some external agent — instructor hints in the simulator exercises or, in actual incidents, when a fresh viewpoint entered the situation.

Implications and Countermeasures

The pattern of results illustrates the importance of concept-driven behavior in operator performance [cf., Woods (6) for a more detailed discussion of concept driven behavior]. The data operators sample and, in particular, how this data is integrated/interpreted depend on the operator's assessment of the situation [cf., Figure 2 for an example of a decision flowchart developed to highlight how internal knowledge structures are activated and how they guide observation and action]. When there is some mismatch

[2] The execution problems can be considered identification problems in that here we are not concerned with the initial source of the execution problem but with the operator's failure or success in assessing the effect of the action or non-action on process state and goals.

TABLE 1 — Operator performance: Error correction in simulated emergencies.*

	No Correction	Corrected Only Through External Agent	Corrected
Problem In State Identification	14	5	0
Problem In Execution	10	0	10
Total	24	5	10

*Data on operator performance in simulated emergencies from (1) and (2). These data account for 70% of all of the operator problems in these studies, the remaining operator problems were responses judged as too slow or that were noncorrectable. Given the number of test scenarios (99 using 23 experienced crews in eight different events), there were very few operator problems and those that did occur were of little consequence to the final outcome.

between actual and perceived process state, it is very difficult for those involved to modify their view given today's control rooms. Misperceptions of process state are often corrected only when a fresh viewpoint enters the situation. This pattern can be described as a type of fixation or perseveration effect, in that, an assessment of plant state tends to persist independent of supporting data. The crew's problems in the Three Mile Island accident could also be described as the result of a fixation effect, and some of the recommendations/requirements to prevent re-occurrence of such accidents can be seen as classic methods to prevent or reduce this type of decision problem (the requirement for a Safety Parameter Display System to provide a concise statement of plant safety status, i.e., provide improved feedback about goal achievement; the requirement for a Shift Technical Advisor can be seen as a way to institutionalize a fresh viewpoint).

The observation of fixation effects in operator state assessment indicates that operational problems are often related to poor feedback about the effect of control actions on process state and on goal achievement. One of the studies in the operator decision making data base (1) examined how concepts for computer-based displays (i.e., safety parameter display systems) might influence operator performance. Results on prototype display system usage suggest that computer-based aids can reduce fixation effects by providing improved feedback especially to senior staff members acting in an emergency or process management role. Table 3 contains examples where feedback was obtained from a computer-based display to correct operational problems.

The error correction results are consistent with the Bartlett (7) multi-level view of cognitive processing [cf., (5) and Broadbent (8) for particular examples of this class of models]. The key elements of this view are:

- o Human processing of information is organized at different levels which operate simultaneously over different time spans.
- o Some (presumably "higher") levels modify or control the operations of others.
- o Lower levels are capable of independent function.

TABLE 2 -- Operator performance: Error correction in actual incidents.

Study	Decision	Brief Description
Pew et al (3)	NA1 (pp.B-35 and B-41)	Failure to detect execution problem: Shift supervisor ordered Main Steam Isolation Valve closure, but operator was interrupted before action was taken; shift supervisor was unaware action was not taken.
	NA2 (pp.B-37 and B-45 to 46)	Failure to detect execution problem: execution error during realignment to normal charging and letdown; 19 minutes were available to detect and correct error.
	OY1 (pp. B-17)	Delayed detection of execution problem: serendipitous detection and correction of misaligned valves by external agent 33 minutes after error occurred.
	OY2 (pp. B-18 to 19, B-22, and B-28 to 34)	Failure to correct state identification problem: due to above (OY1) execution error, there were conflicting measures of reactor water level and no natural circulation; crew was unable to explain conflicting measures, unable to accurately assess inventory status, and erroneously assumed natural circulation was occurring until serendipitous discovery of misaligned valves by external agent (31 minutes elapsed).
Woods (4)	1.C.2 (pp.3-5 to 3-6)	Failure to correct state identification problem: Crew and Technical Support Center failed to re-evaluate an earlier action in light of later changes in plant state; as a result, a potential safety function threat was not detected.
	3 (pp. 3-9, 3-11 to 3-13)	Failure to correct state identification problem: failure to detect and correct conditions leading to pressurizer relief tank rupture into containment (19 minutes available).

TABLE 3 — Examples where the feedback used to correct operational problems was obtained from a Safety Parameter Display prototype [Results from Woods et al (1)].

*In event TR2-H the reactor operator detected that the faulted steam generator level was within the wide range instrumentation from Safety Panel B plant status and wide range iconic displays. The balance of plant operator had reported earlier that the faulted steam generator was empty by misreading narrow for wide range level from the control board.

*The senior reactor operator (TR2-H) detected low steam generator levels in two unaffected steam generators from Safety Panel B plant status display. (The balance of plant operator had been slow in re-establishing auxiliary feedwater flow to the unaffected steam generators after stopping all auxiliary feedwater to aid in the steam generator tube rupture diagnosis.) The senior reactor operator then directed the balance of plant operator to increase auxiliary feedwater flow to the unaffected steam generators.

*Safety Panel B plant status display helped the senior reactor operator detect that auxiliary feedwater had not been isolated completely from the faulted steam generator (TR2-H). The faulted steam generator had been isolated, but the balance of plant operator turned on the turbine driven auxiliary feedwater pump to increase unaffected steam generator levels. However, auxiliary feedwater flow also began to the faulted steam generator.

*In event TR2-H the senor reactor operator detected from the Safety Panel B plant status display that only 2 of the 3 unaffected steam generators were being used to cool the primary system. He directed the balance of plant operators to open the third steam generator power operated relief valve.

*In another event (FW3-G), a crew detected that pressurizer level was low and decreasing. The crew isolated letdown and then consulted Safety Panel B wide range iconic for feedback. The iconic display showed the crew that the pressurizer level decrease halted.

The result is that there is a multi-level (not necessarily hierarchical) architecture of cognitive processes. Lower level processes, which might be characterized as more ballistic or parameter driven behavior modes, bring efficiencies to behavior (e.g., stereotypical jumps in Rasmussen's step ladder model) but operate only over a limited range of situations. This tradeoff is balanced by other layers of processing, in the multi-level view, which monitor and modify the application of the lower level routines with respect to error correction (are skilled routines proceeding correctly), goal achievement/setting (are skilled routines achieving the desired effects), and responses to novel situations (which includes the ability to distinguish novel from stereotypical situations). If only the upper levels were available, performance would be slow, awkward and demanding as when we learn a new skill. On the other hand, if only lower levels were available, performance would be effective only when the novel or unexpected do not occur. Cognitive architectures that consist of multiple levels combine the advantages of these two kinds of processing while minimizing the disadvantages. The multi-level view is related to Poulton's distinction between open and closed skills:[3] Open skills employ a relatively variable sequence of components and require extensive feedback from the environment in order to adapt behavior to unpredictable constraints or disturbances; closed skills employ a relatively

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[3]Poulton's terminology does not correspond to the control engineering terms of open and closed loops.

static sequence of components, operate with little or highly stereotypical feedback from the environment, and therefore function successfully only in highly regular or predictable domains.

The error correction data show that many operational problems are related to a lack of feedback on the success or non-success of recovery actions. From the multi-level view, this is due to lower level, closed routines running on in the absence of higher level control based on monitoring changes in process state and goal achievement. One avenue then to design more error corrective person-machine systems is to model the control room functional architecture [i.e., the person-machine cognitive system; c f., Hollnagel & Woods (10)] on the multi-level structure of internal cognitive processes. This establishes, in effect, a criterion of cognitive diversity, that is, a philosophy of defense-in-depth with respect to cognitive behavior.

The error correction data also show no sign of a speed-accuracy tradeoff, i.e., longer response times were not correlated with higher quality responses. Similarly, Beare et al (11) found no relationship between speed and accuracy for nuclear power plant operator performance in emergency events, and Wohl (12) found two performance regions for maintenance diagnosis in aerospace applications (performance improved with time only up to some critical time). These results show that, for major operator tasks in emergency events, the quality of operator performance is not time dependent (cf., Woods et al (13) for more detailed discussion of the relationship between speed and accuracy in operator tasks).

PROCEDURE UTILIZATION DURING EMERGENCIES

Static Procedures - Dynamic Events

Procedures (especially procedures embodied in a paper medium) are a static, sequential list of activities. However, the data base shows that actual operations are dynamic: events occur at indeterminate times, operations can occur in parallel, items may need continuous or semi-continuous monitoring.

Continuous control tasks are one area where this mismatch is acute. In these tasks a continuously variable output parameter is to follow some target trajectory or avoid some dynamic limit[4]; in discrete control, the operator places a component or system into one of several discrete states (e.g., align a series of valves to provide a flow path from a source to a destination). For the latter class of tasks, traditional procedure can work well, in principle, because there is a relatively fixed sequence of actions to be performed[5]. However in continuous tasks, there is a dynamic component to skilled performance based on manipulating inputs contingent on output-goal relations; tuning inputs to achieve output goals is a skill that defies complete expression as a fixed sequence of discrete actions. This dynamic component is particularly strong in a type of task that occurred frequently in this data base -- a task where several interacting continuous control tasks must be balanced (e.g., the cooldown and depressurization tasks in steam generator tube rupture events on nuclear power plants).

[4]Note that these tasks are essentially continuous even if the controls available to the operator (the inputs) are discrete and are adjusted intermittently.

[5]Note that skilled performance at discrete control tasks falls towards the closed end of Poulton's open-closed dimension, in that a basically fixed sequence is followed and feedback requirements are local and stereotypical.

Review of the data base with respect to continuous control tasks reveals that two types of operational problems result from the static procedure/dynamic event mismatch. On one hand, many crews tried to perform continuous control tasks in a more open skilled fashion, but operational problems occurred when the crew did not have complete guidance or knowledge of the constraints and goals that should govern process tuning. On the other hand, crews often performed only a discrete control version of the continuous control task, but here operational problems occurred when there was some disturbance that required flexibility in the deployment of the component actions available to achieve task goals.

To take one case of the latter from the simulated emergency trials (2), a crew violated an outcome measure of performance (maintain greater than 50° subcooling — a dynamic limit) in one continuous control task (primary system cooldown in a steam generator tube rupture event). The crew rotely followed and correctly executed the sequence of procedure steps relevant to this task. However, the goal violation occurred because the crew failed to monitor the goal of the task (subcooling), so that, when the event later deviated from expected course and the crew was further along in the rule sequence, the crew failed to detect and correct the deviation over a period of 14 minutes.

The static procedure/dynamic event mismatch is also relevant to another aspect of procedure utilization. Error checks are often annotated to particular steps in a procedure in order to make sure that operators are using the correct procedure or subprocedure out of the total set available. Operational problems such as those described in the previous example are often treated in procedure space by placing instructions to perform error checks downstream in the rule sequence.[6] While there are specific places in action sequences that suggest or demand such checks (e.g., permissives such as do not begin primary system cooldown until the faulted steam generator is isolated), the data base shows that the dynamic aspects of emergency events allow for the possibility that the symptom that activates the check may not occur until after the crew has passed the particular step containing the rule [e.g., Meyer (14)]. As a result, these error checks also represent a higher level task of semi-continuous monitoring of output measure - goal state relationships that requires support from the interface system (e.g., training, guidance, data, and data organization).

Goal Oriented Versus Goal Controlled Procedure Usage

A goal oriented system is designed to achieve a goal but operates without explicit use of goal information. A goal controlled system explicitly uses goal information in order to adapt its behavior to changing circumstances in order to achieve goals (5).

It is often assumed that operators do or should rotely follow the sequence of choice and action rules contained in procedures. This philosophy of "take care of the steps and the goals will take care of themselves" represents a goal oriented approach towards procedure usage. However, the data base review shows that emergency operations often demand greater response flexibility, where procedural information about how goals can be achieved is a

[6]Note the significant secondary design problems that arise in the development of complete coverage: identify steps that tell operators when to go back and monitor output goals, place these steps at appropriate points downstream in the action sequence, test placement of these steps in dynamic trials to show that, given the time operators take to complete tasks, typical or important disturbances will be caught in the error check net.

resource to improve goal controlled operator performance (Figure 2 contains a decision flowchart of operator performance in a simulated emergency where goal controlled procedure usage occurred, i.e., the crew treated major recovery tasks as goals which guided their detailed observations and actions).

This finding is supported by the error correction and continuous control task results discussed earlier, and it is supported by problems that occurred in operator assessment of the relevance of the currently or nominally active rule set to actual plant conditions. For example, how does a crew decide if a procedure or subprocedure is still relevant after a second failure occurs? In two cases in actual emergencies (2; 14), the crews involved thought that a second failure invalidated the procedure they had been using. In another actual event [Brown & Wyrick, (15) pages 3-21 to 3-52], a crew correctly began to follow one procedure; but later, when the leak increased in size, they failed to activate either the newly relevant procedure or all of the relevant recovery goals. In other cases, operators sometimes successfully adapted and sometimes failed to adapt a procedure or rule to unexpected variations in plant behavior [e.g., NRC (16)]. In addition, there were examples in the data base where rote procedure execution broke down once an operator error occurred. In one case (2), the original error invalidated subsequent steps; the crew's attempts to continue to follow the procedure led to further erroneous actions. These results illustrate the two kinds of operational problems that are the consequence of the mismatch between goal oriented procedures and the goal controlled requirements of emergency operations: (a) problems where rote rule following persists in the face of changing circumstances that demand adaptable responses and (b) problems where goal controlled performance is attempted without the knowledge or guidance to successfully manage resources to meet recovery goals.

The results on operator procedure utilization in emergencies show that rotely followed procedures are inherently "brittle," in that, they are not readily able to handle novel situations, adapting routines to special conditions or contexts, underspecified instructions (e.g., "stop all unnecessary safety injection pumps"), and recovery from errors (cf., Suchman (17) and Brown, Moran, and Williams (18) for more discussion of the semantics of procedures and similar results on instruction following from other work domains). Good operations requires more than rote rule following; it requires the operator to "understand how the various steps of a procedure work together to produce intended effects" (18, p.2).

Countermeasures

The procedure utilization results demonstrate the need for guidance and tools to help operators meet the goal controlled performance demands of emergency operations. For example, foldout sheets can be used to specify important operator activities which could be triggered at indeterminate times during some procedure and items that need continuous or periodic monitoring during that segment of operation (cf., new nuclear power plant procedures such as the Westinghouse Owners Group Emergency Response Guidelines). Procedures can be developed to support periodic monitoring of recovery goals (e.g., safety function status monitoring through decision trees as in the Westinghouse Owners Group Emergency Response Guidelines or periodic monitoring of an event diagnosis/rediagnosis procedure).

Computerized procedures can also aid continuous monitoring and control tasks. Computer displays can lessen paper management problems with current procedures by showing items that should be monitored at any stage in the recovery process. The advantage over the foldout page is additional flexibility, the ability to show actual values as well as criterion values,

and the ability to alert crew members when boundaries are approached or crossed. In addition, operator monitoring and goal achievement assessment tasks can be supported through new computer display systems which present data about the relationship between output measures and process goals. In general, techniques that identify and embody envelopes of performance are an effective means to keep operators from losing sight of the forest when enmeshed in the detailed steps of various procedures.

DISCUSSION

The data base review with respect to issues of error correction and procedure utilization indicate that operator performance is well described by a multi-level view of human cognitive processing: goal controlled, open skill executive processes monitor and control the deployment of semi-autonomous resources which are more goal oriented, closed skills. This class of models emphasizes that all human behavior is knowledge (or concept) driven; what varies with layer of processing is the type of knowledge that drives behavior: knowledge embedded in a motor program, knowledge built into automatic mental skills (e.g., the heuristics of figure/ground organization and other forms of tacit knowledge), knowledge in the form of explicit rules (derived, learned, or written), knowledge in the form of conscious reasoning. In addition, the multi-level view (and the specific results) points out that the criterion for skilled operator performance is the ability to adapt behavior to changing circumstances in the pursuit of a goal.

There is a mismatch between the model of the operator implicit in past process control interface systems and the above model of operator performance. As a result and as the data base review reveals, two general kinds of operational problems occur. In one case, lower level routines are misapplied or run on in the absence of higher level control based on goal monitoring. In the second case, operators attempt to adapt component skills or maneuvers to achieve perceived goals, but problems occur due to incomplete knowledge of the relevant goals and constraints. The implication is that operator performance can be improved through an operational system (training, guidance, information) that is explicitly based on the multi-level view. New process control interfaces are being developed, tested, and implemented that begin to accomplish this goal; examples include new procedures that incorporate guidance on goal monitoring, computerized procedures, and goal directed information systems/decision aids.

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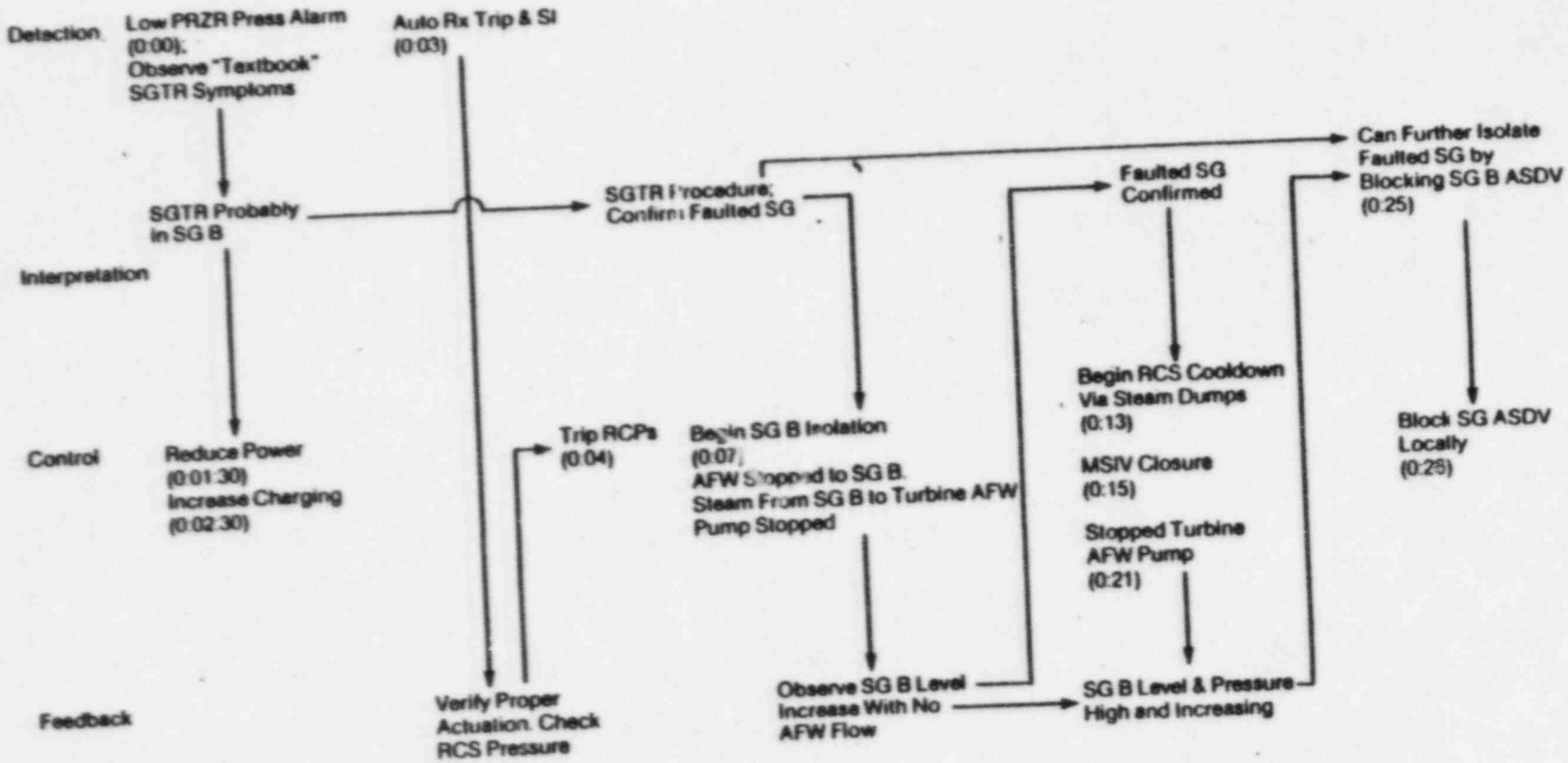

Figure 1 Portion of a decision flowchart from on of the studies in the database (4) that illustrates how decision making concepts were used to understand, not just what actions were performed, but also the decision process and context that led to the actions.

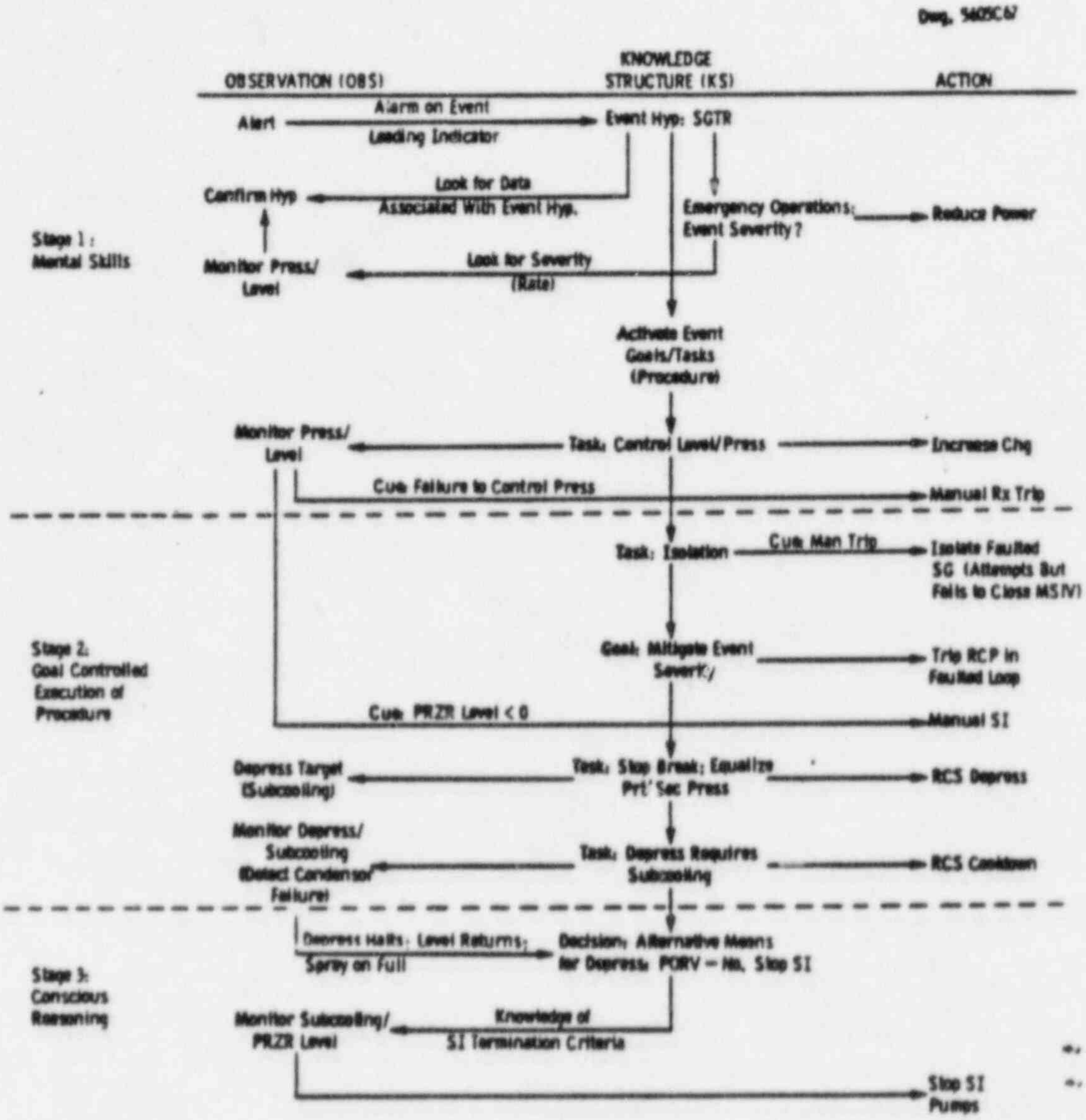

Figure 2 Decision flowchart of crew response in a simulated emergency [steam generator tube rupture from Woods et al (1)]. The format was developed to map how knowledge structures are activated and how they control observation and action. Also note that, during a portion of the recovery, operator performance was based on goal controlled procedure usage.

SYSTEMS WITH HUMAN MONITORS: A SIGNAL DETECTION ANALYSIS

R. D. Sorkin, Purdue University

and

D. D. Woods, Westinghouse Research and Development Center

To be published in: Human Computer Interaction

Requests for reprints should be sent to R. D. Sorkin, Department of Psychological Sciences, Purdue University, West Lafayette, IN, 47907.

Running Head: Systems with Human Monitors

ABSTRACT

Automated factories, the flightdecks of commercial aircraft, and the control rooms of power plants, are examples of decision-making environments in which a human operator performs an alerted-monitor role. These human-machine systems include automated monitor or alerting subsystems operating in support of a human monitor. The automated monitor subsystem makes preprogrammed decisions about the state of the underlying process based on current inputs and expectations about normal/abnormal operating conditions. When alerted by the automated monitor subsystem, the human monitor may analyze input data, confirm or disconfirm the decision made by the automated monitor, and take appropriate further action. In this paper, the combined automated monitor-human monitor system is modeled as a signal detection system in which the human operator and the automated component monitor partially correlated noisy channels. The signal detection analysis shows that overall system performance is highly sensitive to the interaction between the human's monitoring strategy and the decision parameter, C_a, of the automated monitor subsystem. Usual design practice is to set C_a to a value which optimizes the automated monitor's detection and false alarm rates. Our analysis shows that this setting will not yield optimal performance for the overall human-machine system. Furthermore, overall system performance may be limited to a narrow range of realizable detection and error rates. As a result, large gains in system performance can be achieved by manipulating the parameters of the automated monitor subsystem in light of the workload characteristics of the human operator.

Systems with Human Monitors: A Signal Detection Analysis

1. SYSTEMS WITH AUTOMATED AND HUMAN MONITORS

One component of human-machine systems in complex decision making environments such as power plant control rooms, air traffic control, or commercial aircraft flightdecks, is the alerted-monitor function. An alerted-monitor system consists of an automated monitor subsystem operating in conjunction with a human monitor. The automated alerting subsystem makes preprogrammed decisions about potentially troublesome situations by comparing incoming data on process state with stored expectations of normal and abnormal operating conditions. When alerted by an output from the automated subsystem, the human monitor may analyze input data, confirm or disconfirm decisions/actions made by the automated subsystem, or take appropriate further action. For example, in the computerized air traffic control system (Goldmutz et al., 1981), there are subsystems which will monitor incoming flight data, predict potential air traffic problems, and call the human monitor's attention to these problems. This paper uses the techniques of Signal Detection Theory (see Green & Swets, 1966) to model and explore the performance of the joint automated monitor-human monitor system. The analysis shows that overall alerted-monitor performance is highly dependent on the interaction of the parameters of the automated alerting subsystem and the operator's workload and monitoring strategy.

Traditionally, automated monitors have consisted of messages about simple set-point violations. The set-point is a preset threshold value. When the measured condition exceeds (or drops below) this level, a message is displayed to the operator. Experience has shown that operators frequently have problems identifying, prioritizing, and responding to abnormal conditions with this type of alarm system (Cooper, 1977; Banks & Boone, 1981; Kragt & Bonten, 1983). For example, one review of power plant control rooms found that:

"Operators at all plants complained about the high number of nuisance alarms. The reasons for their occurrence varied. At one plant there was a blank, supposedly nonfunctional, annunciator window that would occasionally alarm. The maintenance and operational people had been unable to determine its cause, but an acknowledgement, silence, and reset were required on each occasion. In many cases alarm set-points were known by operators to be too sensitive to normal transients. As a consequence slight deviations or transients, thought of as normal, would set the alarm off even though no further operational action was required. Maintenance or calibration operations often caused recurring alarms that were a nuisance. The net results of the many false alarms is a "cry-wolf" syndrome which leads to a lack of faith in the system and a casual attitude towards the constant presence of certain alarms. On many occasions operators were observed to casually silence and acknowledge alarms without further concern or surveillance of plant status; the alarms had become 'old friends' (Seminara, Gonzalez, & Parsons, 1977)."

As a result, there is considerable interest in applying computer technology to develop new types of automated monitoring systems that can improve the detection and correction of abnormal occurrences. One approach focuses on improved organization and presentation of alarm data (cf., the alarm presentation techniques described in Visuri, 1982; Berson et al., 1982; NASA, 1979; Thompson, 1981). Another avenue is the development of automated decision systems which monitor multiple parameters on a number of input channels and use more complex (algorithmic or potentially heuristic) information processing to identify potential abnormal conditions, cf., the alarm analysis techniques described in Bastl & Felkel (1981; cause-consequence models); Bray, Nelson, Blackman & Fowler (1984; rule based); Lind (1981; function based); and Gimmy & Nomm (1982, decision tables). While there is considerable activity in the design of automated monitors, there is essentially no theoretical or empirical information available to guide designers with respect to how human or machine subsystem characteristics affect the performance of the overall alerted-monitor system.

What subsystem factors might affect overall system performance? To explore this question consider a simple example of an alerted-monitor system: the familiar smoke detector. Smoke detection systems can vary in their ability to

discriminate fire from non-fire conditions. In addition, there are different consequences associated with the different types of possible outcomes--failure to detect and respond to an actual fire has much higher negative consequences than a false alarm. Therefore, the designer can vary the amounts of evidence required for a "fire" decision on the part of a smoke detector in order to take into account the relative consequences of the different possible outcomes. In this example, designers might reasonably require relatively little evidence of a fire before outputting an alarm. This strategy will maximize the smoke detector's hit rate (correct detection of actual fires), but it will also increase the detector's false alarm rate (and the overall number of alarms), for a fixed ability to discriminate fires from non-fires. However, consider the consequences of a high false alarm rate on the performance of the subsequent human monitor. A busy human monitor may soon learn to ignore the smoke detector's alarm signal, attributing it to a false alarm and not worthy of a shift in attention from more pressing duties. The performance of the overall smoke detector-human monitor system would be worse than if the smoke detector were set to emit fewer alarms.

2. SIGNAL DETECTION ANALYSIS OF ALERTED-MONITOR SYSTEMS

The smoke detector example points out the need to understand how subsystem characteristics determine overall system performance. To begin to provide guidance for the design of alerted-monitor systems, we explore some possible interactions between the automated and human monitor subsystems. This analysis is based on the techniques of Signal Detection Theory; the results show that the automated monitor's response criterion and the human monitor's workload and time sharing strategy are important determinants of overall alerted-monitor system performance.

2.1 Signal Detection Systems

Systems that monitor selected process data (a noisy input channel) for potentially abnormal conditions (signal events) can be modeled as signal detection devices. These devices must discriminate between the presence of signal-plus-noise (abnormal condition) events and noise-alone (normal condition) events. Figure 1 illustrates such a signal detection system. This system first makes a measurement (an observation), which can be considered as a multidimensional input vector, X, and then computes a unidimensional statistic, Z, base on the observation vector and on stored information about the expected characteristics of signal and nonsignal events.

Insert Figure 1 about here

The statistic, Z, is then evaluated against some criterion value, C, which is the output threshold or set-point. If the statistic is greater than or equal to C, the output will be "Yes, there is a signal". If not, the response will be "No, there is no signal". The criterion, C, is usually chosen on the basis of the prior probability of signal (or noise) and the costs and benefits of the possible decision outcomes (correct detection, missed signal, false alarm, correct rejection).

How well the detection system can discriminate between signal-plus-noise and noise-alone events depends on the probability density distributions of the statistic, Z (Figure 2). The probability (density) of obtaining a particular value of Z given a signal plus noise event is f(Z/SN); the probability (density) of obtaining a particular value of Z given noise-alone is f(Z/N). If these distributions are widely spaced with low variance, there will be few errors in attributing a given value of Z to a signal-plus-noise or noise-alone cause.

Computation of a good statistic requires prior knowledge of what input vectors will usually be generated by signal-plus-noise or noise-alone events. (An optimal statistic for this process is the likelihood ratio). The assumption that the distributions on Z are normal (Gaussian) in form is a good approximation to the behavior of many detection systems.

2.1.1 Sensitivity (d') and Criterion (C) Parameters

Signal detection systems can be represented by two parameters: (1) a sensitivity parameter, d', which specifies how effectively the system can discriminate signal-plus-noise events from noise-alone events on the channel, and (2) the response criterion parameter, C, which specifies how much evidence is required for a "yes" decision. The d' parameter is defined as the normalized separation between the distributions; that is, the difference between the means of the distributions, $\mu_{sn} - \mu_n$, divided by the standard deviation of the distributions (assuming that the distributions on Z have equal variance). Values of d' near zero will yield performance at chance levels; levels of d' above 4.0 will yield essentially errorless performance. It is convenient to consider the decision dimension Z as normalized, so that the standard deviation of the distributions is equal to one and the separation of the means is equal to d'. It follows that d' and C are expressed in standard deviate units.

The second parameter, C, is the criterion value used to partition Z into the response categories of "yes" or "no". The important aspect of C is its position relative to the means of the two distributions. The probability of the system correctly responding "yes" given that a signal has occurred, P(Y/SN), is called the hit probability. The probability that the system incorrectly responds "yes" given that no signal has occurred, P(Y/N), is called the false alarm probability. These probabilities are computed from the density distributions on Z as follows:

$$P(Y/SN) = P[(Z \geqslant C)/SN] = \int_{C}^{\infty} f(Z/SN)\, dz \qquad (1)$$

$$P(Y/N) = P[(Z \geqslant C)/N] = \int_{C}^{\infty} f(Z/N)\, dz \qquad (2)$$

Now suppose that d' = 2.0, that is, $\mu_n = 0$ and $\mu_{sn} = 2.0$. If C were equal to 1.0, it would be centered between the means of the two distributions. The resulting hit and false alarm probabilities would be, from a table of the normal distribution, .841 and .159 respectively. For a particular value of d', one can evaluate the hit and false alarm values resulting from any value of C. Table I gives hit and false alarm rates for some representative values of d' and C.

Insert Table I about here

Moving C along the Z dimension toward the noise distribution (smaller values of C) yields both higher hit and higher false alarm rates. Moving C toward the signal-plus-noise distribution (higher values) yields lower hit and lower false alarm rates. A small value for C implies that the system is liberal at responding "yes"; a high value of C implies a conservative criterion for responding "yes".[1]

Insert Figure 2 and 3 about here

2.1.2 Receiver Operating Characteristic

The performance of a signal detection system can be characterized by a Receiver Operating Characteristic (ROC), which is a plot of the hit probability, versus the false alarm probability, for all possible values of C and a fixed value of d'. The d'=1 and d'=2 curves of Figure 3 are thus complete plots (all values of C) of the hit and false alarm values shown in Table I. The curve

labelled 3 is the plot of hit and false alarm values for all values of C for the more sensitive system with a d' equal to 3.0. It is evident that systems with higher d' values will have higher hit rates and lower false alarm rates. The higher the d', the farther the ROC will be from the positive slope diagonal (which is the ROC for d'=0 or chance performance). Since each ROC curve is computed with a fixed d', each curve represents a constant ability to discriminate signal-plus noise from noise-alone. However, the particular operating point on an ROC (a particular hit and false alarm pair) reflects the liberal or conservative aspect of the system's response criterion, C. As C shifts toward smaller values (move from point 0,0 toward 1,1 along an ROC curve in Figure 3), there is an increase in both hit and false alarm rates and in the overall (yes) response rate. For single stage detection systems, the best operating point on a given ROC (i.e., the optimal C value) depends on the costs and benefits of the various outcome categories as well as the prior probability of a signal occurring (see Egan, 1975). For example in some situations it will be desired to maximize total percent correct, while in other applications it will be necessary to minimize the number of missed signals or false alarms. Different decision strategies prescribe different settings of the C parameter (Green & Swets, 1966; Swets, 1964; Sheridan & Ferrell, 1974).

2.2 General Model of the Alerted-Monitor System

An alerted-monitor system consists of an automated monitoring subsystem operating in conjunction with a human monitor. An automated subsystem monitors a noisy input channel (i.e., selected process data) on which occasional signal events occur (i.e., potential abnormal conditions). When alerted by subsystem output, the human monitor may analyze input data, confirm or disconfirm the decisions/actions made by the automated monitor, or take appropriate further action. The operator also may be busy with tasks not related to the monitor

task.

In signal detection terms the alerted-monitor system can be represented as the two-stage detection system shown in Figure 4. Each stage is specified by its own sensitivity (d') and response criterion (C) parameters.[2] A statistic, Z_a, is computed by the automated monitor based on its input, X_a. The magnitude of Z_a relative to the criterion, C_a, determines whether or not an alarm is sent to the human monitor control stage. If an alarm is sent, the human monitor may compute a statistic, Z_h, based on its input, X_h. If Z_h is greater than or equal to C_h, a "yes" (confirming) system response will be made. It thus takes a "yes" response from both the automated and human subsystems for a "yes" system response to any input, X.

Insert Figure 4 about here

The human and automated monitors do not necessarily observe precisely the same noisy input vector, X. The data input, X_h, to the operator and the input, X_a, to the automated subsystem are subsets of X and may include elements not available to the other system. For example, the operator may have historical or contextual data unavailable to the automated system, while the automated subsystem may include complex data processing algorithms or heuristics (e.g., expert systems), which the human cannot duplicate within task constraints. Differences in sampling rates, precision of measurement or display, or offset in the time of observation by each subsystem, also decrease the overlap between the channels monitored by the human and automatic systems. In signal detection terms, the two subsystems can be described as monitoring channels that possess some statistical correlation or, equivalently, some degree of common noise. The magnitude of the common noise source, compared to the total noise in each channel, defines the correlation between the channels (Jeffress & Robinson, 1962).

In actual systems one would expect to find the correlation between the automated and human channels to range from 0 to 1, depending on the particular application. For example a smoke detector may continuously test the conductivity of the air near the ceiling of a room, while a human's observation may be based on a visual check for smoke in lower areas. The correlation between these types of observations may be fairly low. In an automated chemical plant, the same unprocessed sensor data might be available to both the human and the automated monitor; in that case the correlation between those channels could be very close to one.

While the literature includes descriptions of many situations where responses to alerting signals were delayed or omitted (e.g., Kantowitz, 1982; Seminara et al., 1977; Reason & Mycielska, 1982), there is little data that describes the effect of variations in alerting subsystem parameters on the behavior of the operator who must receive and process the output. Reviews of problems with actual alarm systems suggest that operator behavior depends on assumptions about the alerting system's sensitivity, its response criterion (false alarm rate), and the relative importance and likelihood of the condition being signalled. For example, airline pilot ratings of the acceptability of flightdeck alerting signals depend on the perceived false alarm rates as well as the perceived urgency or importance of the alerted condition (Williams & Simpson, 1976).

The effect of alerting system characteristics on the human monitor's performance may also depend on the operator's workload (monitor task load plus other task loads). Prediction of the accuracy and speed of human performance on one task in a multi-task environment has been a major concern (cf., Enstrom & Rouse, 1977; Whitaker, 1979; Wickens, 1979). The alerted-monitor task can be considered a special case of the multi-task or time-sharing situation. While

there is some controversy about the nature of limitations in human information processing in different types of multi-task situations (Allport, 1980; Lane, 1982; Norman & Bobrow, 1975; Kantowitz & Sorkin, 1983), we would expect workload factors to be important determinants of the interaction between the automated and human monitor subsystems. In the next sections we analyze the performance of the alerted-monitor system as a function of the key subsystem parameters of alerting subsystem response rate and operator time sharing strategy.

2.3 Alerted-Monitor Operating Characteristics

The performance of a two-stage detection system such as shown in Figure 4, can be analyzed by determining the effect of various assumptions about the parameters of each of the detection subsystems on the overall system operating characteristic. To get an idea of the range of system performance possible, consider a hypothetical two-stage detection system in which the two stages possess equal detectability and the observations made by each stage are optimally combined for a system decision. The overall detectability of such a system is given by $\sqrt{2}\, d'$, where d' is the detectability of each stage.[3] In the alerted-monitor system the observations are not combined optimally because the alarm is a binary signal to the operator, and because the operator usually observes the input channel only when alerted by the automated monitor stage.[4] Hence, overall performance in the alerted-monitor system generally will be less than the optimum value of $1.414\, d'$.

The performance of a two-stage detection system in which binary responses from the two stages are combined for a system decision, was examined by Pollack and Madans (1964). The alerted-monitor system is a special case of the Pollack and Madans two-stage system, in which the second stage (the human operator) only observes the noisy channel when alerted by a signal from the first stage (the automated monitor). Pollack and Madans found that the maximum system d' occurred for such a system when the two stages had equal detectabilities and

equal response criteria. They found that over an intermediate range of response criteria, maximum system performance was approximately equal to 1.2 d', a possible 20% performance advantage for the two-stage system.

Insert Figure 5 about here

Figure 5 illustrates the effects that different response criteria have on system performance for an alerted-monitor system with equal subsystem d's, $d'_a = d'_h = 2.0$. Each curve is the overall system operating characteristic for all possible operator criteria and a fixed setting of the automated monitor's criterion, C_a. For example, a stringent C_a value of 1.5 results in few false alarms (and few correct detections). Each curve starts at the origin (0,0), moves toward (1,1), and suddenly terminates.[5] Recall that these system operating characteristics were computed by fixing the parameters d'_a, d'_h, C_a and by sweeping through all values of C_h. When C_h is sufficiently small, the human operator is so liberal that he/she says "yes" whenever any observation is made. At that point, the human simply mimicks the behavior of the automated stage, that is: given no alarm the human says "no", and given an alarm, the human automatically says "yes". This is the condition that exists in the region where each operating characteristic terminates. Hit and false alarm rates higher than these termination values are not achievable. Because the system is mimicking the automated stage at these points, the locus of all the termination points is in fact the ROC for the automated stage alone. It follows from examination of the operating curves that the lowest system d' will be equal to the d' of the automated stage alone.

The outer envelope of the system operating curves in Figure 5 represents the highest d' available with the alerted-monitor system. This envelope is

approximately equivalent to an ROC for a system with a d' slightly more than 1.2 times the individual subsystem d's, as shown by Pollack and Madans. In cases where the between-channel correlation is greater than zero the same general relationships hold, but there is a smaller gain in the combined system d'. Unequal subsystem d's also result in lower system d's (See also Swensson, 1980 for a related analysis).

Pollack and Madans also collected data on the performance of combined person and machine (simulated) monitors using an auditory signal detection task. Their study employed a set of six observers whose response ratings were pooled on each trial. They found that the performance of the combined observers/machine system was generally superior to that of the observers alone, but less than that predicted by the optimal combination rule. This discrepancy was especially evident at high signal-to-noise ratios.

2.4 Automated-Monitor-Human-Monitor Interactions

In this section we investigate the effects on system performance of different forms of interaction between the human operator's parameters (d'_h, C_h) and the automated monitor's criterion (C_a). It is the case that the higher is d'_a (and d'_h), the better will be overall system performance. Obviously, the system designer will want to maximize d'_a. This parameter will generally be limited by automated detector hardware considerations and by lack of knowledge of the to-be-detected events, such as the particular patterns of sensor data that correspond with abnormal events. However, the automated monitor's response criterion, C_a, is normally <u>not</u> limited by similar considerations; it can be set to any desired level. The setting of C_a will determine the relative proportion of the various outcome categories (e.g., the number of false alarms relative to misses) and the overall alarm rate of the automated monitor. Since the C_a parameter is not limited by hardware and software factors, we confine our

analysis of system interactions to those between C_a and the human subsystem parameters, C_h and d'_h.

2.4.1 Dependence of C_h on C_a: 'dependent criterion' strategy

One interesting form of interaction between the human and automated monitor subsystems would results if C_h were some function of C_a. This could occur if, as the number of false alarms from the automated monitor increases, the human monitor required more evidence to confirm the alerted condition (that is, if the human became more conservative as the automated monitor became more liberal). We call this possibility the 'dependent criterion' strategy. To illustrate this strategy, we have assumed that the operator criterion increases with the probability of an output from the automated subsystem, P(alarm):

$$C_h = 2\ P(\text{alarm}) \tag{3}$$

where $$P(\text{alarm}) = P_a(Y/SN)\ P(SN) + P_a(Y/N)\ P(N) \tag{4}$$

where $P_a(\ \ )$ refers to the hit or false alarm rate of the automated subsystem and P(SN) and P(N) are the prior probabilities of signal and noise. In these calculations we have assumed P(SN) = P(N) = 0.5.

Insert Figure 6 about here

Figure 6 shows the system operating characteristic that results from these assumptions. The curve has a prominent peak along its lower portion; it increases from (0,0) to a peak hit rate of about 0.74 and then falls rapidly. This means that effective system performance will be possible only over a very narrow range of low output rates from the automated monitor. At intermediate or high rates, system performance quickly drops off to a level determined by the sensitivity and criterion parameters of the automated system alone. High system hit (and false alarm) rates are impossible to achieve with the human in the

system.

2.4.2 Dependence of d'_D on C_a: 'operator sampling' and 'd'-allocation' strategies

In addition to the possibility that the operator criterion may depend on the alerting signal rate, high rates may lead to situations where the operator either ignores some alerting signals or makes observations with a reduced detectability. Suppose that the operator is sufficiently 'busy' that there is a limit to the operator's ability to process information in all of the tasks (cf. Lane, 1982; Allport, 1980). That is, there is a set of primary tasks that demands attentional capacity, and only the remaining attentional resources are allocated to the input channel. Given this situation, there are at least two types of strategies that would result in a dependence of operator sensitivity on the automated system's parameters. We call the first possibility the 'operator sampling' strategy. Under this strategy, the operator makes observations only on a subset of the alerted events; the rest are ignored. The second type of strategy is termed the 'd'-allocation' strategy. In this case we assume that the operator will make an observation on the input channel whenever alerted, but will observe with a reduced d'.

Insert Figure 7 about here

Figure 7 shows combined system performance under the operator sampling strategy. Given an alerting signal from the automated subsystem, the operator will observe the input channel with some probability, P(observe). To show the general effect of an operator sampling strategy, we have assumed that P(observe) decreases linearly from a value of 1.0 when the alerting rate, P(alarm), is zero, to a value of 0.5 when P(alarm) is 1.0. That is, when alarms occur

infrequently, the operator will observe the input channel on every occurrence of the alarm. When alarms are very frequent, the operator will only observe the input channel half of those times. This is not an extreme assumption, since the human monitor observes the input channel on at least half of the alerted events. On those occasions when the operator does not make an observation, the alarm is ignored and the system makes a "no-signal" response.

Each of the curves shown in Figure 7 corresponds to a fixed value of C_a (shown) and a corresponding value of P(observe), evaluated over all values of C_h. High values of P(alarm), e.g., negative values of C_a, result in operating characteristics close to the chance line (e.g., the $C_a = 0.5$ curve). In general, under operator sampling strategies the system operating characteristics trace out curves in the lower left quadrant of the ROC space. If the sampling probability decreases to zero, system performance will decrease all the way to chance. One example of the sampling strategy may be seen in the reaction of busy air crew personnel to flight-deck warning signals. The flight crew may be set to automatically cancel a warning signal as soon as it occurs, rather than investigate the potential problem signalled by the warning.[6]

Insert Figure 8 about here

The second type of dependence between operator sensitivity and alerting subsystem parameters follows from the assumption that there are limits to the amount of detection capacity that can be assigned to the alarm channel. Operator observations are made on all alerted events, but high alerting rates lead to a decrease in the d' that the operator may use. To examine this idea, it is necessary to postulate how detection capacity might be allocated across different numbers of observations. We have postulated two different functions relating d'_h to the alerting rate, P(alarm), as illustrated in Figure 8. The

solid curve of the figure results from the assumption that $(d'_h)^2$ decreases linearly with the number of observed events: That is,

$$d'_h = d'_a \sqrt{1-P(\text{alarm})} \tag{5}$$

where $d'_a = 2.0$.

This function was chosen to provide detectabilities between 1.0 and 2.0 over most of the range of P(alarm). These values generally constrain d'_h between modest above-chance performance and the moderately good performance of the automated stage (d'=2.0). The effect of this strategy on system performance is shown in Figure 9. Each operating characteristic corresponds to a fixed value of C_a (shown) and a corresponding value of d'_h, evaluated over all levels of C_h. The system operating characteristics approach chance performance as C_a gets increasingly negative and P(alarm) goes to 1.0.

Insert Figures 9 and 10 on same page

An alternative relationship between d'_h and P(alarm) is shown as the dotted curve of Figure 8. In this case, d'_h is equal to 4.0 when very few alerting events occur. When P(alarm) is high, however, d'_h decreases to a limiting value of 0.5. These values were chosen to illustrate the case when increases in low alarm rates can produce significant effects on operator detectability. The equation describing this relationship is:

$$d'_h = 2d'_a/[7P(\text{alarm})+1] \tag{6}$$

where $d'_a = 2.0$. Figure 10 illustrates the effect of this strategy on the system operating characteristics. The curves are similar to those of Figure 9 but reach a minimum level of system performance equal to $d' \simeq 1.0$ for increasingly negative values of C_a.

This analysis of automated-human subsystem interaction indicates

that the dependent criterion, operator sampling, and d'-allocation strategies each result in characteristically different effects on system performance. Figures 7, 9 and 10 also illustrate that the particular interaction function assumed will determine (1) how rapidly the family of operating curves will shift toward the chance line, and (2) whether they will reach a limiting value of d' which is greater than zero.

The particular d'-allocation strategy specified by equation (6) (the dotted curve of Figure 8) has the interesting property that high values of P(alarm) do not produce additional decreases in d'_h. That is, as the number of alerting events rises and the operator's workload increases, performance on the alerted-monitor task suffers smaller and smaller decrements. This implies that the operator's performance is not limited by a fixed amount of processing capacity that must be shared among the alerted-monitor and the other operator tasks. Rather, the operator's information processing capacity is "elastic" and may increase somewhat as the total task demands increase. This idea is consistent with the reports of some investigators (cf., Kahnemann, 1973; Allport, 1980; Wickens, 1979). Whether operator performance exhibits fixed or elastic capacity properties depends on the specific characteristics of the operator tasks and the operator training. Lane (1982) and Wickens, Sandry & Vidulich (1983) have reviewed many of the issues involved in this question. In general we would expect that operator strategy in an alerted-monitor task would depend on the precise nature of such task and training factors. If the alerted-monitor task were a salient absorber of operator processing resources compared to other tasks, then small changes in the automated subsystem's criterion might result in large changes in operator resource allocation.

Insert Figures 11, 12 and 13 about here

One interesting consequence of task interaction may be a combined sampling and d'-allocation strategy. Figure 11 illustrates one version of such a strategy. The operator sampling probability (dotted line) is fixed at 1.0 for values of P(alarm) less than 0.5, then decreases linearly to a minimum value of 0.2; that is, the operator observes the input channel at least 20% of the time he or she is alerted by the alarm subsystem. The relationship between d'_h and P(alarm) is assumed to follow a function similar to equation (6) but decreases to a minimum d' of 1.0 rather than 0.5. These particular values were chosen to illustrate the general effects of combining the two operator strategies. These assumptions are given by the following equations:

for P(alarm) <0.5,

$$P(\text{observe}) = 1.0 \text{ and } d'_h = 1.33\,[0.33 + 1.67\,P(\text{alarm})]^{-1} \qquad (7)$$

for P(alarm) ≥0.5,

$$P(\text{observe}) = 1.8 - 1.6\,P(\text{alarm}) \text{ and } d'_h = 1.0 \qquad (8)$$

Figure 12 illustrates the effects of these assumptions on the system operating characteristics. The parameter of the curves is the value of the alerting subsystem criterion. This figure has both the sampling and d' allocation aspects shown in the previous figures. As P(alarm) increases, the system performance curves drop toward the chance line and toward the origin.

We can make the additional assumption that the human operator will attempt to match his or her criterion to that of the automated subsystem, e.g., $C_h = C_a$. This strategy maximizes the system d' when the automated and operator subsystems are independent and have equal d's. The result is the operating characteristic shown in Figure 13. This curve has one prominent peak at a low criterion level and a second apparent peak at an intermediate criterion value. Thus, for this system, efficient performance is possible only for certain values of C_h and certain system hit and false alarm rates. These values may not correspond to

those required for a given application and probability of signal. Furthermore, the complexity of the operating characteristic may be unknown to the operator and the system designer; system performance at desired hit and false alarm rates may never be achieved because of improper specification of C_a. Although the distinctive operating characteristic of Figure 13 results from arbitrary assumptions about operator monitoring strategy, we have included it to illustrate the potential impact on system performance that may result from interactions between the human and automated subsystems.

2.4.3 Summary of the Interaction Analysis Results

This analysis of representative types of interaction between the human and automated subsystems has pointed up the following relationships between the subsystem parameter's and their effect on overall system performance.

1. The operator's criterion may depend on the parameters of the automated subsystem, especially C_a. This may be a rational operator strategy in high information-processing load circumstances, although overall alerted-monitor system performance can be impaired. Effective system performance may be limited to very narrow ranges of (low) system hit and false alarm rates (Figure 6).

2. Operator sampling or sensitivity (d') allocation strategies may result if the total task loading (alerted-monitor task plus other tasks) is sufficiently great. As a consequence, good system performance may be limited to certain hit and false alarm levels. For example, under the sampling strategy, performance may be restricted to the lower left quadrant of the ROC space. A sampling or d'-allocation strategy will cause system performance to drop rapidly either to an asymptotic level or to a chance level, depending on the parameters of the interaction function (Figures 7, 9, and 10).

3. The types of interaction between the operator and automated subsystems will depend on the characteristics of the particular alerted-monitor task

situation, including the operator's task load, the expected probability of signals and non-signals, and the desired system hit and false alarm rate. Appropriate system design and operator training could: (a) reduce the task loadings and interactions and increase the operator's effective processing capacity; (b) provide accurate specification to the operator of the desired system operating point and of the automated system's criterion, detectability, and relative importance; and (c) improve the accuracy of operator monitoring performance (and possibly reduce the correlation between the operator and automatic subsystems).

3. DISCUSSION AND IMPLICATIONS FOR SYSTEM DESIGN

The preceding analysis demonstrates the importance of designing automated monitoring systems based on the performance of the total human-machine alerted-monitor system, rather than on the performance of the automated subsystem alone. A critical parameter of automated monitors with respect to overall system performance is the criterion, C_a. This parameter can be set to any desired value because, unlike d'_a, the criterion is usually not constrained by considerations of cost or computational capacity. The designer of an automated subsystem is likely to set C_a so as to minimize the number of signals missed by the subsystem. This is because, from the point of view of subsystem performance alone, there is usually a greater cost associated with a miss than with a false alarm. However, our analysis of the combined human-machine monitoring system shows that this approach can lead to the impaired performance of the total system. In other words, optimal criterion placement for one stage of a two system detection system may not be identical to optimal placement in the single stage case.

Analysis of the two stage signal detection model also demonstrates that quantitative predictions can be made about alerted-monitor system performance via system operating characteristics, if some data is available about how

operator detectability and criterion depend on the characteristics of the automated monitor and on other task conditions. Our analysis provides a conceptual framework to guide empirical studies of automated monitor-human monitor performance. The important independent variables in such studies are the processing load imposed by non-monitor tasks and the response criterion of the alerting subsystem, C_a. Relevant dependent variables include operator criterion, C_h, operator observing probability, P(observe), and operator sensitivity, d'_h. These variables should be assessed in conditions which include a range of operator and automated subsystem criteria. We are presently working toward obtaining this empirical specification of alerted-monitor system performance.

3.1 Complex Alerted-Monitor Systems

The signal detection analysis also suggests possible design features for advanced alerted-monitor systems. One possibility involves the use of multiple output criteria in the automated subsystem. A simple example is an alerting signal explicitly coded to indicate the conservatism of the criterion (C_a) that has been exceeded. The operator could then shift resource allocation strategies based on the level of alarm. Designers of alerted-monitor systems might also use multiple subsystem criteria in more complex ways, such as having different modes of human-machine interaction triggered by different criterion values (cf. Sheridan, 1982 for one categorization of levels of automated decision system-human decision maker interaction). For example, a monitoring system might combine a relatively liberal subsystem criterion which signals an advisory or decision support mode of human-machine interaction. A more conservative criterion could trigger a second mode of interaction where the automated subsystem directly activates control systems subject to subsequent operator review and intervention.

A second possible design feature is to directly present to the human monitor the likelihood estimate, e.g., the value of the decision statistic, Z, computed by the automated subsystem. From a display point of view, this suggestion could imply an analog form of data presentation (i.e., presentation of automated subsystem output as a continuous variable, "degree of alarm", with response criteria highlighted, rather than only as alarm/no alarm categories); A report by Woods, Wise & Hanes (1982) contains an example of such a display. Likelihood presentation is one mechanism that could allow the human monitor to inspect (although not necessarily duplicate) the process by which the automated subsystem reaches its conclusion in cases of uncertainty or conflict. Finally, interface features that reduce the correlation between the automated and human monitor's input channels can increase the performance capability of the combined system. This is a subtle aspect of system design, because in many situations there may be an advantage in redundancy between these channels.

In some task environments there is the possibility of considerable interaction among the alerting signals themselves, and alerting signals may be missed or confused (Cooper, 1977; Patterson & Milroy, 1980). Patterson & Milroy (1980) discussed the confusability of auditory alarm signals on aircraft flight decks. The present analysis does not address this problem, since we have assumed that the detectability and discriminability of the actual alerting signals is infinite. Extending the signal detection analysis to include these factors introduces two kinds of complications. The first is that the presence of noise in the task environment can impair the detectability of the alarm signal itself. The general problem of an alerting subsystem whose output signal is communicated over a noisy channel is part of a problem described by Dr. James P. Egan as the "telegraph relay" problem. This assumption increases the complexity of the alerted-monitor model; the system becomes a three stage detection system.

The second complication results from the existence of multiple alarm channels. How would an operator establish response priorities to a set of four automated monitors, each of which has unique pay-off/penalty contingencies, prior probabilities of signal, and sensitivity and criterion parameters? It is clear that the allocation of processing resources would be a significant aspect of such a task.

As technological changes shift the human role to primarily one of supervisory control (National Research Council, in press; Woods, 1983), monitoring an array of multiple automated monitors could well be the major function of the operator. Describing and predicting the performance of such a system would be critically dependent on describing the system behavior on each channel (and the channel interactions) in terms of the models proposed in our analysis. Indeed, the alerted-monitor system could provide a general paradigm for describing the behavior of operators in a variety of multiple channel and time-shared tasks.

ACKNOWLEDGMENTS

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NOTES

1. In the signal detection literature it is customary to define the response criterion parameter as β rather than C; β is the ratio of the ordinates of the decision distributions when Z equals C. That is, $\beta = [f(C/SN)]/[f(C/N)]$. We use C in this paper for ease of exposition of the theory.

2. There is evidence supporting modeling of human monitors as a signal detection system in a variety of different tasks and work environments including industrial inspection, supervisory control, sonar/radar, and medical image systems (e.g., Davies & Parasuraman, 1981; Bisseret, 1981; Kantowitz & Sorkin, 1983; Swets & Pickett, 1982).

3. If there were n stages, the overall detectability would be $\sqrt{n}\ d'$. This relation follows from the assumption that the noise or variability of each stage is equal and statistically independent. The standard deviation of a detection statistic based on n independent observations is thus $1/\sqrt{n}$ times that based on one observation.

4. We recognize that in actual work environments the human operator may also monitor the input channel independent of outputs from alerting subsystems. For example in one nuclear power plant critical incident (NUREG-0977), the operators correctly detected abnormal plant conditions requiring operator action independent of automatic monitoring subsystem output.

5. The curves are not proper receiver operating characteristics in the decision theory sense, since P(Y/SN) does not increase from 0,0 to 1,1 with monotonically decreasing slope (see Tanner & Sorkin, 1972).

6. The motivation for this behavior may not be only because a false alarm is expected; the air crew may quickly cancel warning signals because of the signal's aversive and distracting nature and their potential to disrupt vital communications (Patterson, 1982).

FIGURE CAPTIONS

Figure 1. The basic signal detection system. (See text for discussion.)

Figure 2. Probability distributions of Z, the decision statistic. Values of Z greater than C lead to a "Yes" response.

Figure 3. Receiver Operating Characteristics for d' values of 1, 2, and 3.

Figure 4. Signal detection model of an alerted-monitor system. The inputs to the automated monitor (X_a) and the human monitor (X_h) are subsets of the input vector, X. An output from the automated monitor subsystem may cause the human operator to make an observation on the input channel.

Figure 5. System operating characteristics for $d'_a = d'_h = 2$. Each curve is the system operating characteristic for a fixed value of C_a, evaluated over all possible values of C_h. The highest curve is for $C_a = -0.5$; C_a increases in steps of 0.5 for the lower curves. (C_a is in d' or standard deviate units.) The outer envelope of the curves approximates the receiver operating characteristic for a detection system with a d' = 2.4.

Figure 6. The consequences of subsystem interaction if the human monitor's criterion depends on the output (alarm) rate of the automated monitor. Each subsystem d' = 2. Performance is evaluated for all values of C_a under the assumption that C_h = 2 P(alarm).

Figure 7. The consequences of subsystem interaction under the sampling assumption. Each curve is the system operating characteristic for a fixed value of C_a (shown in d' or standard deviate units) and all possible values of C_h; $d'_a = d'_h = 2$. The human monitor is assumed to make observations on the input channel with a probability that decreases linearly with the alarm rate of the automated monitor: P(observe) = 1 - [P(alarm)/2].

Figure 8. Two forms of the assumed dependence of operator detectability on the alarm rate of the automated monitor (see text).

Figure 9. The consequences of system interaction under a d' allocation strategy (the solid curve of Figure 8). Each curve is the system operating curve for a fixed value of C_a (shown) and all possible values of C_h; $d'_a = 2$.

Figure 10. The consequences of system interaction under a d' allocation strategy (the dotted curve of Figure 8). Each curve is the system operating curve for a fixed value of C_a (shown) and all possible values of C_h; $d'_a = 2$. The curves converge on the ROC for a single stage system having a $d' = 1.0$. The last three curves plotted are for C_a values of -1.5, -2.0, and -2.5.

Figure 11. An example of a combined sampling and d' allocation strategy. Neither the operator's d' nor the operator's probability of observing decreases to zero at high alarm rates.

Figure 12. The consequences on system performance of the combined strategy shown in Figure 11. Each curve is the system operating curve for a fixed value of C_a (shown) and all possible values of C_h; $d'_a = 2$.

Figure 13. The system operating characteristic for the system shown in Figures 11 and 12 under the additional constraint that $C_h = C_a$. Performance is evaluated over all possible values of C_a.

Table I

Hit [P(Y/SN)] and False Alarm [P(Y/N)] Probabilities for Selected Values of d' and C.

d'	C	P(Y/SN)	P(Y/N)
2	0	.977	.500
2	1	.841	.159
2	2	.500	.023
1	0	.841	.500
1	0.5	.691	.308
1	1	.500	.159

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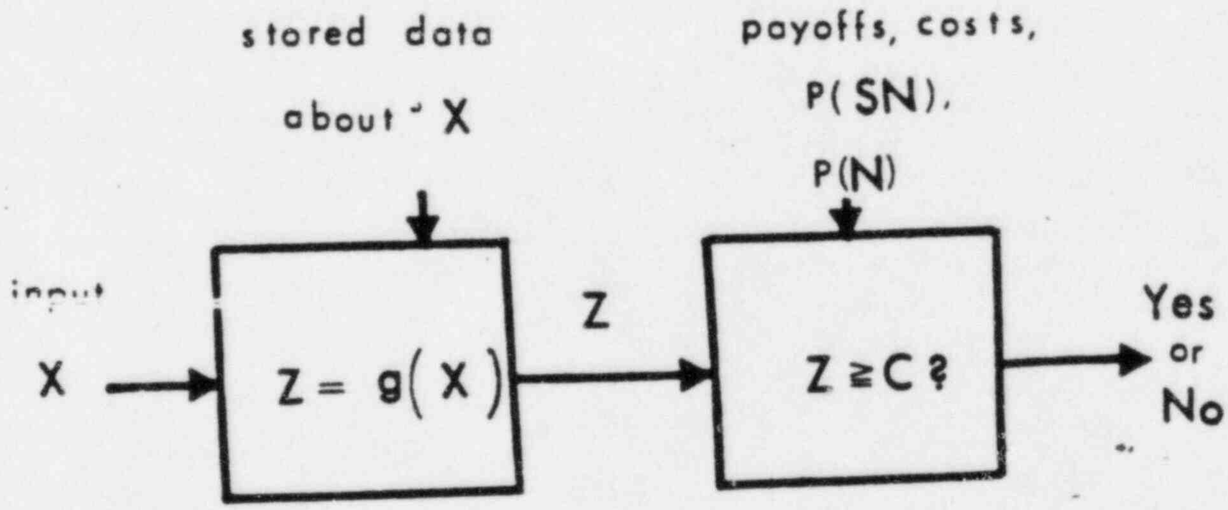
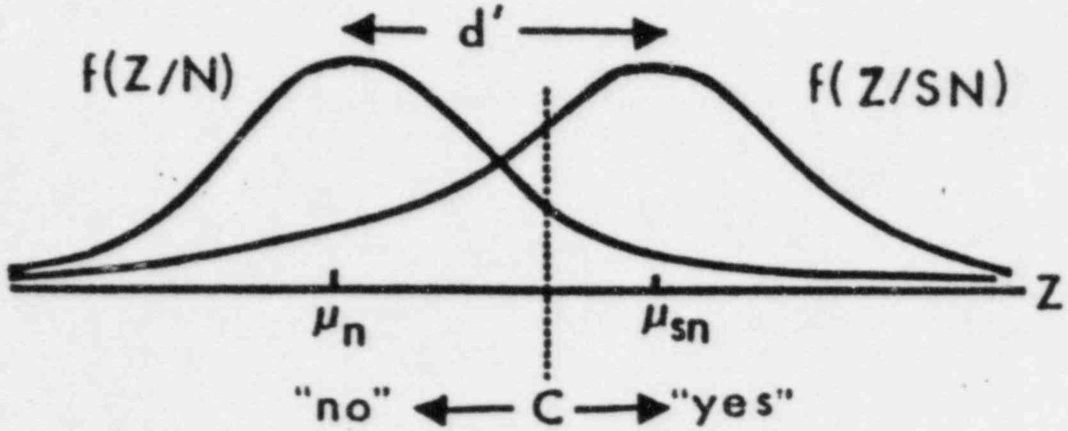
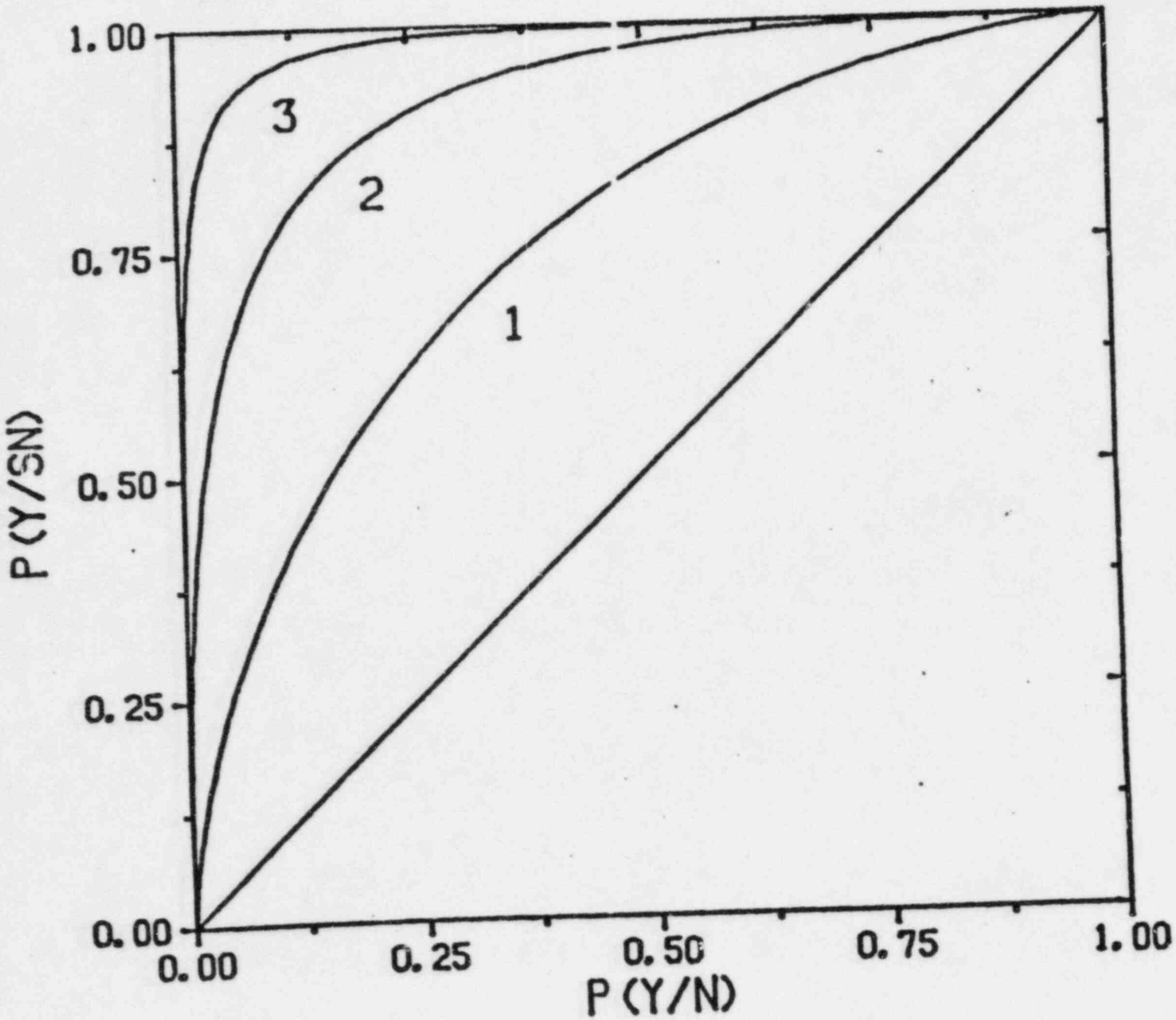
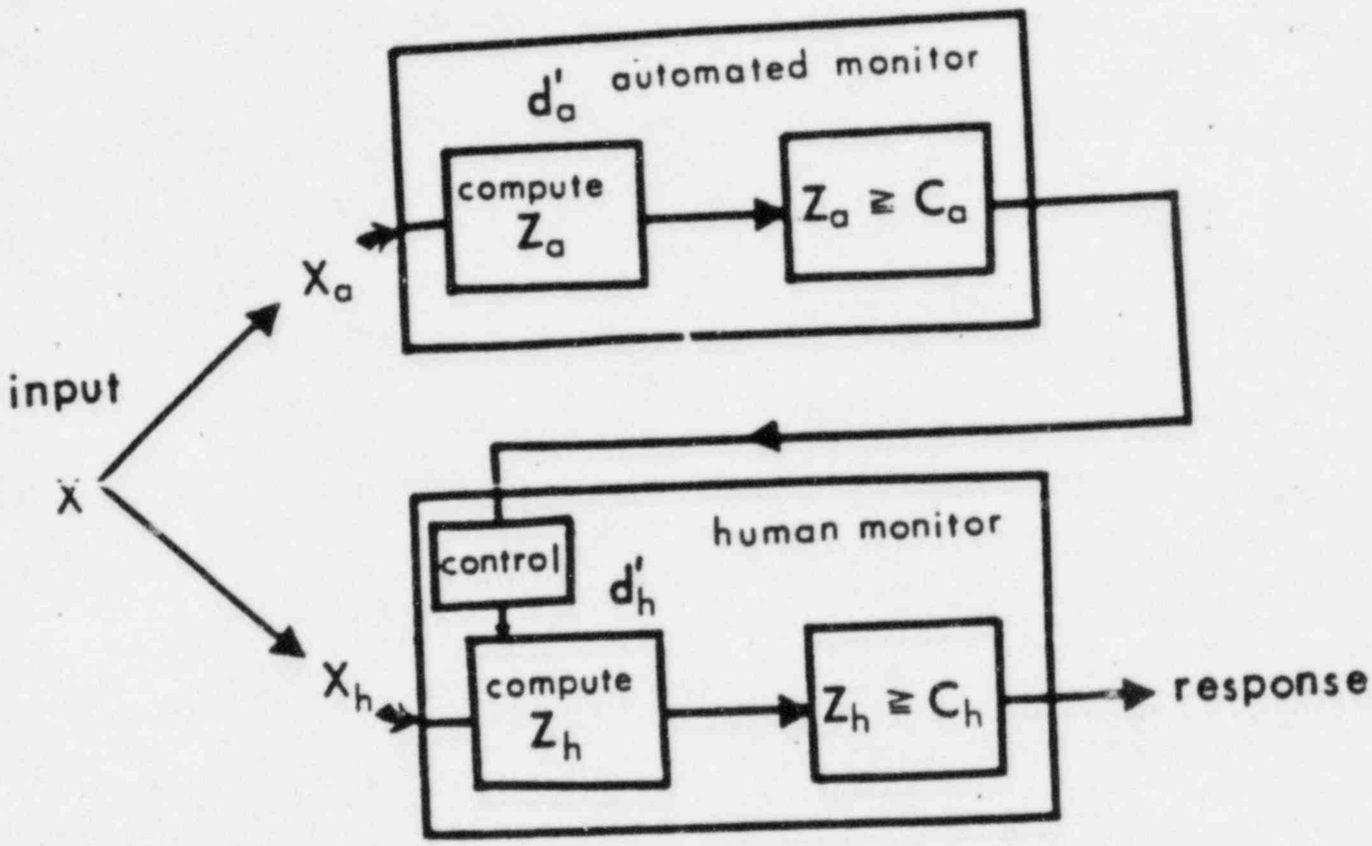

stored data
about X
payoffs, costs,
P(SN),
P(N)
input
X
Z = g(X)
Z
Z ≥ C ?
Yes
or
No



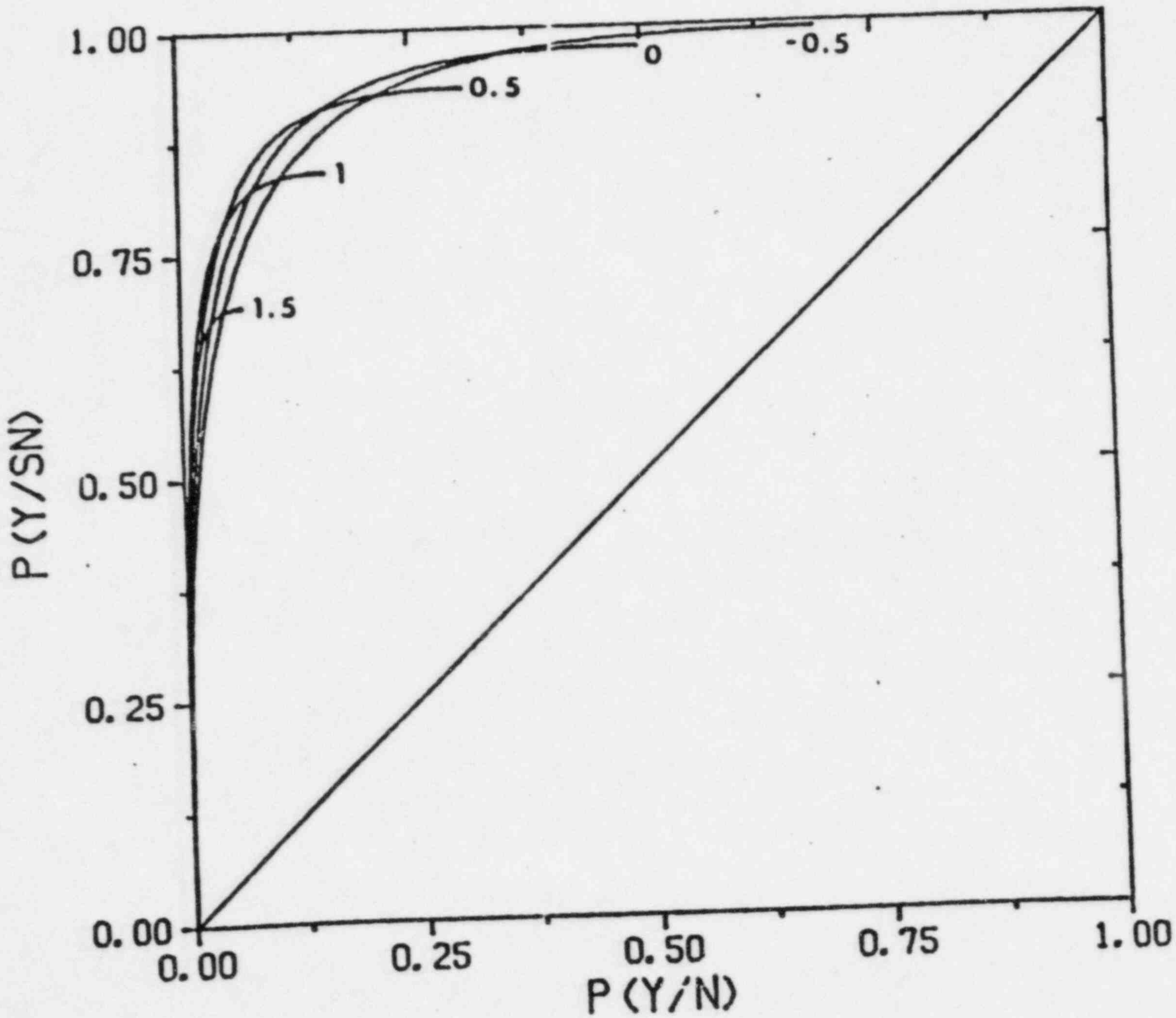
d'
f(Z/N)
f(Z/SN)
Z
μ_n
μ_{sn}
"no"
C
"yes"

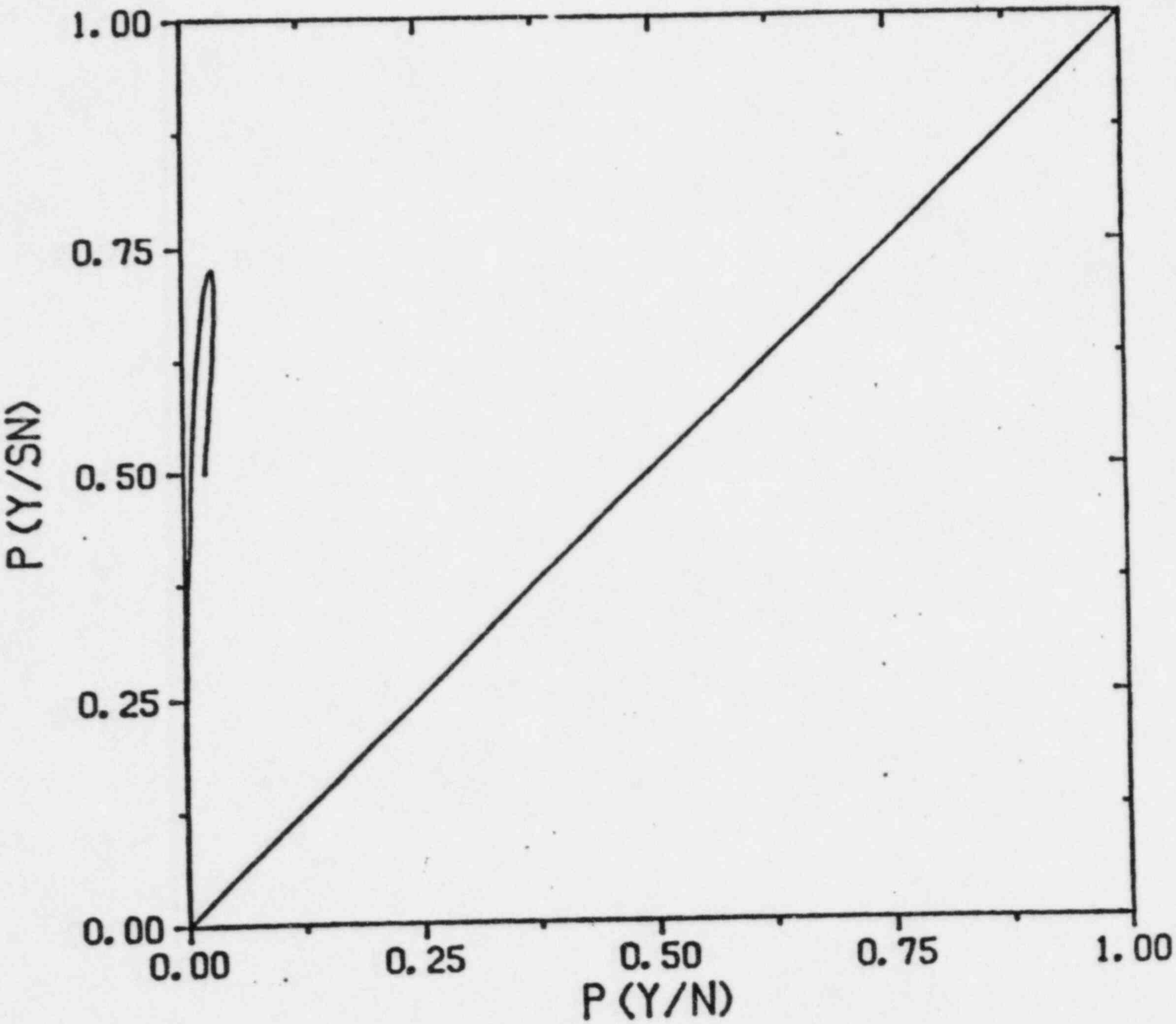


3

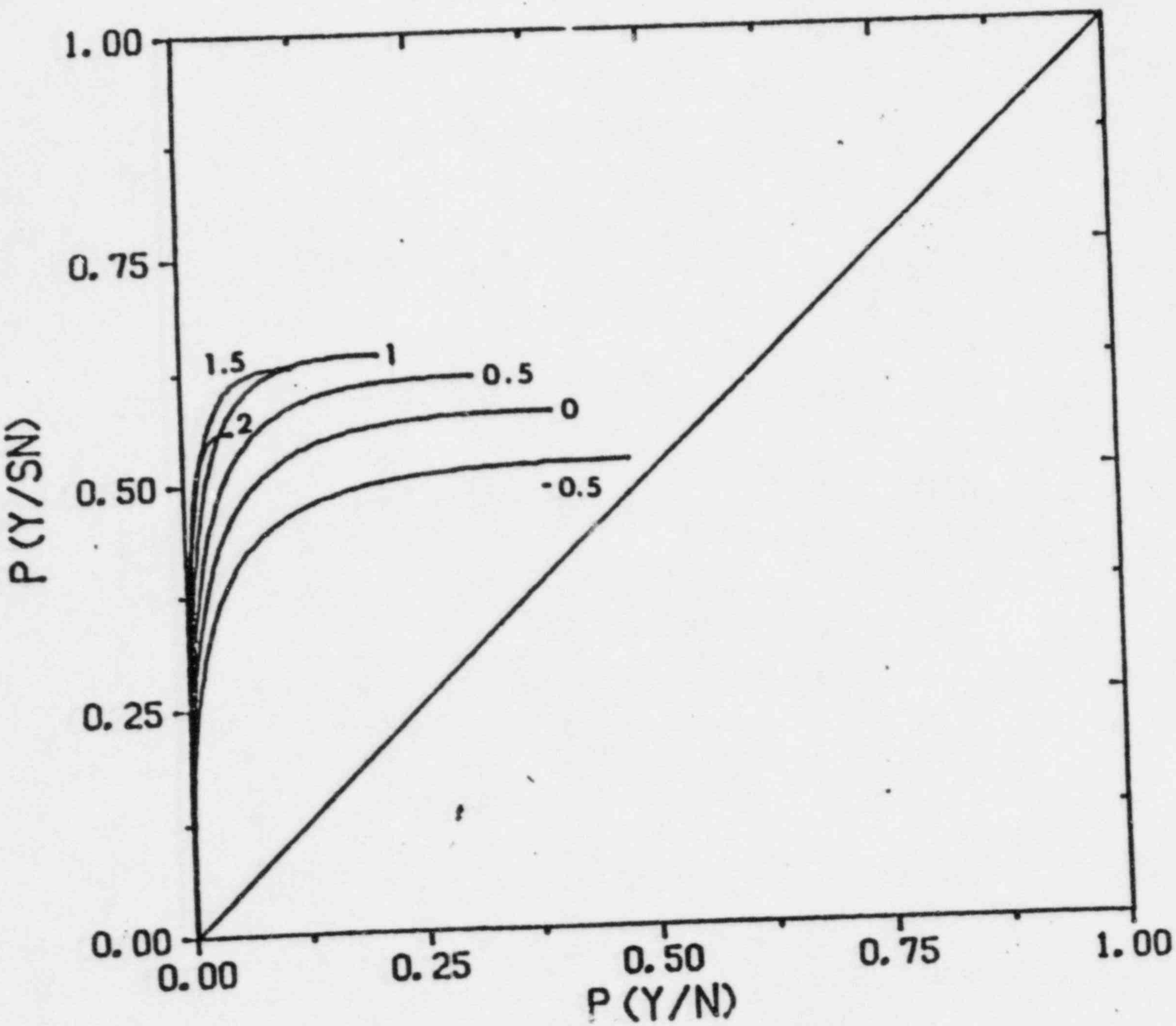


automated monitor
d'_a
compute Z_a
$Z_a \geq C_a$
X_a
input
X
human monitor
control
d'_h
compute Z_h
$Z_h \geq C_h$
X_h
response


1.00
0.75
0.50
0.25
0.00
P (Y/SN)
0.00
0.25
0.50
0.75
1.00
P (Y/N)
-0.5
0
0.5
1
1.5



9


1.00
0.75
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P (Y/SN)
0.00
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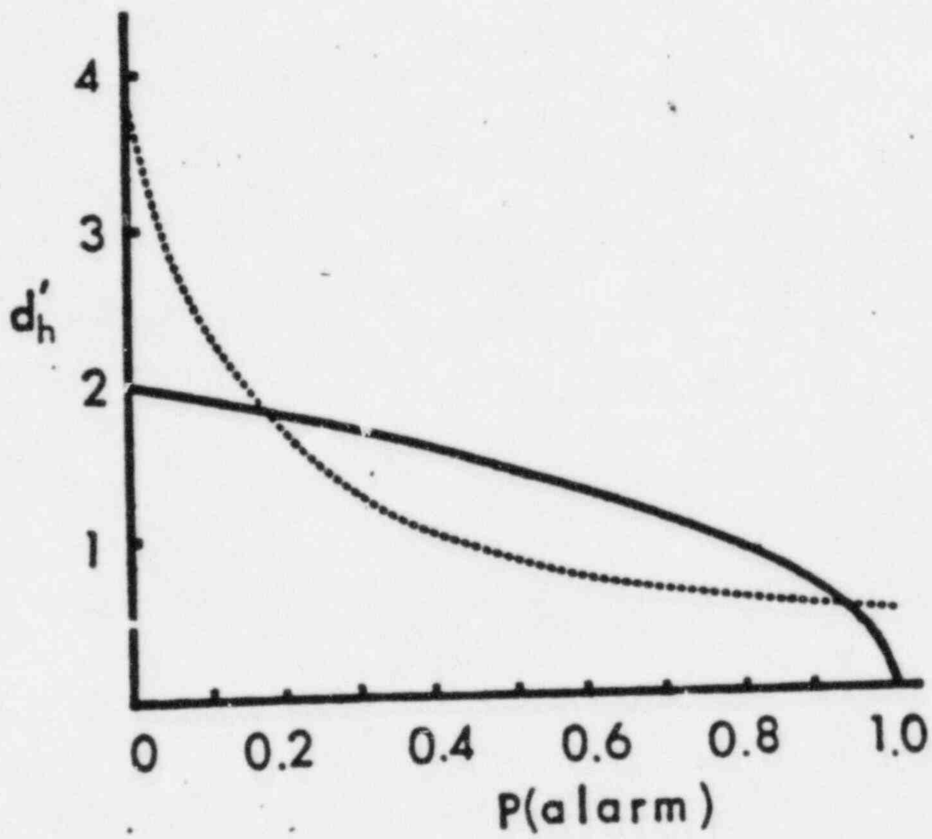
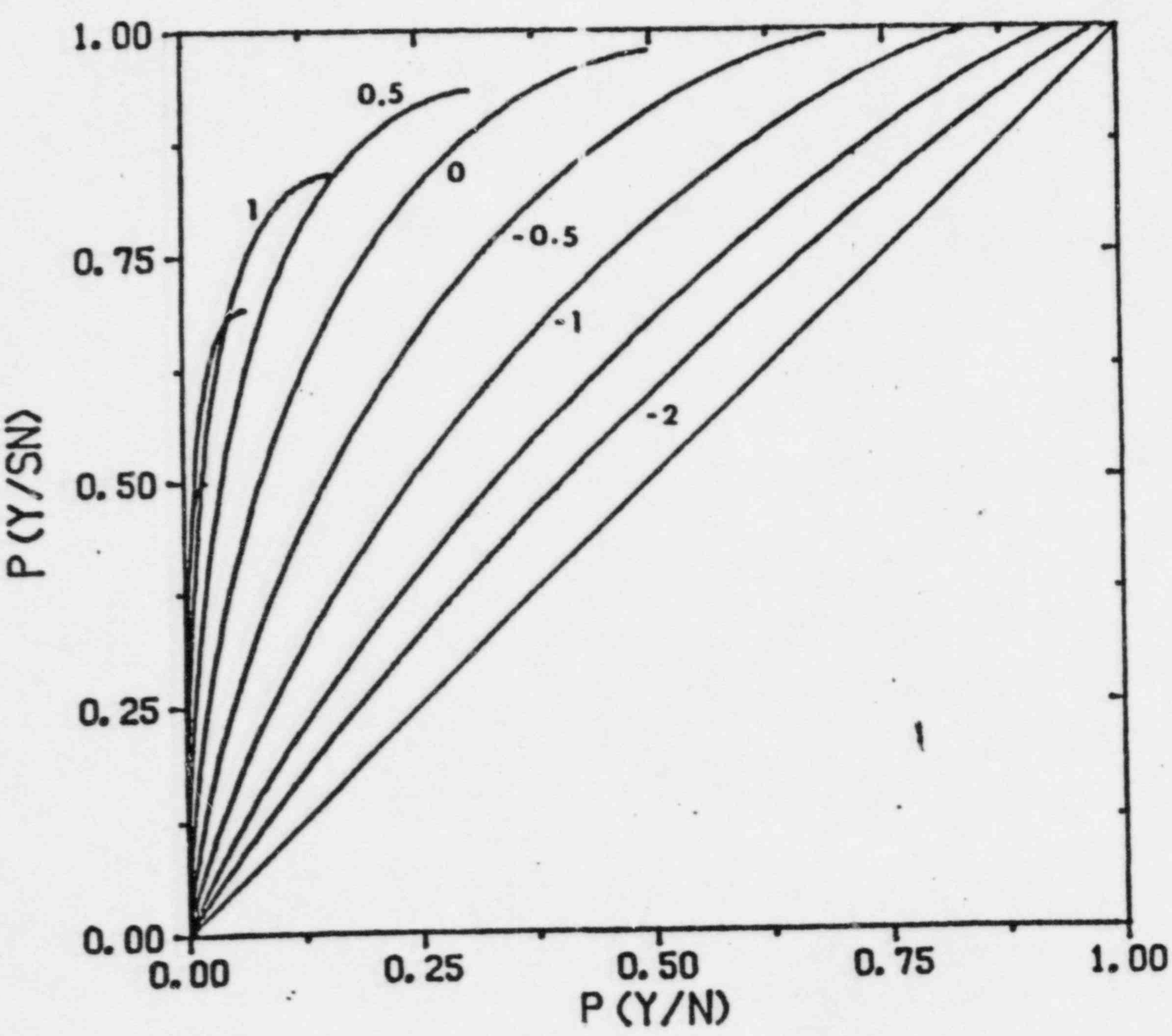
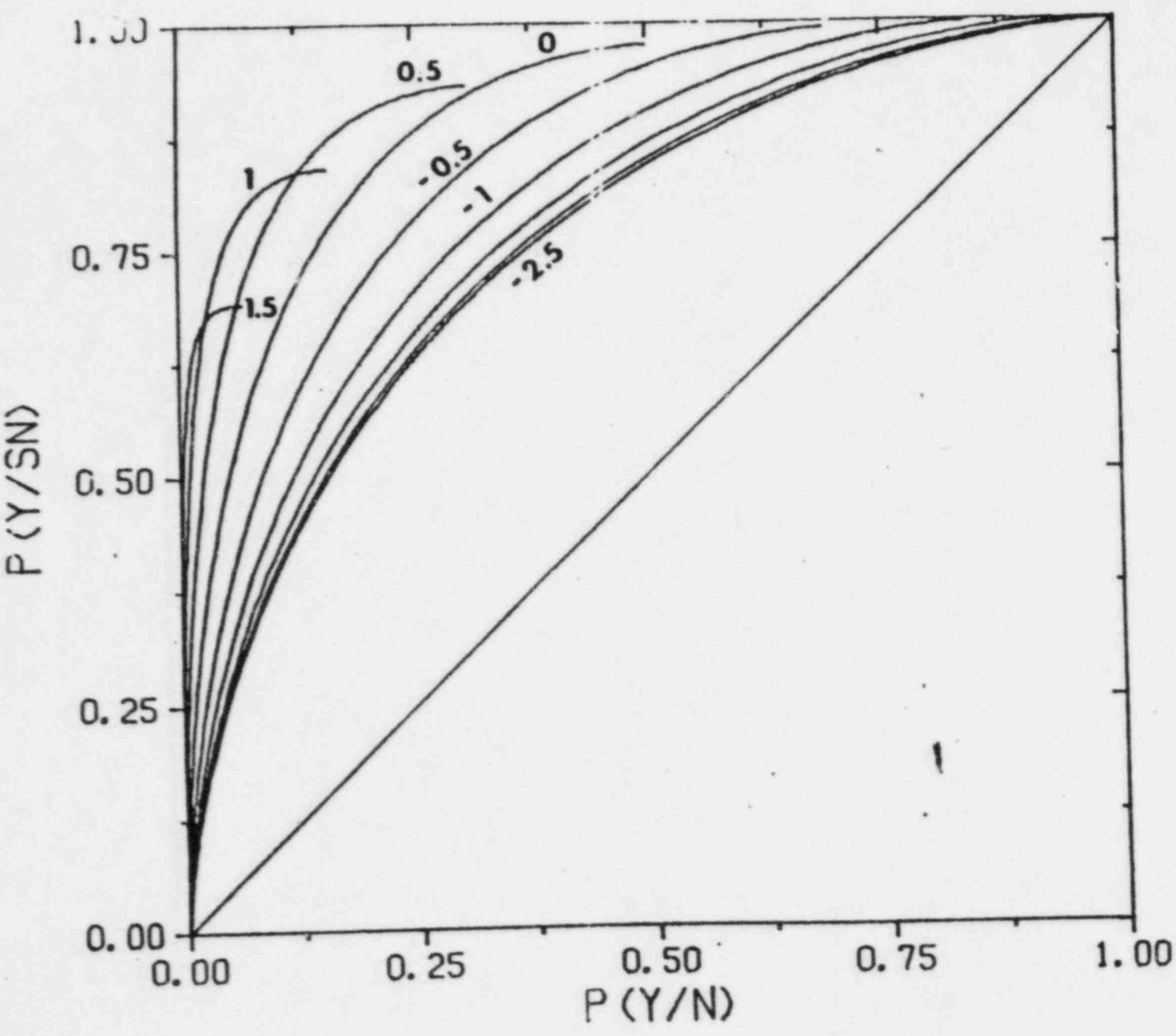
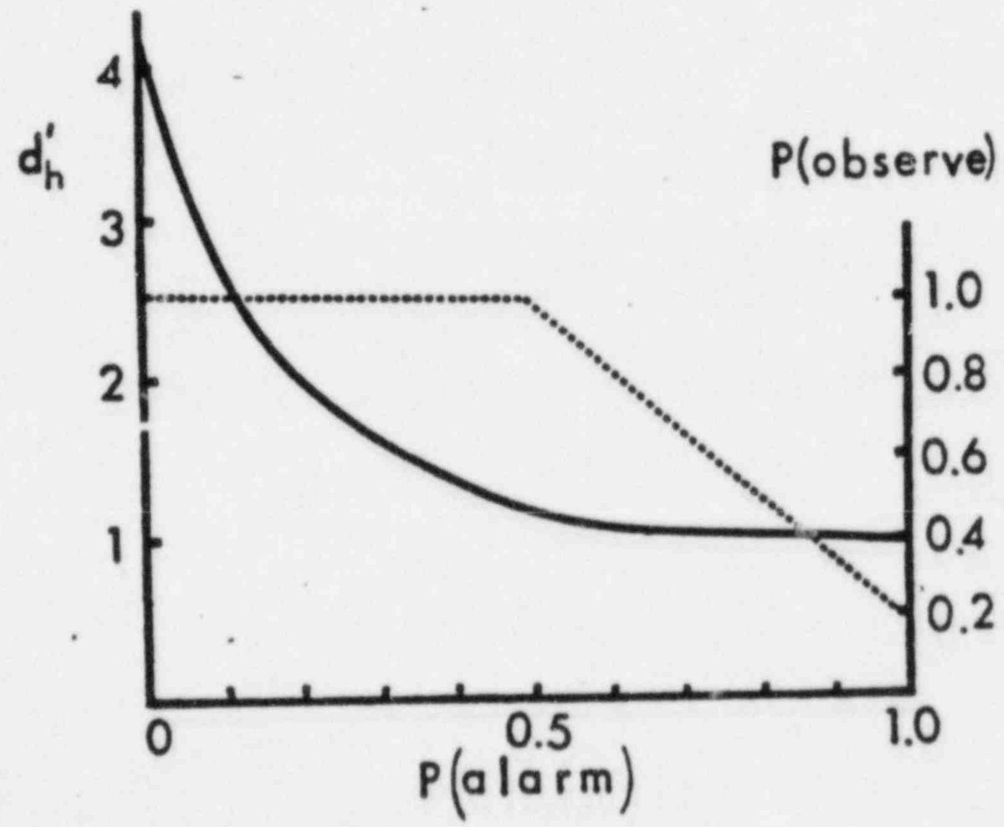
1.00
P (Y/N)
1.5
1
0.5
2
0
-0.5


4
3
d'_h
2
1
0
0.2
0.4
0.6
0.8
1.0
P(alarm)

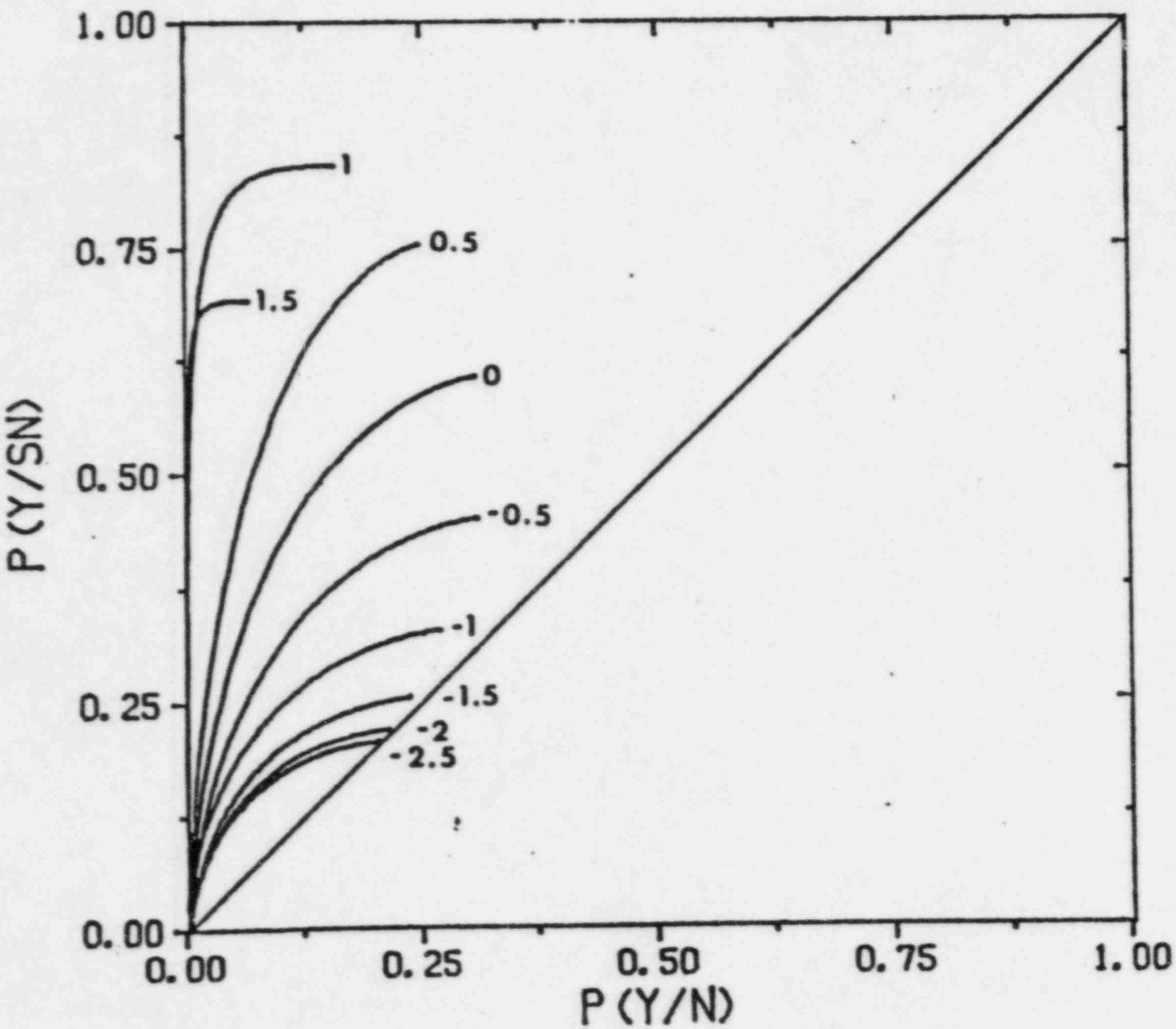


9


1.00
0.75
0.50
0.25
0.00
P (Y/SN)
0.00
0.25
0.50
0.75
1.00
P (Y/N)
1
1.5
0.5
0
-0.5
-1
-2.5



4
d_h'
3
2
1
P(observe)
1.0
0.8
0.6
0.4
0.2
0
0.5
1.0
P(alarm)


P (Y/SN)
P (Y/N)
1.00
0.75
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1
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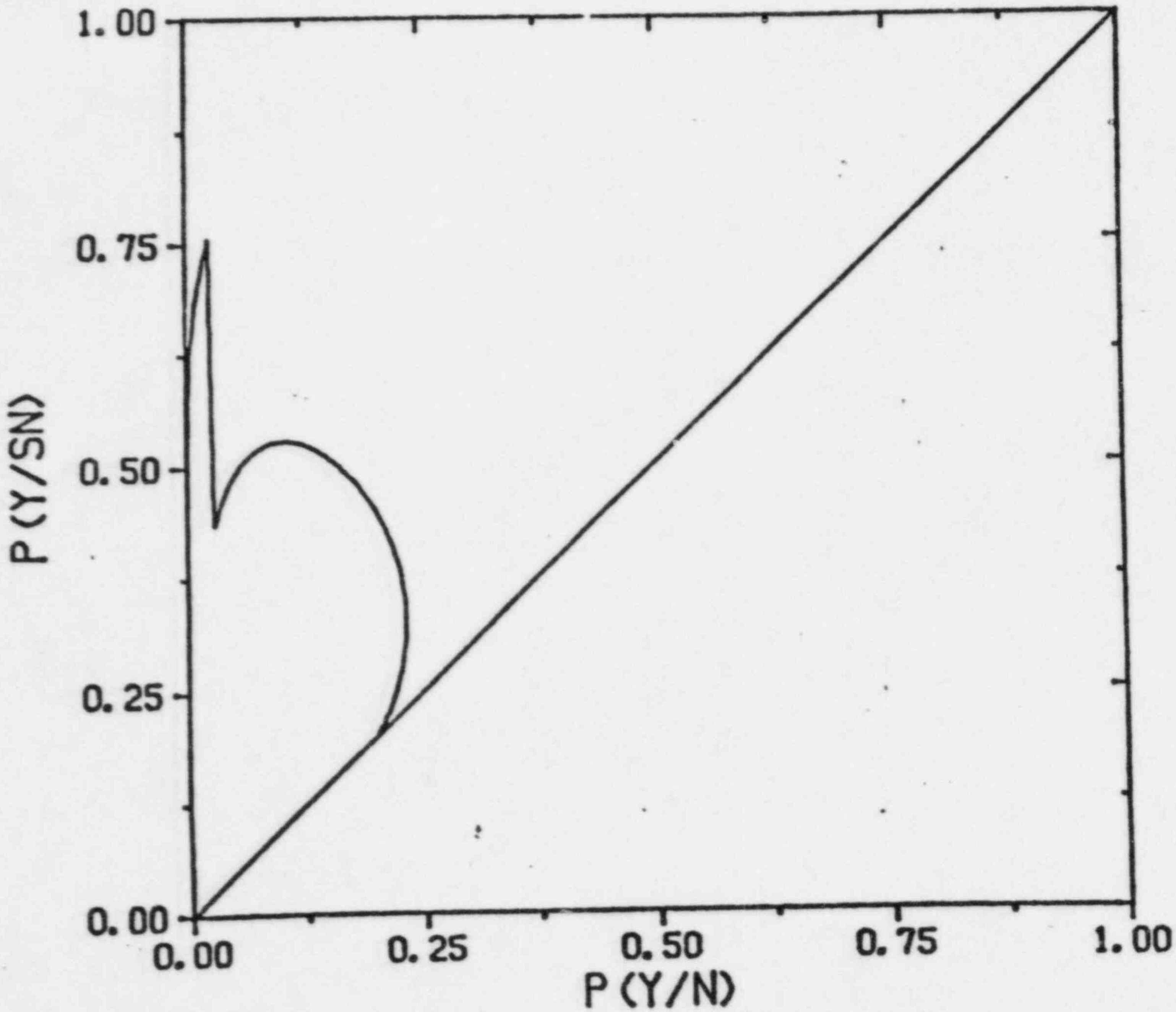
1.5
0
-0.5
-1
-1.5
-2
-2.5


1.00
0.75
0.50
0.25
0.00
P (Y/SN)
0.00
0.25
0.50
0.75
1.00
P (Y/N)

Appendix D

S-125-25

Issues In Cognitive Reliability

D.D. Woods, J.A. Rumancik
& M.J. Hitchler

Proceedings Of ANS Topical Meeting
On Anticipated And Abnormal Plant
Transients In Light Water Reactors,
Plenum Press, In Press.

Human Sciences

Westinghouse Research and Development Center

ISSUES IN COGNITIVE RELIABILITY

D. D. Woods, Research and Development Center

J. A. Rumancik & M. J. Hitchler, Nuclear Technology

Division

Westinghouse Electric Corporation
Pittsburgh, PA 15235

INTRODUCTION

The human role in complex process systems is increasingly to act as a supervisor, that is, to monitor/manage a partially self-controlling process, to handle the unexpected, to provide backup control when automatic systems fail. This means that operators function primarily in a cognitive mode (set/monitor goals, solve problems, make decisions) and only secondarily as a simple sensor or effector mechanism. As a result, techniques to incorporate human performance in probabilistic risk assessment (PRA) need to address operator reliability at cognitive tasks. This paper examines some problems in current methods to assess cognitive reliability[1] and points to new approaches to solve these problems.

PROBLEMS IN COGNITIVE RELIABILITY ASSESSMENT

One can distinguish between two types of human failures:[2,3] errors in the <u>execution</u> of an intention and errors in the <u>formation/selection</u> of an intention. If a nuclear plant operator decides to move the control rods into the reactor but grabs the control device and begins to move them out, then a failure to execute an intention occurred (action not as planned). If the above operator drove the rods in when circumstances did not demand this response, then a failure in the formation of an intention occurred.

However, from the operator's point of view, the action may have been exactly what he intended, given his assessment of system state. Incorporating cognitive performance into PRAs requires an understanding of both the factors that lead to the selection of actions (i.e., when to choose one response given the set possible responses) and the factors that affect successful execution of intended actions.

Types of Description

One problem with human reliability analysis (HRA) techniques in general is the question of what are the units of behavior whose reliability are to be determined.[4] With respect to cognitive factors, this problem occurs in part because current HRA techniques and cognitive psychology use different languages to describe operator behavior. HRA describes operator behavior in the language of the profession focusing on the specific details of some specific malfunction, e.g., the number of times an operator fails to close valve y in event x. This is a description in terms of the external mode of malfunction in the human error taxonomy shown in Figure 1.[5] In contrast, psychological descriptions of operator behavior use a language based on some model of human performance, e.g., the human malfunction was the substitution of a frequently performed behavioral routine for a similar but infrequently performed behavioral sequence. This is a description in terms of internal mechanisms of human malfunctions (the categories of "mechanisms of malfunction" and "internal human malfunction" in Figure 1). Psychological description of operator performance requires knowledge about the context or background for a given action (for example, Woods et al.[6] contains cases where the quality of a given operator action in one event varies depending on the operator's target when he performs the action). However, the psychological descriptor will apply to many different specific operator misactions in many different events, and countermeasures can be devised for the class of misactions which will improve operator action in a variety of specific cases. Thus, psychological description produces more general results than context specific descriptions. There have been several studies of operator behavior in both actual and simulated emergencies that used a simple model of human performance to produce general descriptions of operator performance in emergencies[6,7,8,9] (Table 1 contains an example of results from these studies).

Error Correction

A second problem for HRA is that people often detect and correct their errors. In the same way that a target/actual state mismatch (i.e., an error signal) drives a feedback control system, the person (and especially the man-machine system) can be seen as

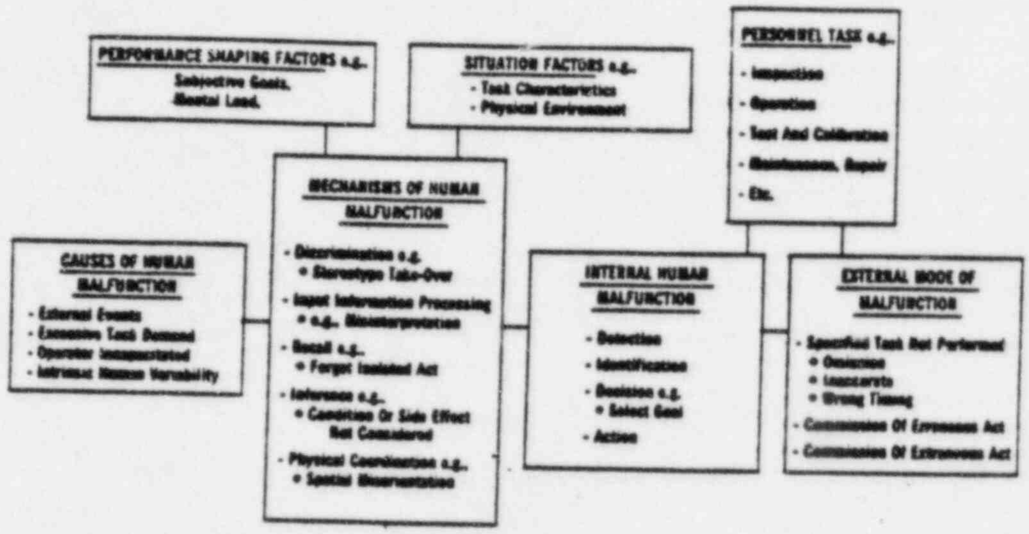


Figure 1. Human error taxonomy.[5]

an error-actuated system. The key then to successful performance is the operator's ability to detect any mismatch in target/actual state (a) in terms of differences between an operator's or a crew's intention and action, (b) in terms of differences between goal state and actual process state at several levels: verify implementation (is the valve open?) monitor process state (is there flow?), and monitor goal achievement (is inventory adequate?). From this point of view, one measure of successful operator performance is the operator's ability to obtain multiple levels of feedback. The question then becomes are HRA techniques sensitive to differences in the man-machine system that affect the operator's ability to obtain feedback at multiple levels. This challenge is closely related to the problem of how to show that operator performance can contribute to, rather than just detract from, overall system performance.

Cognitive Performance and Response Time

There have been attempts to incorporate cognitive aspects of human performance into HRA by relating the quality of performance on cognitive tasks to the time available to perform the task, i.e., the greater the time available, the greater the probability of success.[10] This notion of time-reliability correlation has been expressed by hypothetical and empirical plots of the probability of success or failure versus time on logarithmic or lognormal axes (Figure 2). However, plotting accuracy versus time on log scales obscures critical information about the nature of human performance.

When accuracy versus time is plotted on linear axes (Figure 3), the result is a curve that psychologists call a speed-accuracy tradeoff function. The important thing to note about Figure 3 is that there are two performance regions. For time values less than some critical time, t_c, the curve shows a tradeoff between response time and accuracy, that is, faster response can be achieved only at the cost of impaired accuracy. However, for time values greater than t_c, the curve shows that performance is relatively independent of time, i.e., there is no practical improvement in performance with longer response times (practically speaking this is true regardless of whether the curve is truly asymptotic or still slowly increasing).

The implications of the speed-accuracy tradeoff function for HRA can be summarized as follows: for

t_a = time available to perform a task
t_c = critical time marker for the speed/accuracy tradeoff region, then,

if $t_a < t_c$, then prob. (success) ∝ t_a;

if $t_a > t_c$, then prob. (success) ≈ constant (for some time region of interest).

It is also important to note that the concept of a speed-accuracy tradeoff was developed in the context of perceptual-motor skills. This means that the above relationship between quality of performance and response time applies to all types of operator tasks.

Empirical results on operator performance in emergencies support the above analysis. For example, Table 1[9] contains data from simulated power plant emergencies (from Woods et al.[6] and unpublished data) on operators' ability to identify and correct the control problems they experience.* The data shows that the operators who misidentified plant state or had execution difficulties generally failed to correct their understanding of plant state or to identify and correct execution problems within the duration of the test events.

These results show no sign of a speed-accuracy tradeoff, i.e., longer response times were not correlated with higher quality responses. Similarly, Beare et al[11] found no relationship between speed and accuracy for nuclear power plant operator performance in

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*These data account for 70% of all of the operator problems in these studies, the remaining operator problems were responses judged as too slow or were non-correctable. Given the number of test scenarios (54 using 23 experienced crews in eight different events), there were very few operator problems and those that did occur were of little consequence to the final outcome.

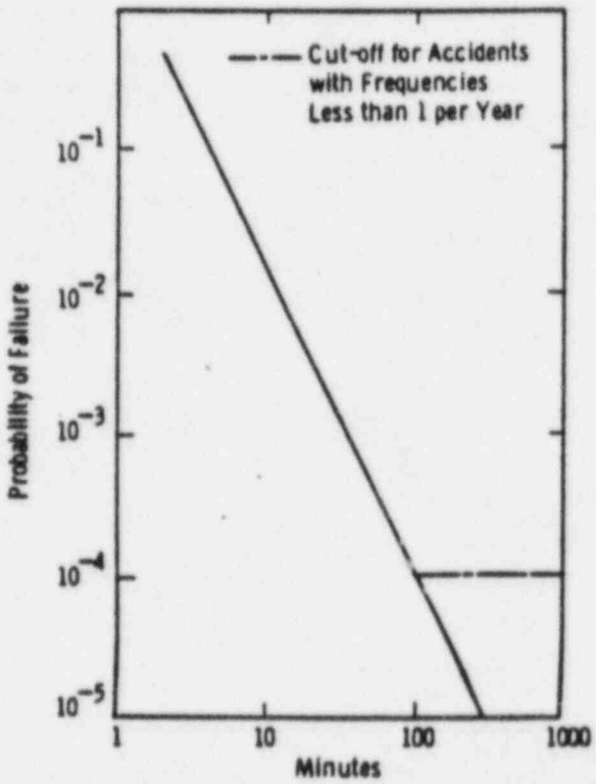

Figure 2. Hypothetical relationship between failure probability and time for cognitive tasks.[10]

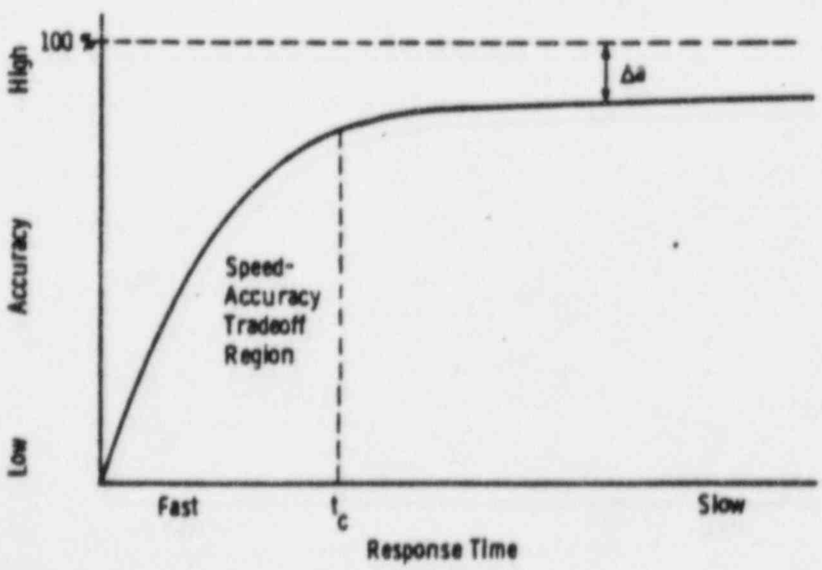

Figure 3. Speed-accuracy tradeoff in human performance.

Table 1. Operator Performance: Error Correction (Data from Woods et al.[6] and unpublished data).

	No Correction	Corrected Only Throughout External Agent	Corrected
Problem In State Identification	14	5	0
Problem In Execution	10	0	10
Total	24	5	10

emergency events, and Wohl[12] found two performance regions for maintenance diagnosis in aerospace applications (performance improved with time only up to some cirtical time). These results show that, for major operator tasks in emergency events, operator performance is not time dependent, i.e., $t_a > t_c$.

NEW DIRECTIONS

Given the above problems, what can be done to develop tools for the assessment of cognitive reliability.

Speed-Accuracy Tradeoff

The speed-accuracy tradeoff function can be used to estimate relative success or failure rates if the general form of this function (e.g., t_c, Δa) is known for the class of operator task in question. For example, deadline studies on tasks that are representative of various operator task categories could be used to compile such information. The family of speed/accuracy functions organized by task category that would result from such studies could then be used by HRA analysts to estimate relative probabilities for operator action in particular contexts. Such a program requires some generic description of operator tasks plus specific tasks that are good exemplars of the categories.

Function Based Task Analysis

One key characteristic of decision making is its goal directed nature. This means that information on the factors that lead operators to select actions can be developed through a function based analysis (i.e., event independent) that maps the goal structure for plant control.[13,14] The plant's goal structure is mapped by identifying relationships between goals and means where each node in

the structure can be seen as a means with respect to higher level nodes <u>and</u> as a goal relative to lower level nodes (Figure 4). The network of relationships that results from this analysis define the problem space for plant operations; it contains the control tasks and decisions that can occur in the pursuit of specific operational goals.

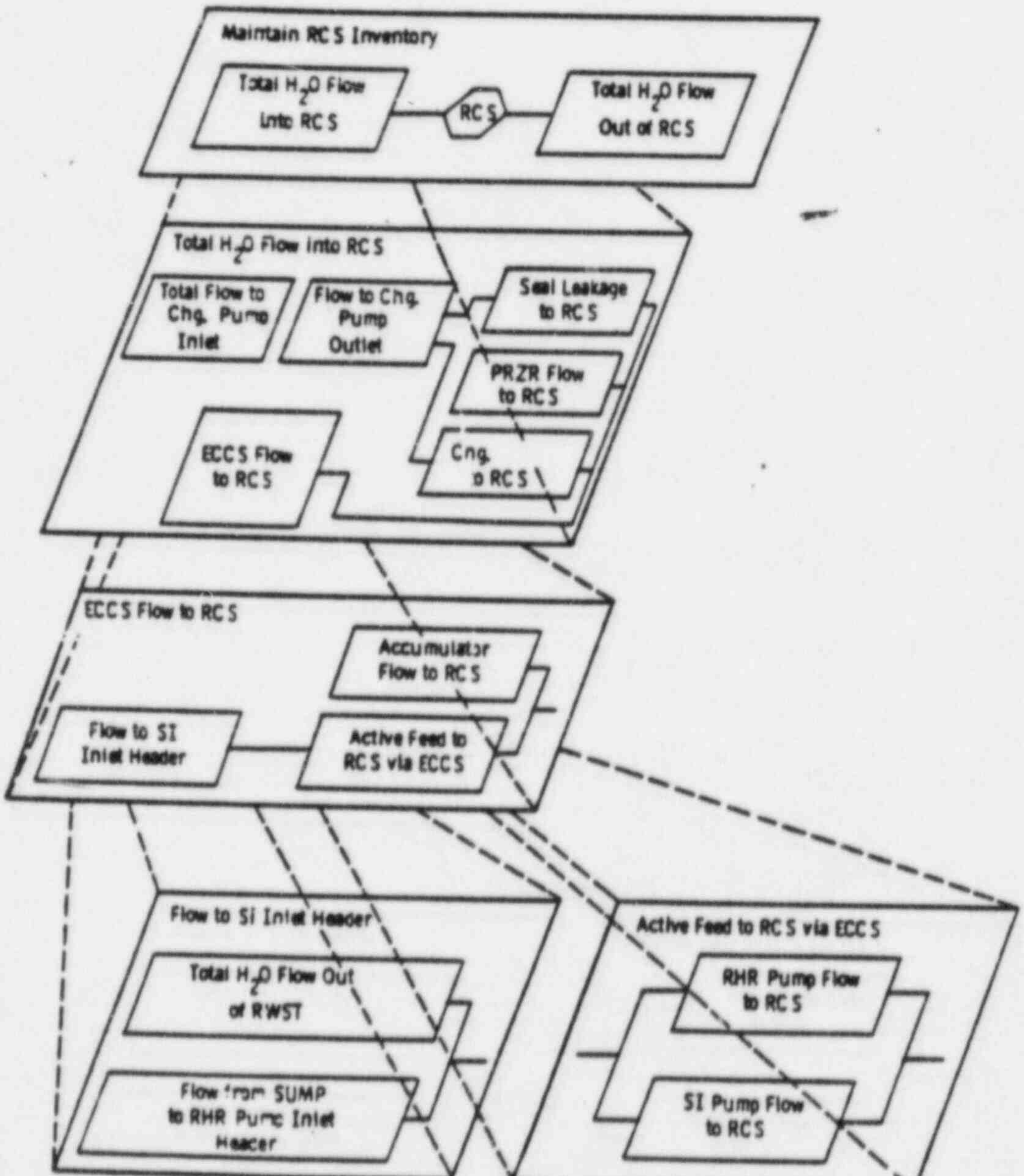

Figure 4. Simplified example of function based analysis of the goal structure for plant control.

The details of a particular event sequence (especially temporal characteristics) can be mapped onto the framework provided by the goal structure in order to identify the important control and decision requirements for that scenario. In other words, the function based task analysis can help define the relevant behavioral units whose reliability are to be estimated.

One example, from an actual PRA study on a PWR, is an event where auxiliary feedpump suction strainers are clogged following reactor trip. The PRA analysis performed on this case considered operator behavior only from the point of view of procedure execution to fix the clogged strainer. Since no procedure to clear the strainers was available, no consideration of operator behavior to prevent or mitigate core damage for this event was included in the PRA.

Operator behavior is goal directed, and in this case, the functional structure reveals relevant goals at several levels (Table 2): repair the strainers (e.g., remove them or backflush), provide an alternative feedwater transport mechanism (e.g., main feed or condensate booster pumps), or provide an alternative means for core heat removal (e.g., feed and bleed operation). Human reliability analysis for this event should consider operator behavior on each of these tasks.

Identifying the various levels at which the operator can halt the event sequence provides a basis to begin to consider operator error correction behavior. For example, if the initiating act was an operator execution error rather than a physical disturbance, the operational staff may be able to directly correct the misaction or to respond to higher level goals affected by the error. A key problem for the HRA analyst then is to determine or estimate the degree to which a particular emergency operations system (instrumentation, training, procedures, TSC, operator aids) supports or provides feedback on goal achievement.

The function based task analysis aids cognitive reliability assessment by providing

- a basis for identifying control and decision requirements
- the potential to capture error corrective behavior.

In addition, the function based approach can

- provide a mechanism to address continuous control tasks (existing techniques are better suited for discrete control tasks)
- provide the potential for analyses of the goal structure to determine the difficulty of control tasks and decisions (e.g., the number of side effects to be balanced)
- mitigate against the completeness problem in event based analysis approaches.

Table 2. Function Based Analysis of Operator Tasks in One PRA Event (clogged AFW pump suction strainers).

Functional Structure	Potential Operator Responses
Core Heat Removal: Via Secondary	Provide Alternative Heat Removal Path, e.g., Feed And Bleed Operation
Secondary Circulation: Auxiliary Feedwater Pumps	Provide Alternative Feedwater Transport Mechanism, e.g. Main Feed Or Condensate Booster Pumps
Component Requirement: Auxiliary Feed Pump Suction Strainers	Repair Strainers, e.g., Remove Or Backflush

Cognitive Task Analysis

The function based analysis maps the problem space for plant control. As such, it provides one element in the development of a cognitive task analysis,[15] that is, a psychological description of operator activities with respect to operational goals. For example, control and decision requirements fall into several generic categories: what data is needed to monitor the success of a goal? what choices can operators face to achieve a goal (e.g., among alternative means)? what control actions can restore a goal (e.g., initiate a process, tune a process, tune an automatic control system). Other generic operator tasks are based on searches across the goal-means topology, for example, searching up through the network involves assessment of the consequences of a failure to achieve some goal; looking down through the network is a diagnostic search through the causal chain that produced a goal violation. Cognitive task analysis also depends on theories and models of cognitive processes relevant to the control room and on the results of studies of operator action selection,[6,7,8,9] for example, Woods[8] examined the role of the concept of a decision criteria in operator decision making during an actual power plant emergency. The result is that developments in the description of operator cognitive activities provides a mechanism to define meaningful units of behavior for reliability analysis and to avoid the limitations of current descriptions of operator performance that focus on the physical sequence of action in specific scenarios.

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Proprietar

Proposal to

U. S. Nuclear Regulatory Commission
Washington, D.C.

MODELING COGNITIVE BEHAVIOR OF NUCLEAR POWER PLANT PERSONNEL

RFP RS-RES-85-103

Volume 1: Addendum to Technical Proposal

Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

NRC-BHD WSH

EASYLINK 1386392A001 21FEB85 15:30/15:31 EST
FROM: TLX 703669 WEST RD PGH UD
      WESTINGHOUSE ELECTRIC
TO: 908142

FEBRUARY 21, 1985
MRS. HELEN HAGEY, CONTRACTS SECTION
NUCLEAR REGULATORY COMMISSION, AR-2223
4550 MONTGOMERY AVENUE
BETHESDA, MD 20814
SUBJECT: RFP RS-RES-85-103 "MODELING COGNITIVE BEHAVIOR OF NUCLEAR POWER PLANT PERSONNEL" WESTINGHOUSE REFERENCE 84M1496A.
PLEASE REFER TO SUBJECT BAFO TRANSMITTED TO YOU ON FEBRUARY 19, 1985.
VOLUME I CONTAINS TWO TYPOGRAPHICAL ERRORS, AS FOLLOWS:
1) PAGE 4, 2ND PARAGRAPH, LINES 2 AND 3, SHOULD READ: ..."THE LEVEL OF
EFFORT FOR PHASE III (IN PARTICULAR, TASKS 1.3, 1.4, AND 1.5) FROM 3805
TO 3005 HOURS. THE ...."
2) PAGE 5, FIGURE 5 SHOULD READ: "FIGURE 1."
WOULD APPRECIATE CORRECTION OF THESE MINOR ERRORS. THANKS.
PAT CAPPETTA
MARKETING
WESTINGHOUSE R&D CENTER
703669 WEST RD PGH UD
EZL2-21-5

MMMM

NRC-BHD WSH

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Question 1: Please discuss your ability to perform Phase III of the requested research at a lower dollar cost. Please review your technical workscope for Phase III for possible economics and identifying areas and magnitude of reduction in effort level that could be effected with only minor impairment in your effectiveness; also, identify what specific benefits to the NRC would be lost by such reduction.

Westinghouse can provide an effective evaluation of the model(s) developed in Phase II at a lower cost, with only minor impairments with respect to the objectives of Phase III.

Figure 1 illustrates the relation between models of human performance and PRA, and the steps involved in using a model of human performance to derive inputs to PRA studies. These steps are reviewed to illustrate the questions to be addressed in the proposed evaluation during Phase III. As can be seen from the figure, in model application, PRA feeds input to the model as well as deriving outputs that form the basis of HRA values. PRA guides the identification of NPP tasks that involve human actions that may have an impact on plant safety (e.g., valve alignment during ECCS switchover to recirculation). These tasks are then analyzed to determine what factors in the specific plant and situation (control board, operator training, etc.) will affect the quality of human performance. The selection of factors to consider is necessarily guided by some underlying model of human performance (either explicit or implicit). This occurs in all HRA: for example, THERP employs baseline reliabilities for standard tasks that are then modified based on additional characteristics of a particular situation (performance shaping factors). HRA studies that rely on expert judgment for deriving HRA values are likely to be based on implicit models of human performance in the expert's head. Whatever the form of the model, it is used to translate the specific task and context into psychological terms (see the capture

error example, p. 3-8) and then to determine or measure the quality of human performance. Finally, the assessment of the quality of human performance must be transformed to be compatible with PRA formats (although some models may directly generate output in the required form).

The proposed program is designed to develop a better specified, testable model that more accurately reflects current knowledge of cognitive processes and human performance and can generate output in a usable form. The evaluation of the model is intended to address all these issues by evaluating the adequacy of the model at each of the steps in Figure 1: (a) translation of NPP tasks and specific contexts into psychological terms, (b) exercising the model based on these inputs to predict performance, and (c) transforming model outputs to be compatible with PRA requirements.

Each of these aspects can be addressed by the evaluation study at lower cost and with only minor impairments by preserving the six major tasks identified in Phase III, but reducing the number of test cases included in the study. In the first task of the evaluation phase, the Question Formulation task, the major categories of events that need to be sampled in the study will be defined. These categories of events or situations will be selected based on two considerations: (a) an analysis of model concepts that specify what kinds of situations and factors are important to the quality of human performance and (b) an analysis of the kinds of NPP tasks that are often risk-sensitive (e.g., valve alignments, diagnosis of multiple failures, severe accident management decisions). Once the major categories are defined, specific test events that represent NPP instances of those categories will be sampled for inclusion in the study.

The impact of cost reduction will be kept to a minimum by maintaining the number of major categories to be examined, but reducing

the number of test events that are sampled from each category. At a minimum the study should include two test events from each category, so that results that are due to idiosyncracies of particular situations can be identified and discounted.

Costs can also be reduced by reducing the number of subjects tested on each event. While the exact number of subjects required depends on the model to be evaluated, a minimum of two subjects per event is needed. A small number of subjects can still meet the evaluation goals because of the use of process, as well as outcome (e.g., errors, response times), measures of performance (see p. 3-42). Process measures trace the operator's decision activities during a test event, and are critical for investigations of the role of cognitive activities in human performance in NPPs. Capturing the decision activities behind actions requires the analysis of multiple data sources on plant behavior, operator actions, and the background for operator decisions and actions. Westinghouse has developed a method to efficiently generate and combine these multiple data sources into an analyzed protocol that describes what happened along with when and how or why it happened. The method is based on determining in the test selection task what the test case is designed to reveal about human performance. Based on this assessment, computer and domain expert (instructor) logs can be preformatted to record this data of interest. Westinghouse has used the method to reduce the cost of empirical data collection and data analysis by a factor of 4 (in ref. 16 twice as much data was analyzed at one-half the cost, as compared to ref. 2).

By reducing the number of events that sample the decision situations of interest and by reducing the number of subjects who are tested on each event, evaluation costs will be reduced. However, by maintaining a wide sample of the decision situations of interest and by using decision process tracing techniques, the evaluation will still

provide an adequate test of model descriptive and predictive power and of model usability with respect to human reliability assessments. Given the basic assessment provided by Phase III, use of the model by organizations in the nuclear industry will also provide feedback about model applicability and will spur further development and extensions of the model.

Reducing the number of test cases in the evaluation will reduce the level of effort for

The cost impact of this change is

Per Pat Capp

In summary, the Westinghouse team possesses the skills to perform cost-effective mixed and high fidelity testing, based on the experience gained fr m designing and conducting simulator studies on operator performance in NPPs (references 2, 3, 4, 16 and pages 7-1 to 7-5) and based on the resources Westinghouse has for gathering data on mixed and high fidelity simulations of NPP tasks (training instructors, control room simulators, engineering working model).

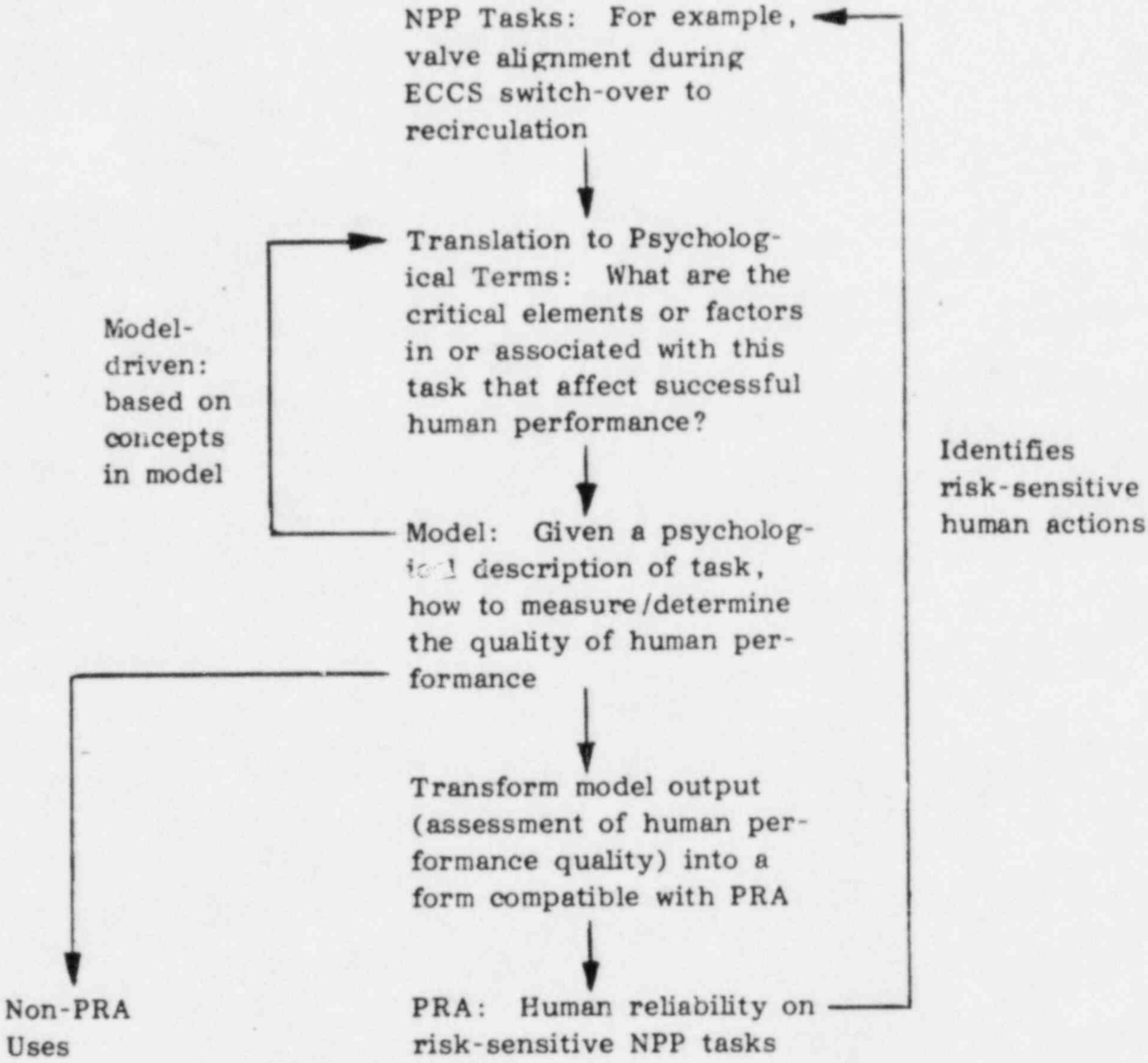

Figure 1 -- The steps (implicit or explicit) in using a model of human performance to provide input to PRA studies.

Question 2: Please provide additional information on specific technical, administrative, and regulatory issues or questions that must be resolved to successfully accomplish Phase I, II, and III objectives of the research, taking into consideration that this research will be performed in a nuclear industry/ regulatory environment.

It is recognized that the technical, administrative, and regulatory issues involved in performing the research and in getting the results accepted and used by the nuclear industry and regulators are difficult.

Technical Quality. There are obviously technical challenges since no existing models adequately describe cognitive behavior of NPP personnel, much less in a form compatible with existing PRA and HRA methodologies. As evidenced by the Westinghouse proposal, the foundation for the proposed technical work will be provided by advances in the past five years with respect to (a) the analysis of NPP decision requirements, (b) applications of models and knowledge from cognitive psychology to the real world, and (c) development of an empirical data base on cognitive behavior in real and simulated NPP plant situations. Due to the development of this foundation (to which Westinghouse has been a major contributor), today a team skilled in applied cognitive psychology and experienced in NPP safety can develop a product to meet the needs of the nuclear industry and the industry regulators.

Producing models of high technical merit requires a unique combination of skills and resources, including access to personnel knowledgeable in all aspects of NPP safety, to NPP personnel who can serve as subjects, and to high fidelity situations for tuning and testing models. The Westinghouse team possesses or has access to all of these resources. Westinghouse has available instructors (both control room

operations and test and maintenance), safety analysts, system designers, and procedure writers to provide any background information needed for the program. Instructors are available to aid in the evaluation of the model (Phase III) by acting as domain experts to measure the quality of operator performance and as subjects in tests to collect empirical performance data. Through Westinghouse's training simulator and through our contacts with utilities who send operators for training on these simulators, the Westinghouse team can obtain access, with utility permission, to actual operators and trainees for data collection purposes. Westinghouse has resources in terms of computer simulations of PWR plants, high fidelity simulators of existing control rooms, and a new facility, the Engineering Working Model (see proposal, pages 7-13 to 7-15), which allows for the introduction of changes to existing control room configurations. These resources, combined with expertise in applying cognitive psychology to NPPs, place Westinghouse in a unique position to successfully product a product of high technical merit in a nuclear industry/regulatory environment.

Impact of Results on HRA and Nuclear Industry. The development of models of NPP cognitive activities will also affect current HRA techniques and PRA studies that use HRA:

- How are inputs to the model established?
- How is model output transformed to be compatible with the needs of PRA?
- What is the cost impact?
- What is the impact on the accuracy and quality of assessments of human reliability?
- How can the results of the program be effectively transferred to users of human reliability assessments (NRC, utilities)?

Models of NPP cognitive activities will improve HRA because there will be a more sophisticated basis for assessing the quality of human performance in specific NPP situations. In addition, the modeling effort should not increase (and may decrease) the cost of HRA because the process will be better defined, more formal, and more rigorous. HRA efforts based on the models developed in this program will also result in a more consistent treatment of human performance both across different NPP tasks and across different plants. Finally, a more formal, rigorous process for assessing human performance can aid in the tracing, management, and control of the human reliability portion of a plant PRA study.

A key requirement in the program is to demonstrate to the nuclear industry, the CRGR, and ACRS, and the NRC Commissioners that application of the results of this program will improve plant safety. The NRC and the industry together recognize that additional or changed requirements are not acceptable unless a significant safety improvement is achieved. Therefore demonstration of the positive safety impact of this research program will be of top priority throughout the effort.

To ensure a positive impact on PRA studies and a product acceptable in the nuclear industry/regulatory environment, Westinghouse will take three actions:

First, we will put together an advisory team consisting of one person from the regulatory side of NRC, two people from utilities, two HRA practioners, and one person who is a recognized expert in developing and applying models of cognitive activities (with NRC input, review, and agreement on team members). This team will hold a meeting at the end of Task 1 of Phase II to review the model development, to identify usability issues important to the Phase III work, and to aid in the development of the final plan for Phase III research. The team will hold

a second meeting during Task 1.6 of Phase III (Evaluating Model in Light of Results) to review the results of the evaluation and to provide input to the evaluation on issues of model usability and acceptance. (More information on these consultants is contained in the answer to Question 5.)

Second, we will engage a non-Westinghouse human reliability practitioner as a consultant in Phase II, Task 1.4 for 75 hours. This consultant will review and comment on the compatibility between model output and PRA requirements and on the method for transforming model output (if such a transform is necessary) to a computable form. (More information on this consultant is contained in the answer to Question 5.)

Finally, under Task 2 of Phase III, Westinghouse will organize and conduct a one-day transfer-of-technology session as an adjunct to a nuclear industry meeting such as ANS or IEEE (subject to NRC review and approval). This session will describe the models developed in the program and how they can be applied to produce improved human reliability assessments within a PRA study context. The session will include hands-on experience in the steps in the process of applying the model to generate human reliability values for a PRA. The hours under Task 2 of Phase III have been modified to reflect the work needed to conduct this transfer-of-technology session.

Question 3: Please provide additional information on how the cognitive process models emerging from this research might be used for purposes (e.g., man-man and man-machine safety system design) other than direct PRA support.

Models of cognitive activities in NPPs have multiple benefits beyond the measurement of human reliability. They can be used to evaluate the impact on safety of proposed changes to the NPP man-machine system and to identify and prioritize potential improvements to the NPP man-machine system, including procedures, control board changes, and decision aids. Models can also aid in the development, evaluation, and regulation of new, advanced operator aids. This is particularly important given that advances in technology (such as predictive displays, voice I/O, disturbance analysis, and artificial intelligence) make possible a wide variety of new advanced computer displays, alarm systems, and decision aids. Models of cognitive activities that improve our understanding of human performance in NPPs can also be used to define training needs (e.g., diagnostic training), to design procedures that avoid or mitigate error-prone situations, and to address human performance in severe accidents.

The output of this program will be sensitive to these other applications, within the constraints imposed by the main use of this work in PRA. To show some of the other uses of this work in the test case selection task (1.2) of Phase III, strong consideration will be given to including decisions related to severe accident management.

Question 4: Please provide additional information on your plan for coordinating Phase I, Task 1 meeting format, content, and agenda with the NRC prior to the scoping meeting called out under that task.

Holding a timely and productive meeting under Task 1 of Phase I requires coordination between the NRC and Westinghouse. Within one week after the project begins, Westinghouse will need the NRC to furnish a list of (1) prospective participants and (2) NRC sponsored programs (both completed and in progress) related to cognitive activities in particular, and human performance in general, in NPPs. The list of programs should include published reports and points of contact for these programs. The NRC should also arrange for NRC facilities (i.e., conference room suitable for about 12 to 15 people) and notify Westinghouse at least 10 days prior to the meeting date.

Westinghouse will contact the prospective participants and inform them of the schedule, agenda, and place of the meeting.

Westinghouse will provide meeting participants, one week prior to the meeting, written material on cognitive activities, models, and NPP jobs, roles, and functions in order to ensure a focused, productive meeting. The written material will provide background information and a point of departure for the discussions. This material will emphasize the different ways NPP jobs, roles, and functions have been analyzed and different ways to describe human cognitive activities so that the group can better choose the NPP scope and working definitions for the project. No later than two weeks after the start of the program, Westinghouse will provide NRC, for review and comment, an outline of the material to be distributed and the meeting agenda and format. NRC comments must be received no later than ten days prior to the meeting date.

Question 5: Please provide additional information on the roles and credentials of "yet to be named" consultants in performing Phases II and III of your workscope, and the bases for estimating staff-hours for those consultants (600 staff-hours during Phase II, 240 staff-hours during Phase III).

Consultants will be engaged in Phase II and III.

One consultant will be a generally recognized expert in the model or modeling approach adopted for Phases II and III. We anticipate that this consultant will spend a total of 365 hrs in Phase II and 105 hrs in Phase III. In Phase II, this consultant will provide written reviews of draft material on tasks 1.2, 1.3, and 1.4. It will greatly enhance the efficiency and quality of the model development effort to use a model originator or major contributor to review and comment on the application of that model to NPPs (335 hours).

In Phase III this modeling consultant will provide written reviews of draft material for tasks 1.3, Prediction Specification, and 1.6, Model Evaluation (75 hours).

The modeling consultant will also participate in the advisory team meeting planned at the end of Task 1 of Phase II (30 hours) and during Task 1.6 of Phase III (30 hours).

The modeling consultant chosen will be a generally recognized expert (model originator or major contributor) in the particular model or modeling approach selected in Phase I. For example, if the modeling approach adopted is based on optimal data sampling patterns, then N. Moray of the University of Toronto and T. Sheridan of MIT, who are among the major contributors to this class of models, would be candidates for the model consultant role. If the approach adopted is based on models of human error mechanisms, then D. Norman of University of California at San Diego and J. Reason of University of Manchester, who are among the major

contributors to this class of models, would be strong candidates. When a modeling approach has been selected, Westinghouse will submit to the NRC a list of such candidates for the model consultant role. The NRC and Westinghouse will then jointly select the consultant from this list.

The second consultant will be a non-Westinghouse HRA practitioner who will aid in assessing the usability of the model in Phases II (105 hours) and III (105 hours). In Phase II, this HRA consultant will provide written reviews of draft material on task 1.4, specification of how the model generates predictions. Specifically, the consultant will review the usability implications with regard to how specific NPP tasks are translated into model terms and to how model output is transformed into PRA input requirements (75 hours). In Phase III, the HRA consultant will provide a written review of draft material on tasks 1.2 and 1.6 with respect to usability issues important to the evaluation and with respect to the implications of the evaluation results for model usability in a PRA environment (75 hours).

This HRA consultant will be one of the two HRA practioners who participate in the advisory team meetings (30 hours in Phase II; 30 hours in Phase III). Westinghouse will provide to the NRC a list of candidates for this role as part of Task 5 of Phase I. Candidates will be HRA practioners active in the nuclear industry. NRC and Westinghouse will jointly select the consultant from this list.

An advisory team will be convened to provide input to and review of model development and evaluation with respect to usability and acceptability of the model effort in PRA environments. The team will consist of a NRC regulator, two utility representatives, two HRA practitioners (one of whom will perform other tasks as discussed above), and the model consultant. The team meetings and preparation will require 30 hours of preparation for the HRA practitioners and the model consultant.

Only travel expenses for the utility participants will be covered by the project; the NRC will provide the regulatory participant.

Westinghouse will provide a list of potential candidates to the NRC for these roles as part of Task 5 of Phase I, and NRC and Westinghouse will jointly select the participants from this list.

Table 1 summarizes this breakdown of consultants and hours per task. A revised Table 6.1 is also included to show the person resources proposed for the program, based on the program changes contained in the responses to all of these questions.

Table 1 -- Consultant Hours/Task

	Phase II			Phase III		
	1*	Advisory Team Meeting	Total for Task 1	1*	Advisory Team Meeting	Total for Task 1
Model Consultant	335	30	365	75	30	105
HRA Practitioner	75	30	105	75	30	105
Second HRA Practitioner	-	30	30	-	30	30
Total			500			240

*Task 1 efforts except for Advisory Team Meeting.

Table 6.1 -- Resources Planned for the Program (Entries in Table are Person-Hours)

	Tasks In Phase I						Tasks In Phase II				Tasks In Phase III		
	1	2	3	4	5	Total	1	2	3	Total	1	2	Total
L. F. Hanes	50	60	80	70	40	300	155	80	50	285	80	120	200
D. D. Woods	60	118	680	70	40	968	1009	140	60	1209	1075	180	1255
E. Roth	20	30	420	80	-	550	699	80	40	819	630	170	800
J. M. Gallagher	-	173	-	-	-	173	-	-	-	-	-	-	-
Human Sciences Personnel	-	-	-	-	-	-	-	-	-	-	750	-	750
Training Instructors	-	-	-	-	-	-	-	-	-	-	400	-	400
Consultants	-	-	-	-	-	-	500	-	-	500	240	-	240
Total	130	381	1180	220	80	1991	2363	300	150	2813	3175	470	3645

Question 6. Please provide additional information on the proposed staff's expertise and experience in human reliability analyses within the context of probabilistic risk assessments of nuclear power plants.

The Westinghouse team consists of experts in human performance and human error in NPPs. This expertise has been obtained through externally funded (EPRI) as well as internal projects over a number of years. Their work on human reliability is based on Westinghouse and others' experience with the inadequacies of existing HRA techniques in the measurement, prediction, and improvement of human performance. This work has focused on improving knowledge about human performance in NPPs through:

1. Providing a sounder empirical base for human reliability estimates.

2. Going beyond existing techniques through data and models on cognitive factors in performance in NPP safety.

The Westinghouse team's work related to human reliability assessment has included:

- Empirical estimates of human reliability on NPP tasks for use in Westinghouse PRA studies (tasks include valve positioning tasks and tasks in eight different types of NPP emergency events).
- Empirical estimates of human reliability for comparison to human reliability estimates generated through the THERP technique (prepared for ESEERCO, 1984).
- Empirical response time data as estimates of human reliability through ANSI's Operator Action framework.
- Research and modeling of cognitive reliability (e.g., NATO Conference on Human Error).
- Consultation on HRA techniques for Westinghouse PRA activities.

- Expert review of nuclear industry documents on HRA (IEEE/ANS handbook).

Westinghouse sees two requirements for a successful model. The first requirement is that the model be able to accurately assess the quality of human performance in NPPs and how human performance changes as a function of a variety of situational, interface, and human characteristics. Success in meeting this requirement will strongly depend on the technical merit of the model development and evaluation. A second requirement is the constraint imposed on model development that the model be compatible with a PRA environment. This includes an effective methanism to generate the input to the model from a specific NPP task (the translation to psychological terms in Figure 1) and a means of tailoring the model output form so as to be compatible (or transformable to be compatible) with PRA input requirements.

This requirement for usability in a PRA environment will be met in several ways. First, Westinghouse will draw upon the Westinghouse team's experience at enhancing existing HRA techniques. Second, Westinghouse will provide in Phase I, at no additional cost, consultation with a non-Westinghouse HRA expert who will provide input to the assessment of the models of cognitive activities with respect to one factor important for successful use of a model (number 8, Table 3.3, p. 3-25): relationship to other, noncognitive techniques to assess the quality of human performance. Third, Westinghouse will convene a meeting of an advisory team -- consisting of an NRC representative, two utility representatives, two HRA practitioners, and the model consultant -- to review the model development and evaluation at the end of Task 1 of Phase II and Task 1.6 of Phase III. Their review will provide an assessment of the validity of the modeling effort in a PRA context. (The answers to Questions 2 and 5 provide more information on these consultants.) NRC input and approval will be solicited in choosing these consultants.