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Criteria for Safety-Related Nuclear Power Plant Operator Actions: Initial Boiling Water Reactor (BWR) Simulator Exercises

A. N. Beare
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This Work Performed for
Nuclear Regulatory Commission
under
DOE Interagency Agreement 40-551-75

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

NUREG/CR-2534
ORNL/TM-8195
NRC Distribution Category RX

Contract No. W-7405-eng-26
Engineering Physics Division

CRITERIA FOR SAFETY-RELATED NUCLEAR POWER PLANT OPERATOR ACTIONS: INITIAL BOILING WATER REACTOR (BWR) SIMULATOR EXERCISES

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Manuscript Completed: October, 1982

Work Performed by General Physics
Corporation under Subcontract No. 40X-40432C

This Work Performed for
Nuclear Regulatory Commission
under
DOE Interagency Agreement 40-551-75
NRC Fin No. B0421-8

Date Published - November 1982

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operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

Ron Morris of the University of Tennessee at Chattanooga performed the statistical analyses and assisted in interpreting their results.

Roy Dorris of General Physics assisted in reduction of the data and prepared the figures.

General Physics Corporation BWR instructors Randy Bovell, Dennis Kabachinski, Greg Mecchi, and Gerald Moody provided valuable technical background and insight into the role of the operator in BWRs.

Judy Dautrich typed the manuscript and the many revisions thereto.

Special thanks are due the control-room operators who participated in the exercises on which this study is based.

ABSTRACT

The primary objective of the Safety-Related Operator Action Program at Oak Ridge National Laboratory is to provide a data base to support development of criteria for safety-related action by nuclear power plant operators. This report presents initial data obtained from ten exercises conducted in a boiling water reactor power plant control room simulator. The ten exercises were performed by 24 groups of operators from three utilities. Operator performance was recorded automatically by a program called the Performance Measurement System run on the simulator's computer. Data tapes were subsequently analyzed to extract operator response time (RT) and error rate information. In addition, demographic and subjective data were collected and analyzed in an attempt to identify and evaluate the possible effects of selected performance-shaping factors on operator performance. Operator RTs to the simulated events generally occurred within the intervals allowed in the draft ANSI-N660 design standard; however, they did not appear to be systematically related to the severity of the event, which was the basis for allocation of time margins in the standard. More collective experience in power plant operations was weakly correlated with faster responses. Limited data on omission errors yielded an error rate of greater than five percent.

The data collected will be compared to field data being collected on similar malfunctions. That comparison will provide a basis for extrapolation of simulator data to actual operating conditions. A base of operator performance data developed from simulator experiments can then be used to establish criteria and standards, evaluate the effects of performance-shaping factors, and support safety/risk assessment analyses.

1. INTRODUCTION

There is increasing recognition on the part of reactor safety analysts of the need to include the effects of human interaction in system reliability and safety studies. The desire is to quantify the impact of the operator on system performance, but the lack of a comprehensive, objective data base has been a major obstacle thus far. Data currently applied to human performance in nuclear power plant (NPP) operations are derived primarily from studies of humans in jobs other than nuclear-power-related fields (e.g. aviation or military operations) or from the (subjective) expert opinion of nuclear industry personnel. Objective data on the behavior of NPP operators under severe accident conditions is particularly sparse. The Safety-Related Operator Actions (SROA) program at Oak Ridge National Laboratory (ORNL) is intended to provide the U.S. Nuclear Regulatory Commission (NRC) with such quantitative and qualitative performance data to help support licensing decisions, development and assessment of design standards, and safety/risk assessment studies.

The initial impetus for the ORNL program was the need to provide data in support of the development of the proposed American National Standard ANSI-N660 "Time Response Design Criteria for Safety-Related Operator Actions" (Ref. 1)*. The ANSI-N660 standard is intended to provide criteria for NPP designers to determine whether safety systems that mitigate the consequences of design basis events may be initiated or adjusted by use of operator action. The approach taken in the draft standard is to specify certain "time tests", or minimum time margins that must be available for operator response. If the designer cannot assure that these time tests are met, the required safety-related action should be automated.

Early in the program, ORNL staff performed a preliminary study (Ref. 2) which included an assessment of data available from operating experience to support development of the response time criteria. A primary conclusion from that study was that a much more comprehensive approach to the question of automation of safety-related operator actions was necessary, but that on an interim basis, the use of response time criteria was not unreasonable. A second major conclusion was that sufficient field data to adequately support development of such criteria did not exist. It was recommended that if NRC made the decision to proceed with the interim approach, the data should be obtained from controlled exercises or "experiments" with qualified NPP operators on full-scope NPP training simulators. In order to address the problem of extrapolation of results from the simulator to the "real-world"

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*This is the current title of the draft standard. The title at the time the ORNL program was initiated in 1978 was "Criteria for Safety-Related Operator Actions."

environment, it was proposed to "calibrate" the simulator results to field data by comparing response times from the two sources for selected abnormal/emergency events. If a reasonably consistent and definable relationship exists between performance during the simulator exercises and during actual abnormal/emergency events, then the simulator exercises can provide a much more extensive data base than would be available from operating experience.

The work described in this report was undertaken primarily to provide empirical response-time data with which to evaluate the adequacy of the "time tests" which are the heart of the proposed ANSI-N660 standard. However, the ultimate goals of the research program are broader and more fundamental than this. It is desired to obtain data on operator error, which may be used to develop more comprehensive criteria for safety-related operator actions and would also be of use for human reliability analysis. Beyond this, we would like to be able to describe or "model" the behavior of control room operators in responding to abnormal/emergency events, to define the performance required, the measures of performance, and the major performance shaping factors (PSFs) affecting performance. The level of detail and the degree of quantification necessary for such a model vary with the intended use, but such a model seems essential to human factors studies in various areas - human engineering of control rooms, control room personnel selection and training, procedures, operator aids, etc. Ultimately, of course, the aim is to use this information to improve the safety and efficiency of nuclear plant operation. A secondary goal of these initial experiments, then, was to observe and as possible record the response of qualified operators to different (simulated) abnormal/emergency events in order to begin to develop an understanding of "typical" operator behavior, and to identify likely PSFs and determine the effects of PSFs hypothesized to be significant.

A third objective was to gain experience in and demonstrate the effective use of NPP training simulators and "quasi-controlled experiments" to provide the necessary data base on operator performance. Thus, the experience gained in conducting and analyzing these early experiments, identifying and overcoming practical constraints, and comparing results to field data was in itself an important objective.

The proposed program of simulator exercises and field data collection was initiated in March, 1980. The first series of simulator exercises, which were for pressurized water reactor (PWR) events, are reported in Reference 3. An internal ORNL report (Ref. 4) summarized initial field data collected on PWR events. The present report summarizes the initial series of boiling water reactor (BWR) simulator exercises. The simulator exercises are being conducted by General Physics Corporation (GP), while the field data collection was performed by Memphis State University Center for Nuclear Studies (MSU/CNS).

The remainder of this report is divided into seven chapters. Section 2 describes the objectives and other considerations affecting the design of the present experiments. Section 3 describes the experimental arrangement and procedures. Section 4 presents the response time data and the statistical analysis of the data. Section 5 discusses the application of the response time data to the currently proposed form of the ANSI-N660 standard. In Section 6 consideration is given to operator error probability as a performance measure, and in Section 7 an attempt to identify the major performance shaping factors and their impact is discussed. Section 8 summarizes the findings from this initial work and outlines suggestions for future simulator experiments.

2. OBJECTIVES

The primary objective of the present experiments, as dictated by the requirement to provide data for SROA criteria, was to obtain data on the time required for correct performance of manual safety-related actions (the proposed N660 standard did not attempt to deal with incorrect performance). Portions of the standard are discussed below to provide background and define the time intervals to which data will be related.

2.1 ANSI-N660 Time Tests

The ANSI-N660 draft (Ref. 1) states that each safety-related action required to initiate or adjust a safety system for which a required operator action is contemplated shall be evaluated in terms of two time tests. If both time tests as well as certain other requirements of the standard are satisfied, the designer may assume that adequate time will exist for a qualified operator to perform the required safety-related action. The symbols and time intervals defined below are illustrated in Fig. 2-1.

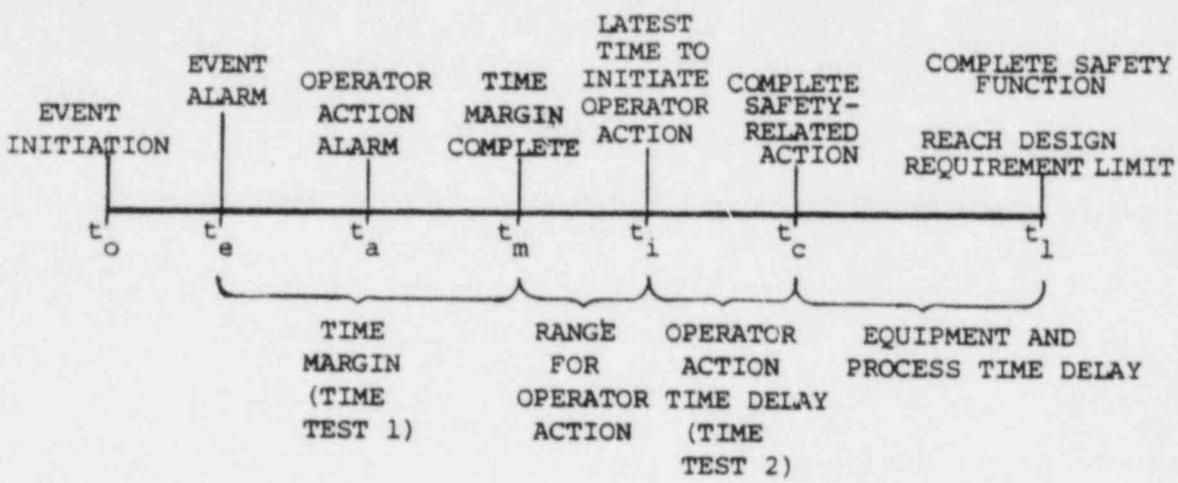

Figure 2-1 Time intervals from ANSI-N660

To apply the standard, the designer determines the interval from the time some event occurs (T_o in Figure 2-1) until the consequences of that event will result in some design limit being exceeded (T_1). From this interval he subtracts the equipment and process delay times of the safety system under consideration. This determines the maximum permissable delay in activating the safety system. From the "front end" of the event time line he subtracts the interval between initiation of the event and the activation of the first alarm to the operator. The time remaining (T_e to T_c in the diagram) is the time available for the operator to take whatever corrective action is required of him. If there is sufficient time available, the designer may assign some or all of the safety functions to the manual intervention of the operators: if there is not sufficient time, the safety function is to be automated. The two time tests described below are used to determine if the time available for the operator to take action is "sufficient."

Time Test 1

This test establishes a conservative time interval during which any required safety-related actions shall be initiated by automatic protection systems. The minimum time margin ($t_m - t_e$) in Fig. 2-1 depends on whether the event is a Condition II, III, or IV event as defined by ANSI/ANS-52.1 for BWRs (Ref. 5). Condition IV events are the most severe, least frequent design-basis events such as LOCA, and Conditions III and II are progressively less severe and more frequent. The time margin for an event is lengthened as (1) the severity increases, (2) the frequency decreases, and/or (3) the familiarity of the operator decreases. This is intended to allow longer time intervals for the operator to recover from his initial stress, diagnose the event that has occurred, and plan his actions. This time margin also is intended to allow the operator time to (1) verify that proper automatic safety-related actions have been initiated, (2) initiate manual backups to automatic safety-related actions, and (3) monitor the correct accomplishment of automatic safety functions.

Range For Operator Action

The Range for Operator Action (t_m to t_i in Fig. 2-1) is not really a standard as are Time Tests 1 and 2. Rather, it represents the time remaining after Time Tests 1 and 2 and the alarm and process delays have been subtracted from the interval $t_o - t_1$.

Time Test 2

A second test is applied to each safety-related action under consideration for operator initiation. It represents a conservative time delay allowed for the completion of each operator action ($t_c - t_i$) in Fig. 2-1. Time Test 2 consists of a fixed and a variable portion.

The fixed portion of the time delay is included to allow for (1) the receipt of very simple readout information (e.g. an indicator or audible alarm) that identifies the need for the action, and (2) additional time to diagnose the need for and plan the action. The fixed portion of the time delay may be eliminated if Time Test 2 starts immediately after the time margin of Time Test 1 (i.e., is being applied to the first distinct sequence of manual actions).

The variable portion of the time delay is included to allow a minimum of 45 seconds for each discrete manipulation needed to complete the safety-related action. Each manipulation is considered to include both performance of the operator action and verification (via status light or meter reading) that the action controlled by the manipulation has been initiated.

2.2 Assumed Behavioral Model

Usually experiments are conducted to test a model, hypothesis, or set of hypotheses. The model defines the dependent (measured) and independent (manipulated) variables and their assumed relationships. With regard to the behavior of interest here, NPP operators responding to an abnormal/emergency event, there is no generally accepted model, nor does there exist a comprehensive identification of the performance measures (dependent variables) or critical performance shaping factors (independent variables), necessary for a conceptual model of behavior.

The only model assumed in designing these experiments is one which we have inferred from the ANSI-N660 standard. It has been discussed in Reference 2. Briefly, it describes the operators' behavior as consisting of two distinct, sequential phases which may be labeled "cognition" and "action." The "cognition" phase includes: (1) a period of psychological "shock" or diminished ability to respond correctly immediately following an alarm signal, (2) verification that automatic protective systems have functioned properly, (3) diagnosis of the situation and planning of corrective action. Step 3 is apparently assumed to consist of (1) identification of the accident event in relation to pre-defined scenarios for which abnormal/emergency procedures have been written and (2) location and reading of the appropriate procedures. The "action" phase consists of manual actions in accordance with specific procedures and/or response to additional indications of system status.

The conclusion in Reference 2, based on interviews with licensed operators and an evaluation of field data, was that this model, though useful at a very general level and reasonably accurate for response to some abnormal/emergency events, was incomplete and probably inaccurate for other events. Often operators respond to plant symptoms without having thoroughly diagnosed the event or planned their actions, as emphasized in new "symptom based" emergency procedures. Diagnosis and manual action are often interative: in fact, system response to manual (or automatic) action may be used as a feedback mechanism to aid diagnosis. In addition, it should be noted that operators are routinely required to memorize immediate actions in response to different alarms or plant symptoms, so that immediate actions often are performed before consulting written procedures, even though those immediate actions are listed in the procedures.

It is clear that in the future the "ANSI-N660 model" will have to be modified. However, for the purposes of this initial work, the model was assumed to be generally applicable and useful as a structure for interim design criteria until an alternate, more comprehensive approach is shown to be valid and practical.

The "ANSI-N660" conceptual model (and the structure of the proposed standard define the experimental variables be examined and much of the rest of the experimental design.

2.3 Dependent Variables

2.3.1 Response Times

The only dependent variable (measure of performance) directly related to the standard is the time required to initiate or carry through response - during the "cognition" phase or during the "action" phase.

2.3.2 Errors

Collection of data on operator error frequencies is an objective of the SROA program*, both because the combination of error probability and response time might provide a more useful, more comprehensive basis for design standards or regulatory review criteria, and because data on operator errors provide important indications for potential system improvement - in training, control room design, procedures, etc.

Because of the emphasis in this program on quantitative design criteria, a second objective of the present study was to obtain quantitative data on error frequencies.

As discussed in Section 6, the general categorization of errors used by Swain and Guttmann (Ref. 6) has been used as a guide for this work. And, in the absence of a more comprehensive analyses, we have assumed that the "correct" behavior is described by the procedures and non-conformance with procedures is an error.

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*Since these experiments were completed, Sandia National Laboratories has initiated a similar program of simulator data collection for the NRC which is directed specifically toward collection of error probability estimates for comparison to data in NUREG/CR-1278 (Ref. 6). Those data, in general, are for tasks (or actions) and situations more like the "action" phase in the ANSI-N660 model. Raw data obtained from experiments in the ORNL program will be shared with Sandia investigators and reported as part of the results of that program.

2.4 Independent Variables

In the draft ANSI-N660 standard the amount of time required by Time Test 1 and the fixed portion of Time Test 2 are determined by the condition* which the safety system under consideration was designed to deal with. Higher-consequence, lower-frequency events (progressively, Condition II, III, and IV) are to be allowed more time for correct operator response. The standard seems to imply that operators require longer to diagnose and plan for responses to more hazardous events, because they will be under greater stress and less familiar with the symptoms and required actions for those events which occur in practice less frequently.

The independent variable in this study was the abnormal/emergency event with which the operators had to contend. A set of 10 events to be simulated was selected on the basis of the criteria listed below.

- Applicability to ANSI/ANS N660
- Safety impact or consequences
- Generic to BWR plants
- Range of complexity of event diagnosis, complexity of accident scenarios, and complexity of required operator actions
- Ease of determining appropriate operator responses (i.e., had identifiable, measurable operator actions)
- Adaptability to simulation
- Acceptability to cooperating utilities for training purposes, i.e., "training value"
- Sufficient frequency of occurrence in operating plants for field data collection

Selection of specific events was done with the assistance of personnel from MSU/CNS, who were responsible for collecting field data to be compared with the simulator data reported in this study. The final list of events (presented in Section 3) contained seven Condition II (Incidents of Moderate Frequency), two Condition III (Infrequent Incidents), and one Condition IV (Limiting Fault) events. It is recognized that the lopsided distribution of events among conditions is

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*The ANSI document <u>Nuclear Safety Criteria for the Design of Stationary Boiling Water Reactor Plants</u> (Ref. 5) assigns NPP operating conditions to four categories or Plant Process Conditions (PCCs). Condition I is assigned to normal operations and Conditions II through IV are assigned to off-normal or accident conditions on the basis of frequency of occurrence and potential hazard to the public. In general, the hazard and the expected frequency are inversely related: the least frequent (Condition IV) events are also the most hazardous.

not ideal for purposes of supplying data for evaluation of the ANSI-N660 standard, but we believe the final list represents a reasonable compromise in the face of sometimes competing requirements and practical constraints.

2.5 Performance Shaping Factors

As noted previously, one of the goals of this initial work is to begin to identify the performance shaping factors (PSFs) that have a significant impact on performance. Swain and Guttmann (Ref. 6) have categorized PSFs as external (those that define the work situation), internal (those that define the individual's attributes) or stress (which results when there is a mismatch between the demands of the task and the capabilities of the individual, i.e., between external and internal PSFs). A listing of PSFs from Reference 6 is reproduced as Table 2-1. Each of the listed PSFs, by itself or (especially) in combination with others, could be a critical factor in performance under some circumstances. Each category of PSF (major heading in the table) is discussed below.

2.5.1 External Factors

External PSFs are properties of the physical environment (e.g. characteristics of the man-machine interface), organizational environment, or specific situation (e.g. task characteristics) which may affect the performance of individuals.

Although experimental manipulation or even adequate measurement of these factors was beyond the scope of the present project, it was desirable to at least determine which of several general classes of external PSFs were perceived by the operators to have affected their performance. This may be best accomplished by means of structured debriefings. However, due to tight schedules in the training programs, such interviews were not attempted. A less satisfactory, but still viable, alternative was the use of questionnaires. A set of very brief forms which asked each operator to evaluate whether the procedures, control board design, lack of "hands-on" training, instrumentation, or familiarity with the plant (simulator) had been "a problem" for him while performing the exercise was used. The five items were chosen because they were felt to be the ones most likely to be perceived as problematic by the operators.

2.5.2 Stressors

Stress is considered to be a performance shaping factor of major significance, and one that is particularly problematic when attempting to relate findings from laboratory or simulator-based research to the "real world". Common sense suggests that most of the physiological stressors listed (with the possible exception of fatigue) simply are not

Table 2-1 Performance Shaping Factors (adapted from NUREG/CR-1278)

EXTERNAL		STRESSORS	INTERNAL
Situational Characteristics	**Task and Equipment Characteristics**	**Psychological Stressors**	**Organismic Factors**
Architectural Features Quality of Environment: Temperature, Humidity, and Air Quality Lighting Noise and Vibration Degree of General Cleanliness Work Hours/Work Breaks Availability/Adequacy of Special Equipment, Tools, and Supplies Manning Parameters Organizational Structure (e.g., Authority, Responsibility, Communication Channels) Actions by Supervisors, Co-workers, Union Representatives, and Regulatory Personnel Rewards, Recognition, Benefits	Perceptual Requirements Motor Requirements (Speed, Strength, Precision) Control-Display Relationships Anticipatory Requirements Interpretation Decision-Making Complexity (Information Load) Narrowness of Task Frequency and Repetitiveness Task Criticality Long- and Short-Term Memory Calculational Requirements Feedback (Knowledge of Results) Continuity (Discrete vs Continuous) Team Structure Man-Machine Interface Factors: Design of Prime Equipment, Test Equipment, Manufacturing Equipment, Job Aids, Tools, Fixtures	Suddenness of Onset Duration of Stress Task Speed Task Load High Jeopardy Risk Threats (of Failure, Loss of Job) Monotonous, Degrading, or Meaningless Work Long, Uneventful Vigilance Periods Conflicts of Motives about Job Performance Reinforcement Absent or Negative Sensory Deprivation Distractions (Noise, Glare, Movement, Flicker, Color) Inconsistent Cueing	Previous Training/Experience State of Current Practice or Skill Personality and Intelligence Variables Motivation and Attitudes Knowledge of Required Performance Standards Physical Condition Attitudes Based on Influence of Family and Other Outside Persons or Agencies Group Identifications
Job and Task Instructions		**Physiological Stressors**	
Procedures Required (Written or not Written) Written or Oral Communications Cautions and Warnings Work Methods Plant Policies (Shop Practices)		Duration of Stress Fatigue Pain or Discomfort Hunger or Thirst Temperature Extremes Radiation G-Force Extremes Atmospheric Pressure Extremes Oxygen Insufficiency Vibration Movement Constriction	

operative in NPP control rooms. Psychological stressors are another matter entirely. Some psychological stressors are the result of task characteristics, such as high loading or demands for speed or divided attention. More elusive, but none the less significant, are those stresses related to surprise (especially an unpleasant one) and the operator's perception of hazard, the potential personal, economic, or public health consequences of the situation facing him. This aspect of stress is impossible to duplicate in a simulator.

We have not been able to measure the stress experienced by operators participating in this study. Measurement of task-related stressors is possible, but beyond the scope of the present effort. It is expected that task-related stressors have been duplicated to the extent that the operators' tasks in the simulator are like those in a real plant, which is to say almost entirely. More subtle psychological stressors are another matter. Performing relatively unfamiliar exercises (emergency procedures are not practiced every day) and having that performance recorded might be moderately stressful to some. We do, however, doubt that the perceived stress would vary with the event category in the same way that it would if the events were "for real." To the extent that higher stress is likely to be a feature of Condition III and IV events, the psychological PSF's for these events have been less accurately simulated than for the Condition II events. Thus, response times and omissions recorded for Condition III and IV events may be a less accurate estimate of the performance to be expected in the field than similar data for Condition II events.

2.5.3 Internal Factors

The last major group of PSFs are the internal, "organismic" factors: those characteristics of the operator himself which may affect his performance. In our judgment the most important of these are the first five listed.

The first of these, "experience," can be roughly quantified as the number of years of job-relevant experience possessed. The other four can be measured, but any valid measurements would require several hours of each operator's time and the construction of special tests. Time for extensive testing was not available in the context of the training programs on which the research was "piggybacked."

Because the organismic PSFs are characteristics of individuals they can be controlled or manipulated only by selection of individuals possessing the desired qualities (although skill and knowledge can be manipulated by training). This was not possible, nor, given the primary objective of the experiments (to determine the time required by representative control-room crews to respond in emergencies) was the creation of special groups desirable.

2.6 Summary of Objectives

The primary objective of the present experiment was to obtain response time data with which to evaluate the "time tests" that are the central feature of the draft ANSI-N660 standard.

A second objective of this experiment was to obtain data on the frequency of errors, defined as deviation from the actions set forth in written operating procedures for dealing with the events of interest.

A third objective was to attempt to determine the relationship between performance, as measured by response time or error rate, and the performance shaping factor "experience," and to determine which general situational characteristics were perceived by the participants to have affected their performance.

3. EXPERIMENTAL PROCEDURE

The data presented in this report were collected during the course of scheduled (license requalification) training exercises on a full scope, high fidelity training simulator. As noted in Section 1, the decision to use training simulators as vehicles for this research was made because of the unavailability of adequate field data from operating power plants. The decision to "piggyback" the research with regularly scheduled training exercises was reached primarily on the basis of practical considerations of cost and the availability of simulator time and qualified operators to serve as research subjects. The requirement not to interfere significantly with the training program allowed the investigators considerably less control than they would have in a laboratory experiment. However, by mutual agreement with the participating utilities, enough control was established to permit a reasonable level of reproducibility of the experimental conditions and as much as possible key variables were, if not controlled, at least identified and recorded. The exercises therefore might be referred to as "quasi-controlled" experiments.

It is our opinion that the constraints on experimental design and control were not critical, and in fact, such quasi-controlled experiments coincident with requalification training are well suited to the objectives to these initial studies.

3.1 Design

Given the objectives of the experiment detailed in Section 2, the design of the study was straightfoward. Control-room crews were presented with a set of abnormal/emergency events in a training simulator and their responses were recorded by means of a special program (the Performance Measurement System described in Section 3.2.2) run on the computer controlling the simulator.

3.1.1 Independent Variable

The independent (manipulated) variable was simply the nature of the specific malfunction presented to the operators. The 10 events listed in Section 3.3.1 were selected on the basis of the criteria described in Section 2.4.

"Malfunction" is not a single variable that can be conveniently quantified, but a set of qualities, the levels and combinations of which vary from one event to another. The malfunctions chosen vary in the specific responses required, and probably in a number of general task characteristics as well. It is beyond the scope of this report to identify these*, but differences between malfunctions in terms of the performance measures used in this study suggest that such differences in task characteristics exist.

3.1.2 Dependent Variables

There were two dependent variables (measures of performance) in the present study. The first was response time (RT), the time elapsed from the first signal that a malfunction was in progress until the first significant action in response to it. The way in which RT was determined is discussed in Section 4. The second performance measure was the (omission) error rate. The way this was determined is discussed in Section 5.

3.1.3 Performance Shaping Factors

Any of the variables discussed in Section 2.5 may affect performance. The only one of these we have attempted to measure is the operators' experience in nuclear and conventional power plants. Other important "organismic" variables (intelligence, motivation, and state of practice or skill) could not be adequately evaluated in the limited contact time available.

The major situational PSFs, most notably the man-machine interface factors, were controlled (held at constant levels for all exercises/subjects) by virtue of the fact that all the exercises were conducted in the same simulator. Task characteristics were also controlled in that the presentation of each malfunction was standardized for all teams. However, the situation during a casualty is dynamic, and the course of a scenario is a function of the specific actions taken and their timing, so task characteristics may tend toward non-uniformity in the later phases of a scenario.

3.2 Apparatus

Two major pieces of apparatus were necessary to conduct this research, a high fidelity training simulator with the capability of simulating the malfunctions of interest and a special data recording program (the Performance Measurement System) run on the computer controlling the simulator.

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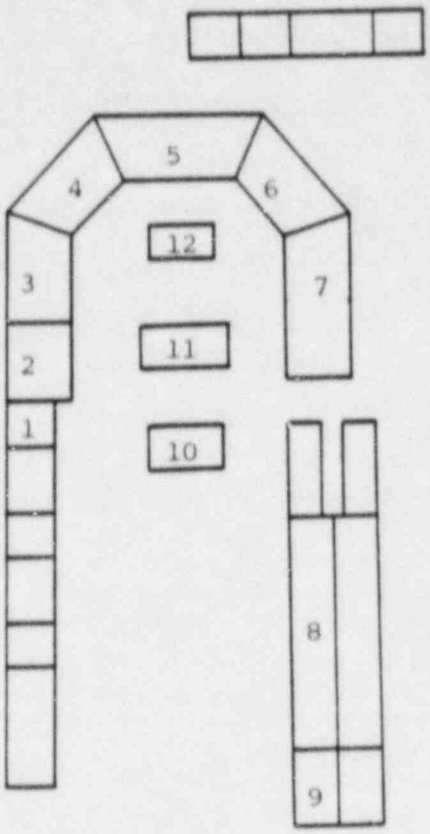
*An analysis of the operators' tasks during the malfunctions employed in this study is currently in progress, and will be published as a report in the SROA series by ORNL.

3.2.1 The Simulator

The training simulator used in this study is shown schematically in Figure 3-1. The simulator is a reproduction of the control room for a 1100 MWe BWR plant. The simulator is driven by a SEL computer. One or a combination of up to 12 of approximately 150 programmed malfunctions may be selected from the instructors' console. The diagram shows the general location of controls for major plant systems.



1. Process and Area Rad. Monitors
2. Electrical
3. Turbine
4. Feed and Condensate
5. Reactor Control
6. Recirculation
7. Main Steam, HPCI, RCIC, RHR, and Core Spray
8. Switch yard
9. Deisel
10. Instructor Console
11. Process Computer
12. Desk

Figure 3-1 Schematic of 1100 MWe BWR training simulator

3.2.2 Performance Measurement System

The Performance Measurement System (PMS) is a computer software system developed by General Physics Corporation for the Electric Power Research Institute (Ref. 7). The PMS is designed to recora simulator and operator actions and provide an easily understandable output. The system consists of an on-line data collection segment and an off-line data interpretation segment. The on-line assembly language data collection program is executed with the basic simulation program in the simulator computer. This program collects all control room data (gage readings, annunciator actuation, switch positions, etc.) during simulator operation. Simulator status is scanned at one-second intervals, but to avoid missing rapid operator actions, switch positions are scanned at 1/4-second intervals. All data are stored on magnetic tape at one-second intervals. To extend the data collection capacity, a dynamic compression technique is used. This technique basically collects data only when successive scans of simulator status indicate changes. When a change occurs, all simulator conditions at that time are recorded. The resulting data tape is a sequence of "snapshots", each containing the status of every light, meter, switch, and knob in the simulator.

The simulator data consists of four types of inputs and outputs as follows:

- Digital Inputs - discrete inputs from the control room to the simulation programs. An example is the position of a two-position switch on one of the control panels.

- Digital Outputs - discrete outputs from the simulation programs to the control room. An example is the signal to an annunciator light, turning it "on" or "off."

- Analog Input - continuous inputs from the control room to the simulation programs. An example is the position of a control knob on one of the control panels.

- Analog Output - continuous output from the simulation programs to the control room. An example is a meter reading on one of the control panels.

These data present a comprehensive description of the simulator status and provide a detailed record of the event sequence.

The data stored on tape is a binary representation of the information displayed in the control room. A switch position or an annunciator light's status is represented by a "1" or a "0" in a specific bit location. An analog output (meter reading) is represented by a 16-bit binary code representing a percentage of full scale. Data evaluation programs run on a PDP-11/34 computer convert this binary data to their FORTRAN data types as the first step in the evaluation. A standard FORTRAN program can then evaluate the converted data and produce output in a form convenient for analysis.

3.2.3 Questionnaires

Two brief questionnaires were used to gather data for the evaluation of PSFs. Both questionnaires are reproduced in Appendix A.

A brief biographical questionnaire requested the respondent's age, number of years of college education, number of years of commercial power plant experience as a control-room operator, number of years in commercial power plants outside the control room, and number of years of military (meaning U.S. Navy) power plant experience.

A second "Questionnaire for the Evaluation of Performance Shaping Factors" was completed by the operators after each was run. This questionnaire asked the operators to check whether each of 5 aspects of the situation had been "no problem," "somewhat of a problem" or a "problem" for them during the event. The 5 things rated were procedures, control board design, lack of "hands-on" training experience, plant indications, and personal unfamiliarity with the plant (simulator) and/or procedures used. The questions on familiarity were of special interest, since the simulator was in many respects different from the plants where some of the operators worked and might, on that account, be perceived as negatively affecting their performance. This questionnaire was a simplified version of the "problem solving" questionnaire used in the first study in this series (Ref. 3), where it was noted that operators seemed less reluctant to admit to having problems during an exercise when using the questionnaire than in face-to-face debriefings.

3.3 Task

The operators' task was to respond to each of the simulated malfunctions the way they would in an operating plant. No special instructions were given, and the operators were not informed before-hand what malfunction was to be presented.

3.3.1 Malfunction Scenarios

Ten malfunctions were selected on the basis of the criteria listed in Section 2.4. These are listed in Table 3-1. Each event, as it was presented in the simulator, is described in Appendix B.

A scenario was defined as the combination of a malfunction and an initial condition or state of the plant on which the malfunction was superimposed. Five of the malfunctions occurred during "routine operations" at 100% power. Malfunction 91 (loss of shutdown cooling) was initiated during cooldown, with the reactor at 0% power and core temperature $\approx 350^{\circ}F$. Four other malfunctions (numbers 34, 25, 3, and 138) were initiated at low power levels ($\approx$ 50%, 56%, 20%, and 56% power, respectively) so that the malfunction did not cause a scram immediately.

Table 3-1 BWR malfunctions simulated

Malfunction No.	Event	% Power
Condition II (Incidents of Moderate Frequency):[a]		
34	Master Feedwater Flow Control Failure (Abnormal Vessel Water Level)	≈ 50
91	Loss of Shutdown Cooling	0
25	Feedwater Pump Failure	≈ 56
3	Turbine Trip	≈ 20
121	Condenser Tube Leak (High Chloride Concentration)	100
138	Reactor Building Closed Cooling Water (RBCCW) High Activity	≈ 56
2	Loss of Condenser Vacuum	100
Condition III (Infrequent Incidents):		
11	Loss of All Off-Site Power	100
9	Main Steam Relief Valve (MSRV) Failure	100
Condition IV (Limiting Faults):		
122	Fuel Element Damage	100

a. Event categories as given in ANSI/ANS-52.1 (Ref. 5)

3.3.2 Written Procedures

Each malfunction presented was the subject of one or more written operating procedures, which were available to the trainees and could be referred to at any time. Each of the three utilities whose operators participated in this study supplied its own operating procedures.

The procedures were "event based," i.e., the operator needed to have recognized the event in progress in order to select the correct procedure(s). A sample procedure page is reproduced as Figure 3-2. The example shown is a general procedure applicable to all scrams no matter

IMMEDIATE OPERATOR ACTIONS

A. Verify existing conditions by multiple indications (i.e., alarms, charts, indicating lights, gauges and other instrumentation).

B. Verify all automatic actions have occurred. If not, place controls on manual and make corrective manipulations.

CAUTION	DO NOT PLACE CONTROLS ON MANUAL UNNECESSARILY WHEN AUTOMATIC IS FUNCTIONING PROPERLY UNLESS UNSAFE PLANT CONDITIONS WILL RESULT.

C. Check reactor in a safe condition, using multiple indications.

1. Check reactor scrammed with all rods fully inserted.

CAUTION	IF 5 OR MORE ADJACENT OR 30 OR MORE CONTROL RODS THROUGHOUT THE CORE DO NOT INSERT PAST (06) REFER TO EOI 47.

a. Mode switch to refuel, one rod permissive light illuminated.

b. Select the rod(s) that is not full-in and manually insert rod.

c. If rod(s) cannot be selected, individually scram rod(s) from auxiliary instrument room.

2. Observe nuclear instrumentation to ensure flux is decaying. Insert IRM and SRM detectors. Switch APRM recorders to the IRM position. Position IRM to maintain on scale readings.

D. Check that a flow path is established and reactor water level is near normal, using multiple indications.

E. Notify supervisor of events and actions taken.

SUBSEQUENT OPERATOR ACTION

A. Verify main generator breaker is open and open disconnects.

B. Check main condenser available as primary heat sink and maintain condenser vacuum until steam is no longer in steam lines, or heat sink is no longer needed.

C. Remove unnecessary equipment from service.

Figure 3-2 Example procedure page

how precipitated. The quality and format are typical of procedures in use in early 1981. Two features of these procedures are particularly noteworthy. The procedure is divided into two sections, "immediate" and "subsequent" operator actions. Operators were expected to have memorized the immediate actions, so that they could be initiated before the written procedure was referenced. The second feature of interest is that the procedure is written as a series of general statements, the interpretation of which requires a great deal of knowledge on the part of the operator. The procedure is more a series of reminders than a list of detailed instructions for the task: it would be of little value to someone who was not thoroughly familiar with the operation of the plant.

3.4 Subjects

Twenty-four four-or five-man groups or "teams" participated in this research. Most of the men in these teams (there was only one woman) worked as reactor operators, but some were supervisors or engineers who did not operate a reactor on a day-to-day basis. With the exception of nine Shift Technical Advisors (STAs) all subjects held NRC Reactor Operator or Senior Reactor Operator licenses. The STAs were all from Utility B, and there was never more than one STA in a group.

The operators participating in this study came from three plants run by different utilities, which we will call A, B, and C to maintain the anonymity of the operators. Twelve of the teams were from Utility A, nine were from B, and three were from C. Teams from A were trained on the day shift (0830-1630), those from B on the evening shift (1630-2430), and those from C on the third shift (2430-0830). The simulator used duplicated the control room of A's plant. Where appropriate, we have examined the data collected to determine if there are significant differences between groups from the different utilities.

The men making up a team were selected by the utilities on an *ad hoc* basis. Thus, the "teams" do not represent intact control room crews, though most of the members had worked together at one time or another. It should be noted that four-man teams are somewhat atypical: usually two or three men are responsible for a single unit, although manning policies vary from one utility to the next. The possible effects of additional personnel on the response measures used will be discussed in the results sections of this report.

3.5 Procedure

The exercises analyzed in this report were conducted as a part of a five-day refresher or "requalification" training program that included roughly 16 hours of classroom instruction and 16 hours of simulator time. The 10 events of interest were run on the second through the fifth days of this program, interspersed with other training exercises which were not recorded.

No special training or instructions were given as part of the study, but all teams had spent some time in the simulator before the first recorded exercise. The recorded events were presented in the same way as the other training exercises, except that the instructor remained at his console and did not interact with the students (except to perform "remote plant functions" if requested from the control room). Each exercise was concluded when the instructor felt the situation was under control, or that there was little instructional value in continuing. After each exercise the operators were requested to complete the one-page "Questionnaire for the Evaluation of Performance Shaping Factors."

An observer who was familiar with control-room operations watched the exercises and administered the questionnaires. In addition, the observer was to record events not captured by the PMS (such as when the malfunction was recognized) on a simple "time-line." This effort was abandoned because the observers felt they could not reliably follow the actions of all four operators during the first moments of the event, which was usually characterized by rapid actions by several or all of the operators.

4. OPERATOR RESPONSE TIMES

4.1 Measurement of Response Time

The draft N660 standard specifies the time that must be allowed by plant designers for the performance of certain control-room tasks. The primary goal of the present study is to determine how long is actually taken by control-room crews to perform these tasks. The response measure of interest is response time (RT), defined as the interval between the appearance of the first cue to the operators that something has happened (the time t_e in Figure 2-1) and the first action they make in response to the malfunction. The draft standard specifies that no response be required before time t_m. The interval t_c-t_m (Time Test 1) is allowed for the completion of various pre-response activities. The best empirical estimate of the time actually required for these activities is thus the time elapsing from the appearance of the cue until the first significant response is made. In order to calculate these times, both the cue and the response must be identified.

4.1.1 Cues Signalling Onset of Malfunction

Table 4-1 lists prominent cues and the annunciators from which response times were measured.

Table 4-1 Cues signalling onset of malfunction

Malfunction	Cue	Annunciator Legend
34[a]	Rx level or flow	"REACTOR WATER LEVEL A ABNORMAL"
91	Annunciator	"MOTOR TRIP"
25	Annunciator	"RFP TURBINE TRIPPED"
3	Annunciator	"TURBINE SHUT DOWN"
121	Annunciator	"DISCH CNDS. PUMPS COND HIGH"
138	Rad Monitor	"RBCCW EFFL RADIATION HI"
2[a]	MWe Decreasing	"CONDENSER A, B, OR C VAC LOW"
11	Multiple[b]	"TURBINE GENERATOR LOAD REJECT SCRAM TRIP"
9	MWe Decreasing	"AUTO BLOWDOWN RELIEF VALVES TEMP HIGH"
122	Annunciator	"MAIN STEAM HIGH RADIATION SCRAM"

a. RT was measured from the activation of the malfunction. The onset of the annunciator was used for all other malfunctions.

b. Loss of off-site power is signalled by a loud bang from the closing of several relays behind the control panels, followed immediately by multiple scram indications.

For malfunctions 91, 25, 3, 121, 11, and 122 RT was measured from the activation of the annunciators listed in the table because they are unmistakable cues with a definite onset, and sounding of the annunciator precedes or is coincident with other cues. Malfunction 138 was also timed from the sounding of the annunciator because the RBCCW radiation monitor is at the end of the left wing of the horseshoe and unlikely to be noticed before the annunciator is triggered. Malfunction 34 (Feedwater Flow Controller fails high) was measured from the insertion of the malfunction because there are immediate multiple indications on instruments that are prominently placed and closely monitored.* Malfunction 2 (loss of condenser vacuum) is signalled by an immediate but gradual decrease in generator output. The most prominent cue is the MWe meter, which is digital ("NIXI" tubes) and flickers slightly when the digits change. Response time was measured from the onset of the malfunction because all but one of the teams responded to this malfunction before the annunciator was triggered. However, the long and variable RTs suggest the cue used was not very conspicuous. For this reason, RT to malfunction 9 (MSRV fails open), which produces similar symptoms, was measured from the sounding of the annunciator (which is triggered after about 40 seconds).

4.1.2 Operator Responses

In most cases several corrective actions are undertaken more or less immediately following the occurrence of a malfunction. Where the first indication is an annunciator, the malfunction is signalled simultaneously to all operators. Each operator generally makes some assessment of the situation and begins to take whatever actions are required at the control panels for which he is responsible (his duty station).

The presence of several operators and the possibility of "immediate" actions involving several systems makes it impossible to predict what particular action will be taken first. Thus several possible actions were identified as critical task elements (CTEs) and extracted from the PMS records. A CTE was defined as a significant control action specified by or inferred from the operating procedures(s) governing response to each malfunction. The CTEs were selected to be specific to the malfunction so that performance of the CTE would indicate that at least an initial assessment of the situation had

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*Eight teams responded to this malfunction before the annunciator sounded, which occurred about eight seconds after the malfunction began. We believe that this reflects the high state of alertness of operators working in a simulator, who are expecting something to happen at any minute. The proportion of such anticipatory responses would probably be smaller among operators on the plant floor who were not expecting something to happen.

occurred. Selection of CTEs was guided by the expected operator actions listed with the scenario cause/effect descriptions in Appendix B. The expected actions described were identified with specific control activations, which are recorded as digital inputs (DIs) on the PMS tapes. This process is illustrated in Table 4-2, which shows the expected initial actions in response to malfunction 34.

Table 4-2 Critical task elements for malfunction 34 (Master Feedwater Flow Controller Failure)

Expected Action	Control Activation Required	DI
1. Maintain manual control of feedwater (FW)	a. FW Master Controller - MANUAL	2006
	(b) FW Pump Turbine "A" speed - MANUAL	2009
	(c) FW Pump Turbine "B" speed - MANUAL	2012
2.* Reactor Mode Switch to REFUEL	a. Rx Mode Switch - REFUEL	2019
	(b) Scram Reset (Gr 1 & 4) - RESET	2022
	(c) Scram Reset (Gr 2 & 3) - RESET	2023
3.* Maintain reactor water level	a. Rx Feed Pump "A" - RESET	2645
	b. Rx Feed Pump "B" - RESET	2646
	c. Rx Feed Pump "C" - RESET	2647
4.* Insert nutron detectors	a. SRM/IRM Drive - IN	1870
5.* - - etc. - -		

* Response to scram

Figure 4-1 is a PMS summary printout of the times (in seconds) from the activation of malfunction 34 to the activation of the controls listed in Table 4-2. Summary printouts for all exercises are reproduced in Appendix C. Each control action is identified by the DI number, which is in the second row in the table heading. Teams of operators are identified by file numbers (which are not necessarily in the correct order). The response times used in this study were those of whichever of the CTEs was performed first. The RTs of Team 1 are given in the first line of the table. The first CTE (at 23 seconds) is DI 2019: Reactor Mode Switch - REFUEL. This indicates that the reactor scrammed on high water level before the operators could deal with the failed flow controller (seven other teams also failed to control water level in time to avoid a scram). The responses of Team 7 are shown in the eighth line of the printout (file 401). By acting very quickly (4 seconds, which was before the annunciator sounded), this team was able to switch the

FILE #	MAL TIME	CTE 1 1870	CTE 2 2006	CTE 3 2009	CTE 4 2012	CTE 5 2019	CTE 6 2022	CTE 7 2023	CTE 8 2645	CTE 9 2646	CTE 10 2647	CTE 11 3051	CTE 12 3152	M. OUT	OCCUR.
204	2832	40	103	****	****	23	150	149	****	****	40	****	81	0	1
~~205~~	~~164~~	~~****~~	~~13~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~28~~	~~****~~	~~****~~	~~99~~	~~2~~
220	125	182	81	63	78	229	259	259	70	92	119	92	39	0	1
333	215	****	252	88	111	****	****	****	****	12	****	****	****	599	1
341	2152	****	****	****	****	****	****	****	38	50	****	42	38	2372	1
345	249	****	****	7	27	****	****	****	****	****	****	****	****	0	1
360	77	70	****	17	11	26	132	131	****	68	66	****	29	0	1
401	13	****	4	****	****	****	****	****	****	****	****	****	****	0	1
413	82	70	161	****	58	23	202	201	61	****	127	49	75	0	1
425	36	****	11	****	****	****	****	****	****	****	****	****	****	0	1
441	1109	****	2	****	****	****	****	****	****	****	****	****	****	0	1
~~466~~	~~136~~	~~****~~	~~2~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~0~~	~~1~~
470	209	****	5	****	****	****	****	****	****	****	****	****	****	0	1
503	29	****	3	****	****	****	****	****	****	****	****	****	****	0	1
514	175	111	13	100	68	27	162	161	102	73	251	****	151	0	1
530	1523	****	11	****	****	****	****	****	****	****	****	****	****	1570	1
542	266	****	****	****	****	****	****	****	****	****	****	****	****	0	1
543	12	****	7	****	****	****	****	****	****	****	****	****	****	0	1
554	28	****	43	****	****	****	****	****	****	****	****	****	****	0	1
571	95	****	59	6	6	****	****	****	****	****	****	****	****	0	1
603	925	****	****	89	88	****	52	52	106	119	57	33	****	0	1
612	967	****	5	****	****	****	****	****	****	****	****	****	****	0	1
630	190	****	****	****	****	22	****	****	****	****	****	****	****	0	1
640	262	63	66	****	****	22	****	****	83	****	****	****	82	0	1
647	56	****	7	****	****	****	****	****	****	****	****	****	****	0	1
663	291	****	****	5	6	23	155	135	43	47	54	****	142	0	1

Annunciator 3720 Reactor Water Level Abnormal

Critical Task Element - CTE		Expected Operator Actions
1870	SRM/IRM Drive (In)	4
2006	Main Feedwater Control (Manual)	1
2009	Reactor Feed Pump Turbine "A" Speed (Manual)	3
2012	Reactor Feed Pump Turbine "[illegible]" Speed (Manual)	3
2019	Mode Switch to Refuel	2
2022	Scram Reset (GR 1 & 4)	5
2023	Scram Reset (GR 2 & 3)	5
2645	Reset Reactor Feed Pump	3
2646	Reset Reactor Feed Pump	3
2647	Reset Reactor Feed Pump	3
3051	Exciter Field Breaker (Control Trip)	* Clearing breaker disagreements
3152	Primary Circuit Breaker 5218 - Generator (Trip)	* Clearing breaker disagreements

Line-out file number was incorrect data for this malfunction.

Figure 4-1 Sample PMS printout showing response time in seconds to each critical task element for malfunction 34 (Master Feedwater Flow Controller Failure).

Main Feedwater Control to MANUAL and control water level so that no further action was necessary.

Table 4-3 presents RTs (in seconds) to each of 10 malfunctions for the 24 teams of operators. Scheduling conflicts or computer problems sometimes prevented recording of a complete set of malfunctions for each team: such missing data are represented by asterisks in the table. The geometric mean RT for each malfunction is given in the bottom row of the table. Geometric means are reported instead of arithmatic means to reduce the influence of the occasional very long RT on the reported average: this is a common practice when dealing with response time data (Ref. 8).

Initial inspection of the data given in Table 4-3 indicated that the distributions of response times were positively skewed. This is a commonly observed property of response time measures. In order to use parametric inferential* statistics to evaluate these data, we used the logarithm of the response time in place of the response time itself:

$$X_i' = \log_{10}(X_i)$$

Parametric statistical tests are valid when the distribution of scores is approximately normal and the variances within the groups being compared are not too disimilar. The logarithmic transform of the scores is generally effective in normalizing positively skewed distributions.

Inspection of Table 4-3 reveals that there were marked differences in the rapidity of response to individual malfunctions. A repeated-measures analysis of variance (ANOVA) was performed on the RTs from the 17 teams completing all malfunctions. The ANOVA indicated significant differences between malfunctions ($F = 44.11$, $df = 9/144$, $p < .001$), and allowed the application of the Scheffe' test (Ref. 8) to determine which malfunctions differed significantly. Two groups of malfuncions were identified. Malfunctions 34, 91, 25, 3, 11, and 122 all had short RTs which did not differ significantly from one another. Malfunctions 121, 138, 2 and 9 had relatively long response times which did not differ significantly from one another (due to the great variability of RTs for a given malfunction) but were reliably longer than the RTs from the short-RT group.

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*Inferential statistics are used to determine how likely an observed difference between samples (groups) is, assuming that there is no real difference between sampled populations. When this likelihood (the "p" value) is small (generally $p < .05$), it is said that the observed differences are "statistically significant," i.e., that there <u>is</u> some difference between groups. Inferential statistics are most helpful when the distributions of scores are overlapping.

Table 4-3 First Action Response Times (Time in Seconds)

	Utility Team	MALFUNCTION 34[a]	91	25	3	121	138	2[a]	11	9	122
A	1	23	**	6	**	70	156	147	7	**	6
	2	39	9	**	26	**	40	**	11	83	6
	3	38	5	26	23	20	285	143	26	164	9
	4	88	3	6	25	15	183	158	27	14	8
	5	7	3	7	30	33	194	321	25	227	9
	6	11	8	14	14	64	106	241	7	104	3
	7	4	5	2	19	46	155	157	8	92	11
	8	23	2	6	9	135	66	180	32	81	5
	9	11	2	9	9	60	127	189	6	140	12
	10	2	6	12	2	63	69	316	7	262	24
	11	5	1	5	16	43	119	214	2	63	11
	12	3	3	49	19	129	65	310	6	118	6
B	13	13	13	11	36	231	172	203	19	56	3
	14	11	4	27	12	81	73	86	23	**	2
	15	7	7	4	16	114	72	**	**	**	5
	16	43	6	3	18	243	195	204	9	45	7
	17	**	29	18	14	**	**	**	**	**	**
	18	6	60	16	36	45	40	113	23	21	4
	19	33	7	14	11	**	200	**	**	**	4
	20	5	50	2	13	191	70	385	23	130	10
	21	22	47	10	13	75	77	100	11	185	5
C	22	22	8	78	11	100	158	**	18	**	14
	23	7	32	11	64	38	166	159	22	72	24
	24	5	1	19	29	299	155	168	6	136	5
	Geometric Mean	11.9	6.9	10.1	16.7	74.7	112.2	185.0	12.2	88.6	6.9

** Missing data

a. Time from activation of malfunction (malfunctions 2 and 34 only)

4.2 Pooling Data From Different Utilities

It is desirable to combine the response times from all teams from the three utilities to produce a single set of response times for each malfunction. This is so for two reasons. The error associated with any statistic, such as a mean response time, varies inversely with the sample size. Secondly, a sample from data from three utilities is arguably more representative of the population of "operators" than one drawn from a single utility.

Before combining the data from the three utilities it is of interest to know if there are any systematic differences in response times between utilities. Operators from one utility were from the plant the simulator used for data collection was designed to mimic: responses from operators from the other utilities might be affected by the unfamiliarity of the simulator. In addition, training, operating procedures, and management practices may vary from one utility to another, and might affect response times. Systematic differences in response times between utilities would not affect the mechanics of pooling the data, but such differences would raise the question of generalizability: if obvious differences between utilities were evident in three samples, a more systematic sampling of utilities would be needed to insure that extremes were included. This is especially important because we are interested in the upper limit of response times for use in a design standard.

Table 4-4 presents the geometric means of the RTs for teams from the three utilities. Appropriate tests, detailed in Appendix D, were used to determine if intergroup differences were statistically significant. Significant differences are summarized in the "Difference" column of the table.

The statistical analysis reported above revealed only three cases in which the group means were significantly different between utilities. Inspection of Table 4-4 reveals that some of the "insignificant" differences appear to be rather large (e.g. malfunctions 3, 25, and 138). There are two reasons for this apparent discrepancy. The power of the tests (the ability to detect a difference of a given size) is a function of the number of cases (of which there were only 3 for Utility C), and variability of the RTs within utilities was quite large.

Since there were no significant differences between the utilities for seven of the 10 malfunctions, and the differences detected form no consistent pattern, it was decided to use pooled data for subsequent analysis of all 10 malfunctions.

Table 4-4 Comparison of response times of teams from the three utilities

Malfunction	Utility A (12)	B (9)	C (3)	All	Test	Difference
34[a]	11.8	13.2	9.2	11.9	ANOVA[b]	A ~ B ~ C
91	3.6	15.8	6.3	6.9	K-W[c]	A ~ C < B
25	8.9	8.7	25.4	10.1	ANOVA	A ~ B ~ C
3	14.5	17.0	27.3	16.7	ANOVA	A ~ B ~ C
121	50.8	118.8	104.4	74.7	ANOVA	A < B ~ C
138	113.3	96.6	169.7	112.1	K-W	A ~ B ~ C
2[a]	206.3	157.9	163.4	185.0	U[d]	A ~ B ~ C
11	10.2	16.2	13.3	12.2	ANOVA	A ~ B ~ C
9	99.2	66.2	99.0	88.6	U	A ~ B ~ C
122	8.0	4.5	11.9	6.9	ANOVA	A ~ C > B

All entries are geometric means.

a. Response time calculated from activation of malfunction.

b. One-way analysis of variance. The Newman-Keuls procedure was used to determine inter-group differences when a significant F was found.

c. Kruskal-Wallis nonparametric one-way ANOVA.

d. Mann-Whitney U statistic to test differences between means of A and B: there were only two scores from C, which fell near the mean of one of the other groups.

4.3 Graphical Analysis

The pooled response times for each malfunction were plotted on log-normal probability paper. This plotting was selected for two reasons: it is a useful way to represent the data, and the plots allow a check on how closely the data approximate a log-normal distribution.

To construct a plot, the n RTs for each malfunction are ordered from the shortest to the longest, $X_1, \ldots X_i, \ldots X_n$, where i is the position of the RT in the ordering. The estimator for the cumulative probability associated with each time, X_i, is then

$$F(X_i) = \frac{i}{n+1}$$

Figure 4-2 is representative of the plots produced (plots for all the malfunctions are presented in Appendix E). These plots can be used to obtain an estimate of the percentage of teams that are likely to respond correctly within a given time, or, conversely, the time within which any given percentage of teams could be expected to respond correctly. It is to be emphasized that these data reflect the performance of teams, not of individual operators. The response recorded is made by one member of a three or four man team. Assume that this response is made by the first of these three or four men to diagnose and formulate a plan of action for responding to the event. The probability that at least one of those men will be above average is $1-1/2^n$ or about .94 for a four-man team. These plots should therefore be used with caution for making inferences about the performance of individual operators.

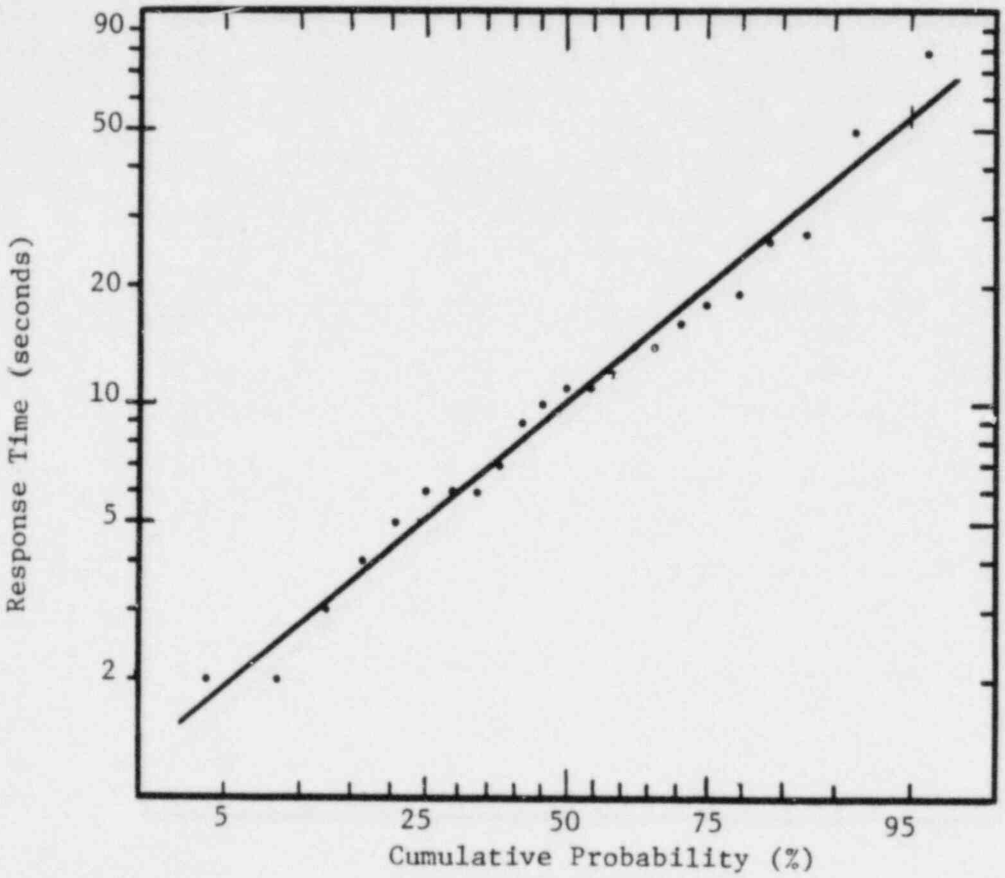

Figure 4-2 Cumulative probability of operator response time to a main feed pump trip (malfunction 25)

The log-normal plotting of response time also allows a check on the assumption implicit in the use of the logarithmic transformation to "normalize" the data for statistical analysis. If this assumption is true, the data points will fall into a straight line in the plots. A line has been fit to the plotted points by the method of least-squares (the data must be transformed to fit the line: see Appendix E). The goodness-of-fit of the line is reflected in the coefficient of determination (r^2) which indicates the proportion of variance accounted for by the line fit to the data. The results of these calculations are presented in Table 4-5. The coefficient of determination is merely descriptive: it does not constitute a significance test because there is no criterion for saying what value of r^2 indicates an unacceptable fit. The non-parametric Kolmogrov Goodness of Fit Test (Ref. 9) was also applied to these distributions: none differed significantly from the hypothesized log-normal form at the $p < .10$ level.

Response times for selected percentiles, as read from the plots, are summarized in Table 4-5. The inter-quartile range (IQR) is included as an indication of the variability of response.

With the exception of malfunctions 2 and 34, the response times in Table 4-5 are the interval from the activation of an annunciator until the performance of a CTE.

Table 4-5 Selected percentile response times

		Percentile					
Malfunction	r^2 [a]	25%	50%	75%	90%	95%	IQR
34	.976[2]	5.8	11.9	24.4	46.7	68.9	18.6
91	.957	2.9	6.9	16.3	35.3	56.2	13.4
25	.980	5.2	10.1	20.1	34.5	54.2	14.9
3	.881	10.2	16.7	28.0	43.9	53.5	17.8
121	.985	42.0	74.7	137.0	234.0	321.4	95.0
138	.939	75.0	112.1	168.0	239.0	296.5	93.0
2	.975	136.8	185.0	250.0	328.4	386.4	113.4
11	.903	7.2	12.2	20.1	34.5	54.2	12.9
9	.926	50.5	88.6	155.5	257.9	349.2	105.0
122	.975	4.3	6.9	11.0	16.8	21.5	6.7

a. The coefficient of determination.

4.4 A Group Performance Measure

In Sections 6 and 7 we will attempt to relate team error rate and collective experience to performance as measured by RT. It makes little sense to do this on a scenario-by-scenario basis. The "mean rank response time" was selected as the statistic representative of a team's overall (relative) performance. This measure was used in preference to the team mean RT because some teams did not complete all exercises. The average RT varied from one exercise to another and the "missing data" entries tended to be for the longer RT exercises. The idea of using the exercise geometric mean RT to "estimate" missing RTs was discarded because such estimates would constitute an unduly large proportion of the scores for some teams.

For each malfunction, all reaction times were rank ordered, with the fastest being assigned the lowest rank. Tied scores were assigned the mean of the ranks that would have been assigned had the tied scores been just slightly different from one another.

According to this principle, the following eight response times:

23 25 25 37 52 52 52 96

would be assigned the ranks:

1 2.5 2.5 4 6 6 6 8.

The mean rank response time (MRRT) was computed by averaging the team's rank for each malfunction across all exercises it completed.

$$MRRT = \frac{R}{K}$$

where R is the rank received by the team for each malfunction and K is the number of malfunctions in which the team participated.

The MRRTs and overall team rankings are shown in Table 4-6.

The MRRT can in theory assume any value between 1 and 21.7*. In practice the rankings (and the RTs themselves) were only weakly correlated over successive exercises, and the MRRTs fell into a relatively restricted range, from 7.75 to 15.5 (1:2).

*A team that was slowest for every exercise would have an MRRT of 21.7 because fewer than 24 teams completed any given exercise.

Table 4-6 Mean rank response times and overall ranking of teams

Utility A			Utility B			Utility C		
Team	MRRT	Rank	Team	MRRT	Rank	Team	MRRT	Rank
1	10.36*	7	13	13.75	21	22	15.19*	23
2	12.36*	15	14	8.44*	2	23	13.60*	20
3	14.40	22	15	9.64*	5	24	11.15	12
4	11.50	14	16	12.85	17		n = 3	
5	13.55	19	17	15.50*	24			
6	10.60	10	18	10.70	11			
7	9.05	3	19	13.17*	18			
8	9.70	6	20	12.40	16			
9	9.60	4	21	11.20	13			
10	10.50	9		n = 9				
11	7.75	1						
12	10.45	8						
	n = 12							

*MRRT computed with less than ten malfunctions.

A between-group analysis of variance was performed to determine if there were significant differences in MRRT between utilities. The test indicated no significant difference ($F = .57$, $df = 2/21$, $p > .50$)

5. APPLICATION OF RESPONSE-TIME DATA TO ANSI-N660

A major objective of the current work is to provide empirical support for guidelines for assigning safety-related actions to operator or automatic functions. This section relates data collected on operator response time to the time tests defined in the N660 draft standard (Ref. 1). Portions of the standard are discussed in Section 2.1.

5.1. Data For Time Test 1

The data on the time required for the first operator action for each of the ten events were chosen as most appropriate for comparison to the values suggested in Reference 1. Since it is the recommendation of the N660 writing group to use the 95th percentile time response (see Appendix B of Ref. 1), the 95th percentile values listed in Table 4-5 (rounded up to the nearest second) were used for comparison.

The malfunctions examined in the simulator experiments included seven Condition II events, two Condition III events, and one Condition IV event. The Time Test 1 values recommended in Reference 1 are 5, 10, and 20 minutes respectively. Table 5-1 shows the classification of the events and lists the 95th percentile response times.

Table 5-1 Comparison Of 95th percentile response times to the Time Test 1 intervals

Event		RT	Time Test 1	Diff
Condition II (Incidents of Moderate Frequency):				
34[a]	Feedwater Flow Controller Failure	69	300	231
91	Loss of Shutdown Cooling	57	300	243
25	Feedwater Pump Trip	55	300	245
3	Turbine Trip	54	300	246
121	Condenser Tube Leak	322	300	-22
138	High Cooling Water Activity	297	300	3
2[a]	Loss of Condenser Vacuum	387	300	-87
Condition III (Infrequent Incidents):				
11	Loss of Off-Site Power	55	600	545
9	Main Steam Relief Valve Failure	350	600	250
Condition IV (Limiting Faults):				
122	Fuel Element Dammage	22	1200	1178

a. Time from activation of malfunction: all other RTs measured from activation of appropriate annunciator.

Recall that the time listed includes the total time from sounding of the annunciator to initiation of the first correct manual action. This includes the time required (for the team of operators) to recognize the alarm, check additional status indicators, diagnose the anomaly, and initiate the required manual action. Inspection of Table 4-1 reveals no relationship between the time specified by Time Test 1 and the amount of time elapsing before the first corrective action. In six of the 10 cases, action was initiated within approximately one minute of the beginning of the event. In three of the remaining cases, the first corrective action took from five to six minutes to initiate. For Malfunction 2 the 95th percentile RT was almost 6 1/2 minutes. However, the malfunction was detected before plant parameters had changed enough to trigger an alarm.

For two of the seven Condition II events, the time taken to initiate action equalled or exceeded the supposedly conservative five minutes specified by Time Test 1. However, for malfunction 121 the excess time is only 22 seconds, which may be largely attributed to the necessity of checking several instruments to determine which of the four condensers was affected and should be isolated. The RT for malfunction 2 is problematic in that we do not know when the early cue, decreasing generator output, was noticed. It seems safe to assume that some large fraction of the recorded RT represents time elapsed before the cue was noticed (though significant diagnosis must occur after this, as the cue is non-specific).

Since we examined only one Condition IV and two Condition III events, we can make no inferences as to the adequacy of the time margins specified for Conditions III and IV. However, taken as a whole, the data suggest that the time required to diagnose and initiate response to an event is not a function of the event category.

If the observed response times are not related to the category of event, how can they be explained? The three Condition II events with 95th percentile response times of about one minute (34, 25, and 3) are signalled by specific, relatively unambiguous indications, and all allow simple and immediate response. Three of the other Condition II malfunctions (91, 121, and 2), involve more of a diagnostic problem for the operators (2), and/or do not require "immediate" response (121). For example, loss of shutdown cooling (91) has a relatively unambiguous indication, but due to low decay heat, immediate initiation of additional shutdown cooling is not necessary.

Similarly, for the Condition III events, the loss of off-site power (11) has specific and unambiguous indications, and requires immediate simple action, while the MSRV failure requires, as part of the verification of the alarm, that an operator physically leave the main control board area to read a temperature recorder on a back panel in order to establish which relief valve has become unseated. The response time (95th percentile) is an order of magnitude greater for the MSRV failure. The Condition IV event (122, fuel element damage), has a very short response time, and it too has specific unambiguous alarms with straightforward, immediate required action (to deal with the resulting scram).

Certainly these data, with only three malfunctions representing Condition III and IV events, are too sparse to be conclusive, but it is interesting to note that the variation in response time is more readily related to these kinds of event-specific factors than to the event categorization ("condition" number) based on consequence and frequency of occurrence.

5.2 Data For Time Test 2 (Fixed)

The reference time for measuring this time margin is the initiation time of the action, usually signalled by some alarm or indication. The fixed portion of the time test allows for receipt of a very simple readout (e.g., a single instrument reading or audible alarm) and additional time for diagnosis and planning. The initial responses to the turbine trip (3), and the two feedwater malfunctions (34 and 25), all Condition II events, were judged to be the kind of operator actions covered by Time Test 2, as were the loss of off-site power (11, Condition III) and fuel element damage (122, Condition IV) events. The time from alarm to initial action on these events was therefore also used to estimate the fixed portion of Time Test 2. A value of one minute, used in the standard for Condition II events, is supported by the data. Longer times for Conditions III and IV are not supported; the longest RT was for malfunction 34, a Condition II event. Of course no very firm conclusion should be drawn on basis of five points, but the limited data available suggest that the values proposed for Time Test 2 are reasonable, at least in the relatively low-stress environment of the simulator.

5.3 Data For Time Test 2 (Variable)

The purpose of the variable portion of Time Test 2 is to ensure sufficient time for an operator to proceed through a multiple switch manipulation sequence. None of the scenarios in this study required a series of manipulations felt to be applicable to this test, and no attempt is made to use these data to evaluate this part of the standard. Data on the time taken by operators to proceed through a sequence of switch manipulations are presented in Chapter 5 of Reference 7.

5.4 Discussion

The N660 standard is intended to ensure that designers assign critical safety functions to operator actions only when the interval between warning and required action is long enough to allow a sufficient time for correct response. The standard is an attempt to define "sufficient time." Assuming that most operator action sequences are comprised of relatively few steps,* somewhere between 30 and 80% of the time specified by the standard is attributable to two constants, the time margin (Time Test 1) and the fixed portion of Time Test 2. The values of both constants are arbitrary, and assigned solely on the basis of the event category. The 95th percentile response times given in Table 5-1 suggest that the time to verify the proper operation of engineered safety functions and select an initial course of action does not necessarily vary as a function of event category. Thus the use of different values of these constants for different categories of events appears to be questionable.

The assignment to a category is determined by potential severity of the consequence of an event, and the relative frequency of occurrence. The allowance of progressively longer time margins for Condition II, III, and IV events is based on two premises related to these assignment criteria.

The first premise is that potentially hazardous accidents will be more stressful to the operators. Stress often causes disorganization of behavior. Further, the consequences of errors in dealing with more hazardous events are potentially much more adverse. For these reasons it makes good sense to allow the operators more time to formulate a plan of action before they are required to act. In our data the 95th percentile response time to the Condition III and IV events was (on average) faster than the response to the Condition II events. However, it is likely that no special stress was experienced by the operators, because the events were just simulator exercises. Thus our data offers no evidence at all as to the validity of the first premise.

The second reason for the allowance of greater time margins for Condition III and IV events is that they are much less common. The second premise is that uncommon events will be more difficult to recognize and develop plans for dealing with. It is true that the operator's ability to recognize and respond properly is likely to be a function of his familiarity with the event. However, his familiarity with the event is more a function of his <u>training</u> than of the event's frequency of occurrence. All operators are familiar with design basis LOCAs because this accident is emphasized in training, but no operator has ever seen one in an operating plant. Secondly, the speed of diagnosis is probably at least as much a function of the information available, and the way in which this information is presented, as it is of the operators' familiarity with the event. There seems no <u>a priori</u>

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*The operator actions for dealing with most events are actually quite numerous. However, the effect of the first few actions is usually to mitigate the event sufficiently to increase the interval before the design specifications will be exceeded.

reason to believe that the information required to diagnose a Condition III or IV event would be more difficult to obtain and interpret than that required for Condition II events.

We do not quarrel with the idea of providing a time margin for operator responses: though adequate time does not insure accurate response, the absence of sufficient time insures failure. We do, however, think there is a good deal more to insuring that the operators are capable of responding properly than simply seeing to it that they have enough time to do so. In this regard, Section 7.1 of the draft standard addresses what we feel is the most significant single aspect of the problem: "The operator shall be provided with clearly presented readout information at the required time for him to assess the need for a particular safety-related action without significant diagnosis."

6. EVALUATION OF OPERATOR ERROR

Because the approach taken in ANSI-N660 is to use time tests as the basis for design decisions, emphasis has been placed throughout the SROA program on obtaining data on the time required for initiation of operator action. The standard does not attempt to deal directly with probability or consequences of incorrect action. One alternative approach would be to base the decision about manual versus automatic actions on a comparative estimate of reliability. That is, one would estimate the probability of correct performance of the required action within the required time for both cases -- operator action and automatic action -- and use that estimate (along with practical considerations such as cost) to guide the decision about automation.

The large gaps in the current state-of-the-art, both in modeling and in data base development, make such an approach, especially as part of a design standard, still impractical. However, to begin to deal with overall operator performance it is necessary to address operator error (error probability), as well as time, as a measure of performance. Certainly the two are interrelated, and this interrelationship needs further examination also.

6.1 Classification of Errors

In order to begin to evaluate errors in performance, it is necessary to define error for the required tasks. It is also desirable to categorize individual errors according to some more or less generic types, depending on the level of generality that is desired and practical within the model of performance being used to estimate reliability. Because of the emphasis of this program to date, such a taxonomy of errors has not been developed, and no specific model of operator performance has been assumed or developed by us, beyond the conceptual model inferred from ANSI-N660. For the time being, the classification of errors into two general categories suggested by Swain and Guttmann (Ref. 6) has been assumed to be applicable and of the appropriate level of detail. These are:

(1) Error of omission - a person fails to perform the task or part of the task (e.g. a step).

(2) Error of commission - a person performs the task or step incorrectly.

   (a) Extraneous act - person introduces some task or step that should not have been performed.

   (b) Sequential error - person performs some task or step out of sequence.

   (c) Time error - a person fails to perform the task or step within the allotted time, either too early or too late.

The sub-categories of errors of commission are listed separately because their causal factors are often different.

Within the basic taxonomy listed above, the kinds of errors for which information is most readily obtained from the current experiments are errors of omission and sequential or time errors. That is, these are relatively easy to identify using the PMS if it can be assumed that the tasks are well defined and reasonably invariant from trial-to-trial. For the PWR exercises discussed in Reference 3, this was generally the case, and it was possible to obtain some data on errors of omission, along with data on time response.

The definition of sequential errors must be considered very carefully. Although actions specified in the abnormal or emergency operating procedure are listed sequentially, the exact order may not be critical, or certain steps can be deleted, depending on the specific conditions at the time of the event. Therefore, the performance of a step "out of sequence," or even omitting a step, might not be an error. However, if a set of actions is well defined by the procedures and an unambiguous definition of sequential errors or errors of omission can be obtained, these can be identified in the PMS outputs.

Errors of commission and extraneous acts are not as easily identified from the PMS data, or by observers, simply because there are (at least conceptually) virtually unlimited possibilities. By careful examination of the simulated event sequences, the control board, procedures, etc. to identify "likely" errors and by comparison of output from different operator teams responding to the same event, it should be possible to obtain meaningful data on errors of commission and extraneous acts. However, the analysis to date does not include an attempt to extract error probability data for errors of commission.

It was decided to examine data available on specific switch manipulations <u>called for in the procedures</u>. These were divided into three classes:

> <u>Class I</u> - manipulations specifically and unconditionally required by the plant abnormal or emergency procedures for response to this event. Each manipulation is a specific, measurable operator subtask or action. An example is "close main steam isolation valves" in the Fuel Element Damage event.
>
> <u>Class II</u> - manipulations required to complete a function related to control of plant process variables, but not necessarily a particular manual action required for this event. Typically there are several options (e.g. several equipment items) available to the operator to accomplish the required function, and often it is not necessary to carry out all of the steps in the specified procedure to assure

completion of the function. An example is "maintain reactor vessel water level" during a reactor scram.

Class III - manipulations designated in the procedures as optional, if required by plant conditions. An example is "reduce reactor power level, if necessary" in the Loss of Condenser Vacuum event.

To date, data have been tabulated for only Class I manipulations. Evaluation of Class II and Class III manipulations is more complex and will require additional data and additional time for analysis. Determining errors for optional or multiple-option manipulations is very difficult since any number of more "cognitive" factors may be involved. Analysis in these cases is essentially a "second-guessing" of the operators and requires detailed examination of the changing state of several plant parameters.

For the events simulated in this study, even the data on errors of omission is somewhat limited. The design characteristics of BWRs permit greater flexibility in the operational control of the plant than do those of PWRs. Abnormal and emergency operating procedures tend to be written less specifically than those for PWRs, and often the critical task elements identified from an examination of procedures are time and/or situation dependent. For example, for a given malfunction, depending on how quickly the operators respond, a significant action like "reduce power level" (which can be accomplished in several ways) may or may not be required. Thus, it is not easy to examine the event scenario and procedures and define a priori what is or is not an error of omission. This situation becomes even more complex when dealing with operators from different plants, since procedures for the same event at different plants can vary significantly.

6.2 Error Probability Estimates

Analysis of the simulator scenarios and the operating procedures used by the participating utilities indicated that eight of the 10 events examined in this study included switch manipulations categorized as Class I (i.e., specific controls were named in the procedure). An overall error probability for omission of Class I switch manipulations in each event scenario was estimated by dividing the number of errors (missed manipulations) by the number of opportunities (required manipulations). Results are tabulated by malfunction and utility in Table 6-1. The estimates range from 0.0 to 20.8 percent. These estimates are based on very small sample size (614 opportunities) and should be used with caution. The number of errors and opportunities used to calculate these error probability estimates are given in Appendix D.

Table 6-1. Probability of omission of Class I manipulations

	Error Probability Estimate (Percent)			
Malfunction	Utility A	Utility B	Utility C	Mean
34	8.3	12.5	0	8.7
91	2.0	4.9	0	2.9
121	0	12.5	0	4.5
138	2.1	12.5	0	5.4
2	0	7.1	**	2.8
11	8.3	16.7	0	9.5
9	0	20.8	0	6.6
122	8.3	12.5	0	8.7
Total Actions	319	221	74	614
Total Omissions	10	23	0	33
Mean %	3.1	10.4	0	5.4

** There were no Class I actions in Utility C's procedure for this event.

Three things are noteworthy in these data:

1. The malfunctions appear to differ in "error proneness" (though we do not know if the apparent differences are reliable - the number of errors was too small to allow statistical evaluation).

2. The overall omission rate of 5.4% is an order of magnitude larger that the "general error of omission" rate of 0.3% posited by Swain and Guttman (Ref. 6, p. 20-34) for items embedded in a procedure. The figure given by Swain and Guttman is a general omission rate for all kinds of tasks: "emergency responses" may have one or more special characteristics (stress, perceived time pressure) which make errors more likely. In this connection it should be noted that the error rate found in this study is lower than the 7.6% found in an earlier study of PWRs (Ref. 3) where the subjects were trainees instead of licensed operators.

3. The error rates for teams from Utility A, for which the simulator was site-specific, are lower than the rates for teams from Utility B, for which it was not. However, teams from Utility C did not appear to be handicapped in this situation. No generalization about the effect of site-specific simulation on error rates (in training) is possible.

No attempt was made to relate errors committed to their probable consequences. However, it was noted that a number of the omitted manipulations could be classed as "minor housekeeping functions" which, though clearly called for by the procedures, were of little real consequence. The operators may treat such manipulations in a different fashion than the control of critical plant parameters. The analysis of errors also did not take any account of dependence relationships between CTEs (see Ref. 6, Chapter 7). Thus the omission of a single procedural step requiring three or four manipulations was counted as three or four errors. It is arguable that only one error, the omission of the step, should be counted. The point is that there is more than one way to define an "error," and the figures given in Table 6-1 are the product of a particular definition.

6.3 Response Time and Error

Closely associated with the idea of a time standard such as N660 is the assumption that a rushed response is less likely to be an accurate one. This is certainly true in the extreme case, where there literally is not enough time to do everything that needs to be done. In this case there will be some kind of a speed-accuracy tradeoff.

6.3.1 Team Response Time and Error

Both response time and error rate are common measures of the "quality" of performance. "Good" operators (or teams) are expected to be quick and to make few errors. That is, there should be a positive correlation between response time and errors. This relation is found in some vigilence measures (Ref. 10) and other situations where time stress is not a significant factor.

Figure 6-1 shows the percentage of errors plotted as a function of each team's mean rank response time. These data are for the 8 malfunctions having detectable Class I errors. Since only one of these malfunctions was among the three recorded for Team 17, only 23 points are plotted. Note that 12 teams had no errors. At first glance, there appears to be no relation between errors and MRRT. A least-squares trend line has been fitted by linear regression (the circled point at MRRT = 13.17, % errors = 29.6 was not included in these calculations.*

*If the circled point is included, the slope of the trend line changes dramatically (to error = 1.338 MRRT -10.006) and r = .35 (t = 1.726, df = 21, p < .15).

The trend line shows that the quicker teams (lower MRRT) tended to have fewer errors. The correlation* (r = .31) is small, indicating a poor fit of the line, and is not statistically significant (t = 1.477, df = 20, p > .10). The slope of the trend line is due largely to the fact that no errors at all were committed by five of the six quickest-responding teams. From these data we can conclude that there is no evidence of a speed-accuracy tradeoff. In fact, the quicker teams also tended to have fewer errors. We do not know if the operators themselves felt rushed, though we do believe that a quick response is a matter of personal pride for most operators.

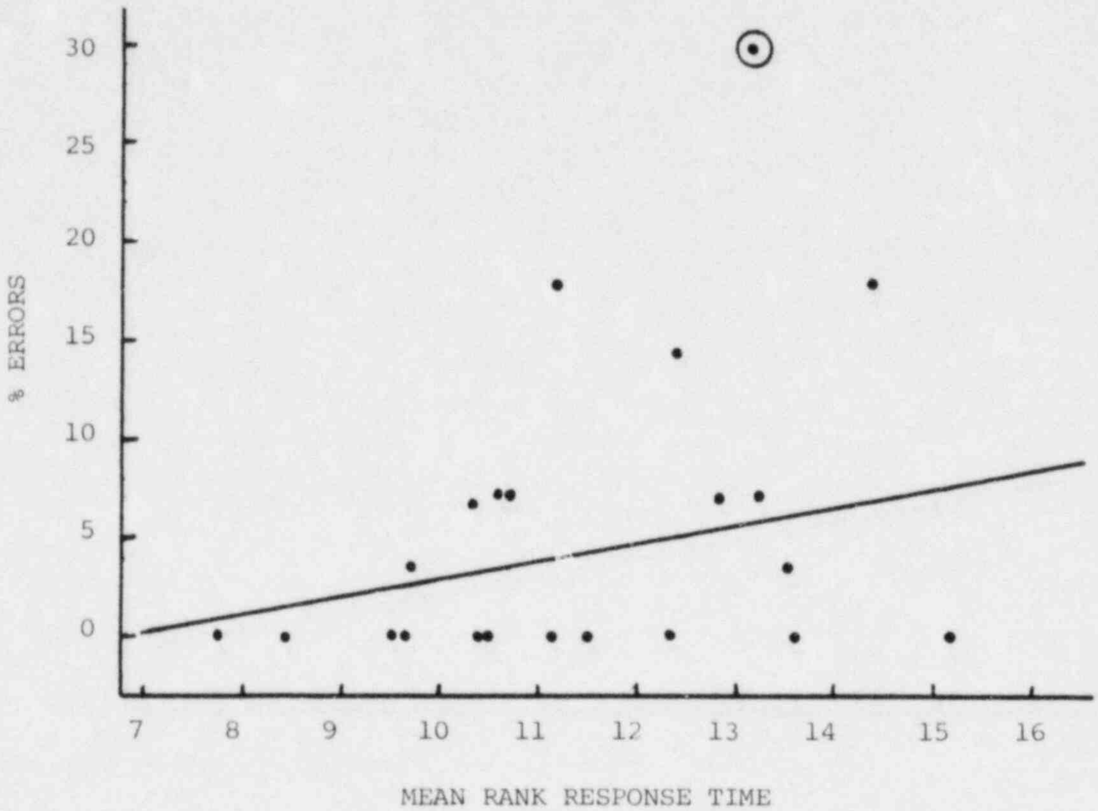

Figure 6-1 Omission error rate as a function of Mean Rank Response Time.

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*The Pearson product-moment correlation coefficient, "r," is a measure of the direction and degree of relationship that exists between two variables. An "r" can vary from +1 to -1. The sign tells whether the relationship is direct (+) or inverse (-), and the value of the correlation coefficient indicates the magnitude of the relationship. A statistically significant "r" means the correlation in the population (the test is performed on a <u>sample</u>) is probably greater than 0. The computed sample "r" is an estimate of the population "r."

6.3.2 Event Response Time and Error

A second way of looking at the problem of the relation between speed of response and error rates is to examine the error rates for individual malfunctions. Figure 6-2 is a plot of the percentage of errors (from Table 6-1) as a function of the geometric mean first response time(from Table 4-2) . Again a regression line has been drawn in. The correlation of $r = -.59$ is marginally significant ($t = 1.79$, $df = 6$, $p < .15$). The correlation is largely due to the fact three of the four events having response times less than 1 minute had high error rates.

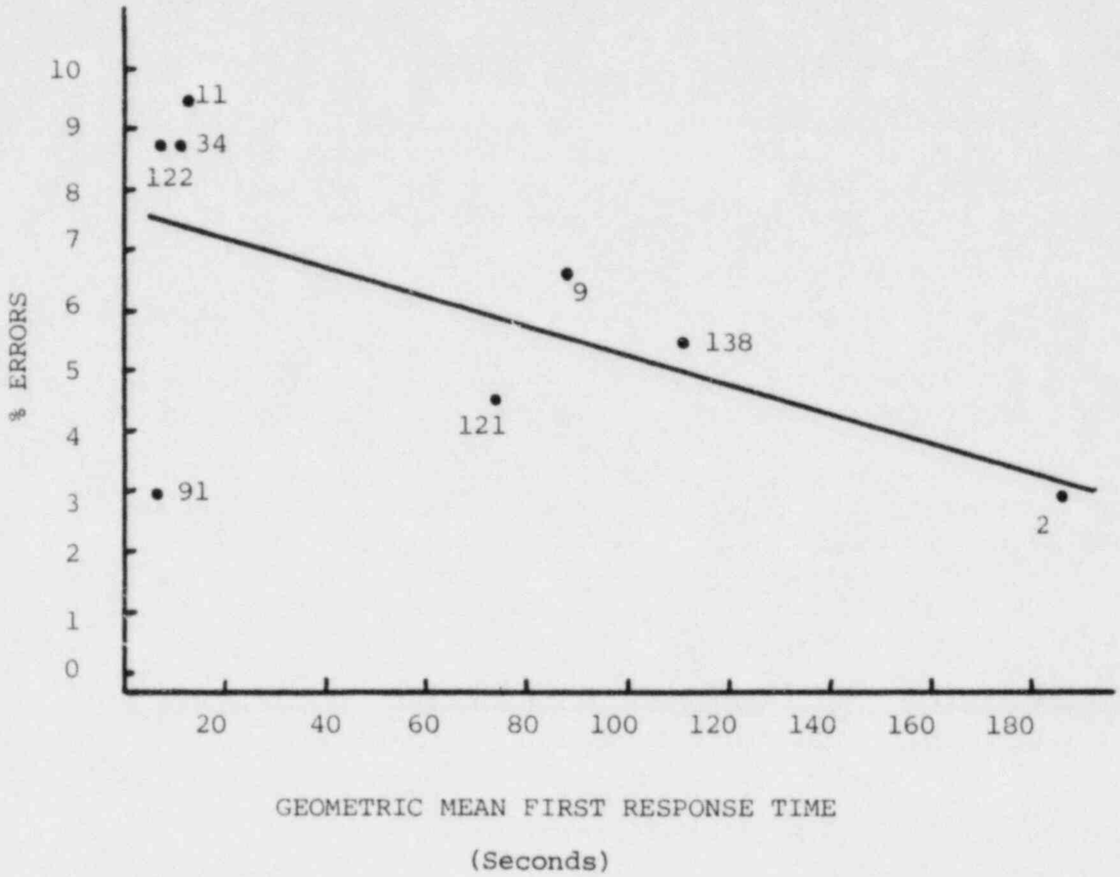

Figure 6-2 Omission error rate as a function of exercise mean response time

When viewed in this way, the probability of error does seem to be a function of the time taken to respond. The probability of omitting a required action seems to vary with whatever property of a malfunction it is that allows or requires a rapid response. In Section 5 we suggested that Malfunctions 11, 34, and 122 allowed rapid response because the indication that something had happened was prompt and unambiguous, and the required response was well known. Do these properties also predispose to a larger number of omissions? It does not seem likely. The result shown in Figure 6-2 could come about if operators relied on their memory for responding to the fast-response events, but were more likely to have consulted the operating procedures when dealing with the longer-response events. This is just a speculation, as we did not keep records on when the procedures were referenced. However, the response times for the group of fast-response events are so short it is doubtful if procedures could have been consulted. Acting before the procedure is referenced is not itself an error on the operators' part: they are required to memorize the "immediate actions" sections of the emergency procedures so that they can respond rapidly.

6.4 Discussion

In 6.3.1 we found that there was a small but not statistically significant tendency for the quicker-responding teams (those having lower MRRTs) to make fewer omission errors. That is, teams that were "better" by one measure of performance also tended to be better by the other.

In 6.3.2 we reported that the omission error rates for events in which the first response was very rapid tended to be greater than for events to which the initial response was (relatively) slow. Since only eight events were analyzed, any interpretation of this finding must be very tentative. However, the general form of the relation between event RT and omission errors seems to be in accord with the logic of the draft ANSI-N660 standard: rushed responses (for whatever reason) are more likely to be incomplete or otherwise in error.

It should be noted that the average event RTs in Figure 6-2 are considerably faster than any addressed by the draft standard. Thus the limited error rate data, while supporting the logic embodied in the draft standard, do not lend much support for the longer times specified for the Condition III and (especially) Condition IV events.

7. PERFORMANCE SHAPING FACTORS

As noted previously, one of the goals of this initial work is to begin to identify the performance shaping factors (PSFs) that have a significant impact on performance.

In these experiments, which were conducted during training (requalification) exercises, it was not possible to control these variables and systematically vary them to quantify their effect on performance. Also, information on many of them is probably best obtained through structured interviews with the operators, but the opportunity for such interviews was very limited. Nonetheless, some demographic data, which provided information on experience, a major internal or "organismic" PSF, and operator opinion about the relative impact of some general categories of PSFs on their performance was obtained by means of two questionnaires (which are reproduced in Appendix A). A background questionnaire asked for age, the number of years of military and commercial power plant experience, and years of college education. The second questionnaire was a set of one-page forms to be completed at the end of each exercise. Using a three-point scale, each operator was to evaluate whether five aspects of the situation had been a "problem," "somewhat of a problem," or "no problem" for him while performing the exercise. The five things evaluated were: procedures, control board design, lack of "hands-on" training, indications, and familiarity with the plant (simulator) and procedures.

7.1 Demographic Data

Demographic data -- age, education, previous NPP control room experience, and previous operating experience outside of the control room -- was collected from each operator. However, since the performance measured is team performance, it was not possible to relate these individual characteristics directly to individual performance. Ideally, one would like to be able to monitor both team and individual performance and obtain data on the dynamics of team response. What are the different behavioral requirements, and PSFs for the different team members (e.g. senior operator versus operator), and how does the performance of each affect the overall team performance? Addressing these kinds of questions will require additional means of observing and recording individual operator performance and more time for operator interviews. In these initial experiments it has been possible to address only team-composite data.

Table 7-1 lists the team averages for the four demographic variables recorded. The values for "education" are years beyond high school. "Control room experience" is the number of years in the control room as a reactor operator or senior reactor operator, and "outside control room experience" is the number of years worked in the power plant in some capacity other than a control room operator.

Table 7-1 Team composite age, education, and experience.

Team	n	Age	Education	Control Room Experience	Outside CR Experience
1	4	33.00	0.50	7.38	6.00
2	4	35.75	2.25	5.86	5.00
3	4	36.50	1.63	4.50	8.75
4	4	36.75	.75	4.13	7.63
5	4	**	**	**	**
6	4	33.75	1.50	5.13	4.24
7	4	44.75	.36	6.38	13.63
8	4	38.00	3.75	8.06	2.25
9	3	38.00	2.67	4.23	5.67
10	4	32.25	.50	2.28	7.50
11	4	39.25	.50	7.63	6.00
12	4	33.00	1.00	3.00	6.50
13	4	32.50	1.25	6.38	1.38
14	4	32.00	.50	6.50	3.25
15	5	32.80	1.10	6.80	2.70
16	4	32.50	.69	7.00	3.50
17	4	39.25	2.25	1.59	2.50
18	4	28.75	2.25	2.69	4.50
19	4	33.25	2.25	6.25	5.00
20	4	42.00	2.00	2.81	5.56
21	4	40.00	2.88	8.25	11.50
22	4	31.75	.25	3.50	1.75
23	3	37.33	1.33	6.33	1.50
24	4	32.50	1.50	2.88	2.00

** Team 5 did not provide any biographical data

The demographic data were first analyzed by means of independent one-way analyses of variance. The results indicated that there were no differences between the three utilities in three of the categories (age, education, and control room experience). However, a significant difference did appear in terms of outside control room experience ($F = 8.63$, $df = 2/88$, $p < .001$).* The Newman-Keuls procedure (see Ref. 8) indicated that the mean length of outside-control-room experience for Utility A was significantly greater than the mean of Utility B, which was in turn significantly greater than that of Utility C.

7.1.1 Demographic Variables and Response Time

The relationship between age, education, experience, and MRRT as a measure of group performance was investigated by use of the Pearson product-moment correlation coefficient. The Pearson "r" assumes that the data are measured on an interval or ratio scale. Since MRRT is a value computed by first ranking the first-action response times across events, use of the Pearson test could be criticized on this point. Therefore, a check was made using another correlational procedure. The Spearman rank order correlation coefficient (rho) is used when one or both of the variables are only of ordinal scaling (see Ref. 11). Spearman rho is the linear Pearson correlation coefficient, r, applied to data that meet the requirements of ordinal scaling. The values of both coefficients are shown in Table 7-2. The two methods give essentially the same results.

Table 7-2 Correlation of education and experience with Mean Rank Response Time

			Experience		
Correlation	Age	Education	Control Room	Outside	Total[a]
r	-.09	.10	-.34	-.30	-.42**
rho	-.08	.20	-.32	-.32	-.36*

a. Total experience is the sum of inside- and outside-control room experience.

n = 23
* p < .10
** p < .05

*A check using the Kruskal-Wallis nonparametric analysis of variance procedure, which does not assume homogeneity of variance, gave an identical result: $X = 21.7296$, $df = 2$, $p < .001$.

In the present case, the average age and education level of the team show no relationship to mean rank response time. Neither control-room nor outside-control-room experience, considered alone, shows much relation to MRRT. These two measures were summed to produce a third measure, called "total experience." There appears to be a small but statistically significant relationship between decrease in mean rank response time (indicating better overall performance) and increase in the team average experience level.

7.1.2 Demographic Variables and Error Probability

As a first attempt to investigate the impact of PSFs on error probability, the demographic data obtained on the control room operators and the observed error frequency were tested for statistical correlation. The correlations given in Table 7-3 are based on data from the 20 teams that completed at least six of the eight malfunctions for which Class I errors were identified. Team 5 did not complete the biographical questionnaires, and teams 15, 17, and 19 were excluded because they completed fewer than six of the exercises scored for errors.

Table 7-3 Correlation of age, education, and experience with error (omission) rate

Age	Education	Experience: Control Room	Experience: Outside	Experience: Total
-.17	.37	.14	.28	.30

n = 20

None of the correlations between team error (omission) rate and team average age, education, or experience is statistically significant, although the r of .37 closely approaches the $p < .10$ level of "marginal" significance (an r of .3783 is required: the computed r was .3717).

Data on education is part of the biographical information requested from all participants in the operator performance studies conducted by General Physics Corporation for Oak Ridge and Sandia National Laboratories. We shall determine if this correlation holds up as larger samples become available.

7.2 Operator Opinion

A one-page "Questionnaire for the Evaluation of Performance Shaping

Factors" (reproduced in Appendix A) was completed by the operators after each malfunction was run. The questionnaire asked the operators to check whether each of five aspects of the situation had been "no problem," "somewhat of a problem," or a "problem" for them during the event. The five things rated were procedures, control board design, lack of "hands-on" training experience, plant indications, and personal unfamiliarity with the plant and/or procedures used in the simulator. This set of questions was admittedly very crude. It was hoped that operators' responses would suggest areas worthy of investigation by more refined techniques. The questions on familiarity were of special interest, since the simulator was in many respects different from the plants where the operators from Utilities B and C worked and might, on that account, be perceived as negatively affecting their performance.

For each aspect, each individual's ratings were scored on a 3-point scale: "no problem" = 1 to "problem" = 3. The scores for each member of a team were averaged to produce a team "problem score" for each malfunction. These in turn were averaged across malfunctions to produce an overall team problem score, which represents the <u>operators' perception</u> of problems encountered. The average problem scores for teams from each utility are given in Table 7-4.

Table 7-4 Perceived "problem" areas

Utility		Procedures	Control Board	"Hands-On" Training	Indications	Lack Of Familiarity
A	P/SP	5/38	25/61	18/61	29/61	1/21
	n	399	399	398	399	395
	$\bar{X}$	1.12	1.28	1.24	1.30	1.06
B	P/SP	2/57	17/91	17/122	9/54	14/104
	n	341	341	341	338	340
	$\bar{X}$	1.18	1.37	1.43	1.21	1.39
C	P/SP	4/24	8/36	7/47	7/20	9/41
	n	110	110	110	110	110
	$\bar{X}$	1.29	1.47	1.55	1.31	1.54
Overall	$\bar{X}$	1.17	1.34	1.36	1.27	1.26

P/SP: Number of "problem" responses/number of "somewhat of a problem" responses.

n: Total number of responses.

$\bar{X}$: Average "problem score" (see text for explanation).

Inspection of the table reveals that the average problem scores are generally higher for Utilities B and C than for Utility A. These differences were tested by means of one-way ANOVAs for each problem area. Only for "lack of familiarity with plant and/or procedures" was the difference between utilities statistically significant ($F = 9.39$, $df = 2/20$, $p < .001$). In this area problem scores from B and C were higher than those from A, and were not significantly different from one another. Operators from B and C were more likely to report feeling that their relative unfamiliarity with the simulator, which mimiced A's plant, had been a problem for them.

The questionnaire completed after each malfunction had two questions assessing attitudes toward simulator training. To the question, "Do you feel that simulator training has enabled you to better operate the plant?" 96.6% of 843 responses were "yes." To the question, "Would you like to see more simulator training incorporated into all phases of operator training?" 86.2% of 841 responses were "yes." These answers are consistent with the fact that a substantial number of operators had reported feeling that "lack of 'hands-on' training experience" (presumably referring to particular emergency procedures) had been something of a problem for them during these exercises.

Table 7-5 shows the correlations of average team problem scores with MRRT, which represents the relative quickness of the first response. Again both the Pearson and Spearman correlations are reported.

Table 7-5 Correlation of perceived "problems" with Mean Rank Response Time

Correlation	Procedures	Control Board	"Hands-On" Training	Indications	Lack Of Familiarity
r	.45*	.14	.67***	.04	.49**
rho	.31	.20	.62***	-.04	.39**

n = 23

* p < .10

** p < .05

*** p < .01

The above correlations show that members of teams having higher MRRTs (relatively longer first response times) were more likely to have felt that lack of "hands-on" training experience and unfamiliarity with plant (simulator) and procedures had been something of a problem for them.

The correlations of overall team problem scores with team error rate are given in Table 7-6. These correlations are based on 20 cases: team 5 did not complete the questionnaires and teams 15, 17, and 19 were dropped because they completed fewer than six of the eight error-scoreable exercises.

Table 7-6 Correlation of perceived "problems" with error (omission) rate

Procedures	Control Board	"Hands-On" Training	Indications	Lack Of Familiarity
-.33	-.14	.48*	-.25	.04

n = 20

* $p < .05$

There is only one significant correlation in the table: teams with higher problem scores for "lack of 'hands-on' training" tended to have a higher percentage of errors.

Poorer team performance by both measures, MRRT and error rate, is correlated with the perception on the part of individual team members that lack of "hands-on" training had been something of a problem for them. We do not know whether individuals reporting problems in this area had in fact received less training than those who did not report problems, so we cannot say that more training would be likely to improve performance. However, a significant number of operators felt that lack of "hands-on" training had been a problem for them, and that nearly all thought that simulator training was beneficial and wanted to have more of it.

7.3 Stress

We did not attempt to measure the stress experienced by operators participating in this study. We do, however, doubt that the perceived stress would vary with the event category in the same way that it would if the events were "for real." To the extent that higher stress is likely to be a feature of Condition III and IV events, these events have been less accurately simulated than the Condition II events. Thus the RTs and omissions recorded for Condition III and IV events may be a less accurate estimate of the performance to be expected in the field than similar data for Condition II events.

7.4 Effects of "Site-Specific" Training/Experience

All of these exercises were performed in the simulator that mimiced Utility A's plant. It is logical to expect some difference in performance between the Utility A operators and those from Utilities B and C, who were not trained on the site-specific simulator. In addition to the possible impact on the experimental results, information on the effect of site-specific simulator training may be of some value in helping to address the question of the need for site-specific simulators in control-room operator training.

The statistical analysis of response times summarized in Table 4-4 showed that there were few reliable differences between the response times of operators from the three utilities. As far as this one rather arbitrary measure of performance is concerned, the operators from Utilities B and C were not much handicapped by their relative unfamiliarity with the simulator.

The breakdown of errors of omission given in Table 6-1 shows that teams from Utility B made many more Class I errors than teams from Utility A. Teams from C made no omission errors at all, but with only three teams this could have been due to chance. If B and C are combined, their collective error rate was more than twice that of Utility A. As far as errors in the simulator are concerned, teams training in a simulator that differs from their plant seem to be at a disadvantage.

The question of the relative merits of site-specific as opposed to generic simulator training is only tangentially concerned with the performance of operators in the simulator, however. The more important question is: to what degree what is learned in the simulator will be "transferred" back to the plant environment, i.e., is transfer from simulator to plant significantly better with site-specific simulators. Data from the present study cannot be used to address this question.

8. SUMMARY

This report has presented the results of a study of operator response times during simulated malfunctions. Data from 10 simulated exercises were collected during periods of annual requalification training from 24 teams of operators representing 3 utilities. A computerized Performance Measurement System provided the data used in the determination of the level of operator performance on critical task elements required by procedural instructions. The use of this evaluation system yielded an objective indication of operator performance and provided for collection of response time data with a one-second time accuracy.

8.1 Response Times

The operator response times appeared to fit a log-normal distribution. This distribution has been noted in previous work (Ref. 3) and could be considered as a possible standard "model" for operator response times in the design of safety-related operator action requirements. Because of this, the geometric mean rather than the arithmetic mean should be considered the "average" response time. The variation in response time from one team to another tended to be large. This variability must be accounted for in any design standard based on response times. Use of the 95th percentile effectively accomplishes this goal, and is recommended.

For the 10 events simulated in this study, RT was not systematically related to the Plant Process Condition number used to assign values to the time tests in the draft N660 standard. Response time appears to be very task-dependent, making it difficult to reliably predict performance on a new task such as would be encountered in a design project.

8.2 Omission Errors

Only "Class I" errors of omission (failure to operate controls named in written procedures) were examined in this study. The overall omission rate of 5.4% observed is an order of magnitude larger than the 0.3% estimated in NUREG/CR-1278 (Ref. 6). The highest error rate (10.4%) was for teams who came from a plant other than the one duplicated by the simulator. However, even teams from the modeled plant experienced 3.1% errors.

It was found that the identification of errors in the operation of BWRs is more difficult than is the case with PWRs. This is because BWR procedures allow an operator much more flexibility of control than do the PWR procedures previously studied. This less prescribed method of operation should not necessarily be considered a sign of inadequate operating procedures; rather, it is a result of BWR design characteristics. While this type of procedure may have little ultimate effect on operator control, it significantly increases the difficulty of error analysis, since in many situations the operator is allowed different options for performance of a given task.

There appears to be no simple relationship between time taken to make an initial response and the likelihood of error. Malfunctions having the quickest response time also tended to have the greatest percentage of omission errors. On the other hand, five of the six quickest-responding teams of operators committed no errors (that were detected) at all.

The limited data we have suggest that response time and error probability are relatively independent. The major implication of this is that a time standard such as N660 is not, by itself, an adequate basis for deciding whether to allocate safety-related functions to operator actions. A time standard is inappropriate as the sole criterion for such decisions, though in the absence of other explicit criteria it might be construed as such. We believe, however, that such a standard can serve a useful function if its limitations are recognized (and probably written into the standard itself). Adequate time in which to perform assigned actions is a necessity for reliable operator response, but it is not sufficient to insure reliability.

8.3 Performance Shaping Factors

Evaluation of operator performance requires more than the collection of response time or error data. Many performance-shaping factors can have a major impact on human performance. Demographic and subjective data were collected in order to supplement the response time and error data. Statistical evaluations were performed in an attempt to identify the correlation of the age, education, and experience, with the performance of (teams of) test subjects. One statistically significant correlation was found: more (collective) power plant experience was associated with faster team response times. No other factor had a significant correlation with RT. The limited error data was correlated with biographical data. No statistically significant correlation was found.

Both Mean Rank Response Time and error rate were significantly correlated with the reported perception that lack of "hands-on" training (presumably referring to practice with the emergency procedures) had been somewhat of a problem during some exercises. The majority of subjects thought simulator training was beneficial and wanted more of it.

8.4 Lessons Learned

The simulator data on which this report is based were gathered in conjunction with scheduled training programs. This practice seems unavoidable, as neither simulator time nor qualified operators are readily available outside of this context. Instructors and operators were generally cooperative, and it was possible to establish a reasonable degree of experimental control, in that the malfunctions recorded were (at least in the initial stages, before the course of events was influenced by the operators' responses) presented in a very uniform manner.

There are, however, significant restraints placed on research conducted in conjunction with training programs. These are related to the common stipulation that the research not interfere significantly with the training. Selection of events tends to be limited to those that fit into the training programs, which are largely predetermined by NRC and utility requirements. A more severe constraint is that there is relatively little free time in a training program in which debrief the operators or administer questionnaires. Significant blocks of time in which to conduct the kinds of psychological testing required to quantify the major organismic PSFs are generally not available, though it is possible they could be set up by special arrangement with the utilities.

The validity of simulator-based research is questioned by some within the industry. It is argued that a number of psychological factors which probably affect performance are markedly altered or effectively absent in simulators. These include surprise, stress arising from the perception of personal danger or having to make decisions which may have serious consequences, and the reluctance to take action until clearly required in ambiguous or slowly developing situations. This argument has some merit, especially in the case of the present study, where performance of emergency procedures was the primary interest. One answer to it is simply that quantitative data on performance during real emergencies in NPPs is (and will, we hope, continue to be) scarce, and, in the meantime, simulator studies can give valuable information on the performance of NPP tasks. In the ORNL SROA program, the possibility of differences between performance in simulators and in operating NPPs was recognized at the outset. The parallel program of field data collection (see Ref. 4) was undertaken to allow "calibration" of the simulator results, so that information obtained from studies conducted in simulators could be extrapolated with greater confidence to "real-world" situations.

In this study we used team first-response time as the measure of performance because the primary purpose of the study was to relate the response times to the time tests in ANSI-N660 In view of the complexity of the operators' tasks in nuclear power plants, RT seems a rather weak overall "performance" measure for any other purposes. Development of more generally useful performance measures should be a top-priority goal of future research.

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APPENDIX A

PERFORMANCE SHAPING FACTORS QUESTIONNAIRES

Questionnaire for the
Evaluation of Performance Shaping Factors

The following questionnaire is designed to help determine factors which affect operator performance; it is NOT an operator performance evaluation. The information contained here will be utilized for research data acquisition to support Human Factors studies conducted by General Physics Corporation for Oak Ridge National Laboratory. In order to maintain anonymity, DO NOT indicate your name or your utility's name on this form. Please answer all questions completely.

Age__________ Height__________ Weight__________

Education: Number of years of college__________

Degree: Yes ☐ No ☐

Plant Experience: (Commercial) Number of years control room operation__________

Number of years outside control room operation__________

Plant Experience: (Military) Number of years control room operation__________

Number of years outside control room operation__________

Questionnaire for the Evaluation of Performance Shaping Factors

	Problem	Somewhat of a Problem	No Problem
1. From the standpoint of adequacy, clarity, accuracy, etc.; evaluate the procedures utilized for this event.	☐	☐	☐
2. From the standpoint of layout, location, operability, etc.; evaluate the control board design as related to this event.	☐	☐	☐
3. With regard to this event, would you say that lack of "hands-on" training experience has been:	☐	☐	☐
4. How would you evaluate the plant indications available to you to combat this event.	☐	☐	☐
5. How would you evaluate your unfamiliarity with the plant and/or procedures in enabling you to combat this event.	☐	☐	☐

6. Do you feel that simulator training has enabled you to better operate the plant? Yes ☐ No ☐

7. Would you like to see more simulator training incorporated into all phases of operator training? Yes ☐ No ☐

Additional Comments: ____

____

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____

____

____

APPENDIX B

SIMULATED CASUALTY DESCRIPTIONS

Loss of Condenser Vacuum (Malfunction #2)

Cause: Loss of steam flow through the operating air ejectors.

Effects: Gradual loss of main condenser vacuum, possible reactor shutdown.

The cause of this event is a partial loss of steam flow through the operating steam jet air ejectors. The reduced steam flow will cause the main condenser vacuum to gradually decrease, resulting in a generator output decrease from a reduction in efficiency.

When it is evident that vacuum is decreasing, the reactor operator should reduce reactor power by reducing recirculation pump speed, or by inserting control rods if initially at low recirculation flow. Also, the alternate set of steam jet air ejectors should be manually started, and the operating air ejectors isolated. This will occur automatically if vacuum reaches 25" Hg.

Expected Operator Actions

1. Reduce power, if necessary.
2. Start alternate air ejectors.
3. Isolate faulty air ejectors.

Turbine Trip (Malfunction #3)

Cause: Failure of the master trip solenoid valve.

Effect: Turbine stop valves close with corresponding opening of bypass valves for pressure control. Transfer of various electrical power service.

This event is initiated by a failure of the master trip solenoid, which results in fast closure of the four turbine stop valves. The malfunction is initiated with the reactor initially at less than 30% of rated power so that a reactor scram does not occur.

When the main turbine trips the power circuit breakers (PCBs) open, giving a breaker disagreement alarm in the control room. The operator should clear the breaker disagreement and open the motor-operated disconnects

(MODs). The turbine shutdown procedure requires the operator to open control and stop valve seat drains and the main steam lead drain valve. The high pressure lift pumps should be started before turbine speed decreases below 900 RPM.

Expected Operator Actions

1. Clear Breaker Disagreements.
2. Open MODs.
3. Open Turbine Drains.
4. Start Lift Pumps.

Inadvertent Opening of a Relief Valve (Malfunction #9)

Cause: Relief valve fails in open position.

Effects: Loss of generator load output, small power excursion resulting from drop in feedwater temperature, suppression pool temperature and level increase.

This event is initiated by the opening of PCV-1-22, one of the thirteen main steam relief valves. The initial indication of this event is a rapid reduction in generator output due to control valves closing to maintain main steam line pressure. This will also be accompanied by a brief level transient due to the mismatch of total steam flow/total steam flow inputs into feedwater level control. An annunciator will be received eventually when the multipoint recorder that records relief valve downcomer temperatures reaches the recorder point for the stuck open valve.

When it is apparent that a relief valve is open, the operator should first check the recorder to determine which valve is open, and attempt to close the valve by placing the control switch first in the open position and then in the closed position.

An important consideration with an open relief valve is monitoring of the suppression pool (torus) temperature. To monitor torus temperature the operator observes the meter indication while changing the position of a select switch which allows the operator to monitor four locations in the torus. If one of these points reaches 95^{o}F the operator must place the Residual Heat Removal (RHR) system in the torus cooling mode. If the torus temperature should reach 110°F, the reactor must be manually scrammed.

Expected Operator Actions

1. Attempt to close open valve.
2. Monitor torus temperature.
3. Initiate torus cooling.
4. Scram the reactor.

Loss of All Off-Site Power (Malfunction #11)

Cause: Loss of transmission lines.

Effects: Loss of all off-site power to station electrical distribution resulting in reactor shutdown. All plant diesel generators start and energize their respective electrical shutdown boards; all other electrical boards will de-energize.

A complete loss of all transmission lines will cause a generator trip, a reactor scram, and a loss of the normal feedwater system. A main steam line isolation may also occur due to low reactor level.

Following any scram, the operator should verify that all rods have fully inserted by placing the mode switch in the REFUEL position and observing the one rod withdrawal permit light. Since this transient involves a loss of normal feedwater, RCIC should be operated manually to recover and maintain reactor level. Source and intermediate range monitors should be inserted to verify that reactor power is decreasing following the scram.

When off-site power is lost, the four diesel generators will automatically start and tie to their respective 4160V shutdown boards. The operator may regain two thirds of the normal feedwater system by backfeeding the diesel generator output to the 4160V unit boards. The unit boards provide power to condensate and condensate booster pumps, which will permit operation of a steam driven feedwater pump.

Expected Operator Actions

1. Mode Switch to REFUEL.
2. Maintain reactor vessel level.

3. Insert neutron detectors.
4. Acknowledge breaker disagreements.
5. Backfeed diesel generators.

<u>Feedwater Pump Trip</u> (Malfunction #25)

Cause: Failure of one feedwater pump due to a locked rotor.

Effects: Instantaneous decrease of feedwater flow through the affected pump, causing reactor level decrease. Operating feedwater pump(s) flow increases to restore level or reach maximum flow limits.

This malfunction is the loss of a reactor feedwater pump by a locked rotor. Depending on other plant conditions (i.e., power level, number of feed pumps running, etc.) level will decrease, resulting in an increase in the speed of any running pumps. If there is an idle pump, and level cannot be maintained, the idle pump should be started quickly. The controller for the tripped pump should be placed in manual and zeroed. Also, the turbine drains on the tripped pump should be opened.

<u>Expected Operator Actions</u>

1. Shift failed pump control to "manual."
2. Open turbine drain valves.
3. Start standby pump, if necessary.

<u>Condenser Tube Leak</u> (Malfunction #121)

Cause: Rupture in one or more tubes in the main condenser.

Effects: Increase in condenser hotwell conductivity, allowing some impurities to reach the reactor.

A leak in the main condenser tubes will result in the introduction of untreated river water into the reactor feedwater system. The reactor feedwater must be maintained within rigid chemistry specification for conductivity (chloride content) and oxygen content. The untreated water will result in an increase in both parameters. To minimize the quantity of impurities reaching the reactor, the operator should initiate an orderly power reduction to reduce the demand for feedwater. Water quality may be maintained within specified limits, and operation continued, if the leaking condenser tube(s) can be isolated. Each of the three condenser sections is equipped with two waterboxes, each waterbox having an inlet and outlet isolation valve. The operator may isolate individual waterboxes until chloride concentration and conductivity begin to decrease.

Expected Operator Actions

1. Reduce reactor power.
2. Isolate faulty waterbox.

Fuel Cladding Damage (Malfunction #122)

Cause: Gross fuel cladding rupture.

Effects: Extreme levels of activity released, reactor and turbine radiation detectors activated, and main steam line high radiation, resulting in reactor shutdown and main steam line isolation.

This incident is a sudden failure of fuel cladding, which releases fission products to the reactor coolant system. The release of fission products to the coolant increases the main steam line radiation levels to greater than three times normal background radiation levels. This will signal the Reactor Protection System to scram the reactor. In addition, the Primary Containment Isolation System will close the Main Steam Isolation Valves (MSIVs), main steam line drains, and the recirculation loop sample line.

Following the reactor scram, the operator should verify that all control rods have fully inserted by placing the mode switch in the REFUEL position. The operator should also insert source and intermediate range neutron monitors to verify that power has decreased.

The isolation of the main steam system shuts off the steam supply to the reactor feedwater pumps. For this reason, Reactor Core Isolation Cooling (RCIC) must be manually operated to recover and maintain reactor water level. Another effect of the isolation is a gradual decrease in control air pressure. This pressure decrease will occur while the control switch for the MSIVs are in the "AUTO/OPEN" position with the valves closed. Therefore, these switches should be placed in the "CLOSE" position.

Expected Operator Actions

1. Mode switch to REFUEL position.
2. Maintain reactor water level.
3. Insert neutron detectors.
4. Place MSIV switches to CLOSE.
5. Transfer RCIC to manual control.

Reactor Building Closed Cooling Water (RBCCW) High Activity (Malfunction #138)

Cause: Tube leak in Reactor Water Cleanup (RCW) System heat exchanger.

Effects: Increase in RBCCW activity resulting in necessity to isolate RCW system.

This event is the leakage of high activity water into the RBCCW system from one of the heat loads served by the system. This will result in a high radiation alarm in the control room, a high surge tank level alarm, and an increase in the temperature of the RBCCW water. The most serious consequence of this occurrence is the reduction in the system's ability to cool certain vital heat loads (i.e., recirculation pumps and motors, drywell atmospheric cooler, etc.).

The operator must determine the source of the leakage into the RBCCW system, and attempt to isolate the failed component. The choices of heat loads operating at a higher pressure than RBCCW are limited. The only two credible sources of such leakage are the recirculation loop sample cooler and the non-regenitive heat exchangers in the reactor water cleanup system. The operator should attempt to stop the leakage by isolating the faulty component, and then return the RBCCW system to normal operation.

Expected Operator Actions

1. Isolate the faulty component.
2. Return RBCCW system to normal operation.

Master Feedwater Flow Control Failure (Abnormal Vessel Level) (Malfunction #34)

Cause: Automatic mode failure of the master feedwater controller, resulting in maximum output from the control element.

Effects: Increase operating feedwater pump(s) output to maximum, causing increase in reactor water level with probable high water level reactor shutdown.

The three reactor feedwater pumps are normally operated in an automatic control mode, which attempts to maintain total feedwater flow to the reactor equal to the total steam flow while maintaining reactor level within a prescribed band (three element level control). An individual failure of any of the three process signals to the control circuit will effect the output of the master controller, or the output of the master controller itself could fail. Two possible effects could result from a failure of the master feedwater control signal. The controller could call for maximum or minimum demand from any feedwater pump whose individual controller is in automatic operation. In this instance the controller demands maximum output from the feedwater pumps, increasing the reactor water level. If the failure is not detected quickly by the operator, level will increase to the point where all turbines (main and reactor feedpump) will trip to prevent carryover from damaging the turbines. This results in a reactor scram if power is greater than 30% of rated load.

If the operator is quick to determine the cause of the level increase, he should place the controller in manual, and control reactor level in this mode until the automatic mode of operation can be restored. If the reactor should scram the operator should follow the normal scram procedure. Following the trip of all turbines on high level, the feedwater pumps cannot be restarted unless the high level trips have been manually reset.

Expected Operator Actions

1. Maintain manual control of feedwater flow.
*2. Mode switch to REFUEL.
*3. Maintain reactor vessel level.
*4. Insert neutron detectors.
*5. Reset high level trip signals.

* If scram occurs.

Loss of Shutdown Cooling (Malfunction #91)

Cause: Loss of operating Residual Heat Removal (RHR) pump(s).

Effects: Shift to alternate RHR loop for reactor decay heat removal capability.

A loss of shutdown cooling is simulated by tripping the operating Residual Heat Removal (RHR) pump. The effect of this failure is a gradual increase in reactor temperature, depending on the decay heat available. The operator should attempt to start the RHR pump in the same loop to restore shutdown cooling. If this pump has also failed (which is part of this scenario) the operator must align the other RHR loop for shutdown cooling. This is accomplished by closing the torus suction valve(s) for the pump(s) to be started, and opening the shutdown cooling suction valve(s). An interlock will prevent operation of an RHR pump without a complete suction path established.

Expected Operator Actions

1. Secure failed pump(s).
2. Attempt to restore operating loop to service.
3. Place standby loop in service.

APPENDIX C

OPERATOR RESPONSE TIMES PRINTOUT SET

The PMS summaries from which the operator response times were taken are given on pages 71 to 80. These printouts give the time in seconds from the sounding of an annunciator (or, for malfunctions 2 and 34, the beginning of the malfunction) to the activation of selected controls (CTEs). These control actions are identified by a DI number, given in the second row of the table heading. Each team is represented by a single row of data, which is identified by a file number. These files are not necessarily in order.

Additional information has been included to make the printouts more intelligible. In the block at the lower left the control action corresponding to each DI is given. These are keyed to the "expected operator actions" of the simulated casualty descriptions given in Appendix B.

STARTING FILE NUMBER 1 TOTAL # FILES 250 FOR MALFUNCTION NUMBER 34

FILE #	MAL TIME	CTE 1 1870	CTE 2 2006	CTE 3 2009	CTE 4 2012	CTE 5 2019	CTE 6 2022	CTE 7 2023	CTE 8 2645	CTE 9 2646	CTE 10 2647	CTE 11 3051	CTE 12 3152	M. OUT	OCCUR.
204	2832	40	103	****	****	23	150	149	****	****	40	****	81	0	1
~~205~~	~~164~~	~~****~~	~~13~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~20~~	~~****~~	~~****~~	~~99~~	~~2~~
220	125	182	81	63	78	229	259	259	70	92	119	92	39	0	1
333	215	****	252	88	111	****	****	****	****	12	****	****	****	599	1
341	2152	****	****	****	****	****	****	****	38	50	****	42	38	2373	1
345	249	****	****	7	27	****	****	****	****	****	****	****	****	[illegible]	1
360	77	70	****	17	11	26	132	131	****	68	66	****	29	0	1
401	13	****	4	****	****	****	****	****	****	****	****	****	****	0	1
413	82	70	161	****	58	23	202	201	61	****	127	49	75	0	1
425	36	****	11	****	****	****	****	****	****	****	****	****	****	0	1
441	1109	****	2	****	****	****	****	****	****	****	****	****	****	0	1
~~466~~	~~136~~	~~****~~	~~2~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~0~~	~~1~~
470	209	****	5	****	****	****	****	****	****	****	****	****	****	0	1
503	29	****	3	****	****	****	****	****	****	****	****	****	****	0	1
514	175	111	13	100	68	27	162	161	102	73	251	****	151	0	1
530	1523	****	11	****	****	****	****	****	****	****	****	****	****	1570	1
542	266	****	****	****	****	****	****	****	****	****	****	****	****	0	1
543	12	****	7	****	****	****	****	****	****	****	****	****	****	0	1
554	28	****	43	****	****	****	****	****	****	****	****	****	****	0	1
571	95	****	59	6	6	****	****	****	****	****	****	****	****	0	1
603	925	****	****	89	88	****	52	52	106	119	57	33	****	0	1
612	967	****	5	****	****	****	****	****	****	****	****	****	****	0	1
630	190	****	****	****	****	22	****	****	****	****	****	****	****	0	1
640	262	63	66	****	****	22	****	****	83	****	****	****	82	0	1
647	56	****	7	****	****	****	****	****	****	****	****	****	****	0	1
663	291	****	****	5	6	23	155	135	43	47	54	****	142	0	1
~~720~~	~~490~~	~~****~~	~~9~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~0~~	~~1~~
~~722~~	~~70~~	~~****~~	~~7~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~87~~	~~2~~
~~800~~	~~70~~	~~****~~	~~7~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~87~~	~~2~~

Critical Task Element - CTE			Expected Operator Actions
1870	-	SRM/IRM Drive (In)	4
2006	-	Main Feedwater Control (Manual)	1
2009	-	Reactor Feed Pump Turbine "A" Speed (Manual)	3
2012	-	Reactor Feed Pump Turbine "B" Speed (Manual)	3
2019	-	Mode Switch to Refuel	2
2022	-	Scram Reset (GR 1 & 4)	5
2023	-	Scram Reset (GR 2 & 3)	5
2645	-	Reset Reactor Feed Pump	3
2646	-	Reset Reactor Feed Pump	3
2647	-	Reset Reactor Feed Pump	3
3051	-	Exciter Field Breaker (Control Trip)	* Clearing breaker disagreements
3152	-	Primary Circuit Breaker 5218 - Generator (Trip)	*

Line-out file number was incorrect data for this malfunction.

Figure C-1 PMS summary printout of response times for malfunction 34

STARTING FILE NUMBER 201 TOTAL # FILES 70 FOR MALFUNCTION NUMBER 91

FILE #	MAL TIME	ANN 8263	CTE 1 1154	CTE 2 1156	CTE 3 1157	CTE 4 1161	CTE 5 1163	CTE 6 1187	CTE 7 1249	CTE 8 1305	CTE 9 1385	CTE 10 1386	CTE 11 1387	CTE 12 1388	ANN. D.T.
206	412	473	****	243	****	315	466	305	****	****	****	9	69	72	61
221	323	325	320	****	486	667	****	492	505	503	257	259	272	5	2
223	633	850	30	22	65	249	****	194	268	265	****	3	****	****	217
231	288	363	25	35	111	****	7	246	****	****	****	10	3	****	75
235	700	781	275	****	404	550	****	295	334	333	****	8	235	236	81
241	350	393	113	113	235	381	****	394	431	244	****	5	79	****	43
245	508	591	****	629	483	638	****	592	590	588	****	2	167	173	83
251	368	369	27	27	157	261	188	259	97	90	2	10	****	3	1
255	687	704	49	51	174	292	****	160	276	271	****	6	37	40	17
261	486	577	323	323	450	****	****	359	****	****	****	1	59	62	91
265	782	804	55	55	207	321	****	254	322	322	****	3	37	39	22
506	979	1018	232	226	400	628	****	589	****	****	133	136	139	13	39
522	796	916	843	****	978	1156	****	854	658	654	408	413	66	4	120
534	644	646	81	106	228	376	418	345	184	247	131	7	****	9	2
544	695	696	194	196	348	184	****	493	207	208	108	111	165	6	1
560	1974	1975	55	****	29	236	****	****	****	****	****	****	1234	****	1
563	506	588	1012	****	1161	1337	****	1289	1035	1026	214	60	****	****	82
575	1424	1439	270	270	397	510	****	466	308	323	****	7	208	210	15
606	788	846	302	302	428	718	****	415	346	****	****	50	105	110	58
620	1965	1971	****	506	****	****	837	964	****	****	368	372	****	47	6
632	78	594	480	480	646	1146	****	469	499	496	157	165	432	8	516
653	1316	1330	126	126	255	364	****	173	160	152	73	93	****	32	14
655	638	955	117	118	****	313	327	160	179	178	****	1	28	35	317

Annunciator #8263 - Motor Trip
Critical Task Element - CTE

1154 - Residual Heat Removal Torus Suction (Close)
1156 - Residual Heat Removal Torus Suction (Close)
1157 - Residual Heat Removal Shutdown Cooling Suction (Open)
1161 - Residual Heat Removal Pump "B" (Start)
1163 - Residual Heat Removal Pump "D" (Start)
1187 - Inboard Injection Valve Open
1249 - HTX Outlet Open
1305 - Residual Heat Removal Service Water (Start)
1385 - Residual Heat Removal Pump "A" (Start)
1386 - Residual Heat Removal Pump "A" (Stop)
1387 - Residual Heat Removal Pump "C" (Start)
1388 - Residual Heat Removal Pump "C" (Stop)

Expected Operator Actions

* Shutdown of failed loop
*
3
3
3
3
3
3
2
1
2
1

Figure C-2 PMS summary printout of response times for malfunction 91

STARTING FILE NUMBER 201 TOTAL # FILES 70 FOR MALFUNCTION NUMBER 25

FILE #	MAL TIME	ANN 7203	CTE 1 2009	CTE 2 2016	CTE 3 2663	CTE 4 2664	CTE 5 2665	CTE 6 2667	CTE 7 2674	CTE 8 2676	CTE 9 2677	CTE 10 0	CTE 11 0	CTE 12 0	ANN. D.T.
202	2374	2375	163	****	169	198	****	197	8	6	6	****	****	****	1
216	25	157	63	****	51	****	50	****	6	16	****	****	****	****	132
225	1303	1304	21	****	19	****	200	****	7	****	****	****	****	****	1
233	211	213	70	53	14	92	101	90	35	40	32	****	****	****	2
237	50	51	****	7	13	37	****	41	2	11	****	****	****	****	1
243	97	99	46	28	41	****	57	****	6	11	16	****	****	****	2
247	8	10	****	13	37	****	****	****	15	11	9	****	****	****	2
253	123	124	12	241	20	45	284	50	78	80	78	****	****	****	1
257	76	77	****	6	****	****	****	****	5	14	****	****	****	****	1
263	37	38	58	115	56	****	****	****	66	52	49	****	****	****	1
510	875	877	113	93	107	181	124	127	12	22	11	****	****	****	2
524	2364	2365	28	31	****	****	****	****	****	****	****	****	****	****	1
536	80	82	43	129	84	****	67	****	4	10	10	****	****	****	2
~~547~~	~~99~~	~~101~~	~~18~~	~~****~~	~~11~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~2~~
550	210	212	41	3	36	58	36	57	****	****	****	****	****	****	2
562	155	156	****	****	100	65	112	64	25	20	18	****	****	****	1
565	43	44	59	28	37	****	52	****	16	23	****	****	****	****	1
577	121	122	****	****	****	****	****	****	14	23	****	****	****	****	1
610	56	57	31	183	172	336	145	336	2	2	10	****	****	****	1
634	348	350	****	****	78	****	87	****	****	****	****	****	****	****	2
657	68	69	36	****	11	****	11	****	18	22	****	****	****	****	1
660	202	412	****	****	85	29	85	43	****	****	****	****	****	****	210

Annunciator 7203 - Reactor Feed Pump Tripped
Critical Task Elements - CTE

		Expected Operator Actions
2009 - RFPT Speed (Manual)	1	
2016 - RFPT Speed (Manual)	1	
2663 - RFPT Motor Gear/Motor Speed Control - Lower Fast	*	Preliminary to restart of tripped pump
2664 - RFPT Motor Gear/Motor Speed Control - Raise Fast	3	
2665 - RFPT Motor Gear/Motor Speed Control - Lower	*	
2667 - RFPT Motor Gear/Motor Speed Control - Raise	3	
2674 - RFPT Motor Gear/Motor Speed Control - Raise Fast	3	
2676 - RFPT Motor Gear/Motor Speed Control - Off	*	
2677 - RFPT Motor Gear/Motor Speed Control - Raise	3	

Data for teams 3 and 21 could not be reproduced with annunciator times. However, information was available from a previous program output which indicated the time from the malfunction to the operator's action. The average malfunction to annunciator time was used to compute the annunciator to operator reaction time as shown.

Lined-out file number was invalid data for this malfunction.

Figure C-3 PMS summary printout of response times for malfunction 25

STARTING FILE NUMBER 201 TOTAL # FILES 70 FOR MALFUNCTION NUMBER 3

FILE #	MAL TIME	ANN 8171	CTE 1 454	CTE 2 458	CTE 3 465	CTE 4 2941	CTE 5 2943	CTE 6 3051	CTE 7 3055	CTE 8 3152	CTE 9 3731	CTE 10 3746	CTE 11 3748	CTE 12 3790	ANN. D.T.
207	548	549	****	****	****	****	****	163	27	26	****	****	****	****	1
214	419	421	230	25	25	****	****	215	28	27	327	****	****	****	2
220	635	636	81	77	76	****	****	28	23	23	****	****	****	****	1
234	428	430	25	25	24	36	37	257	15	14	****	42	40	39	2
240	287	288	****	****	****	710	709	27	19	21	24	712	712	713	1
244	366	367	207	****	****	224	225	204	9	9	303	225	227	227	1
250	311	313	****	****	****	****	****	13	10	9	****	****	****	****	2
254	227	228	20	19	18	239	240	23	3	2	431	237	****	245	1
260	592	593	****	****	****	75	****	55	52	52	16	70	69	73	1
264	616	617	****	****	****	****	****	****	****	19	467	****	****	****	1
507	892	893	****	52	51	802	803	****	36	36	759	801	800	798	1
523	1299	1301	****	25	24	129	134	21	12	17	****	127	131	130	2
535	554	555	****	****	****	****	****	****	17	16	****	****	****	****	1
545	907	908	****	18	****	****	****	24	24	24	****	****	****	****	1
561	1500	1501	****	****	****	****	****	17	14	15	****	****	****	****	1
576	958	959	****	****	****	****	****	11	36	37	****	****	****	****	1
607	712	713	****	****	****	****	****	****	13	14	308	****	****	****	1
621	1539	1540	****	41	41	231	231	30	15	13	****	234	234	236	1
633	1129	1130	****	****	****	****	****	****	11	11	****	****	****	****	1
~~646~~	~~517~~	~~519~~	~~****~~	~~29~~	~~29~~	~~****~~	~~****~~	~~****~~	~~35~~	~~35~~	~~****~~	~~****~~	~~****~~	~~****~~	~~2~~
~~651~~	~~312~~	~~313~~	~~****~~	~~30~~	~~29~~	~~****~~	~~****~~	~~****~~	~~37~~	~~37~~	~~****~~	~~****~~	~~****~~	~~****~~	~~1~~
~~652~~	~~95~~	~~96~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~75~~	~~73~~	~~89~~	~~****~~	~~****~~	~~****~~	~~1~~
654	1032	1034	****	****	****	****	****	****	66	64	****	****	****	****	2
656	1451	1452	****	****	****	****	****	****	31	29	****	****	****	****	1

Annunciator #8171 - Turbine Shutdown
Critical Task Elements - CTE

			Expected Operator Actions
454	-	MODS 5217 & 5219 (Trip)	2
458	-	Primary Circuit Breaker 5218 - Generator (Trip)	1
465	-	Primary Circuit Breaker 5214 - Generator (Trip)	1
2941	-	Stop Valve "D" Drain (Open)	3
2943	-	Control Valve Drain (Open)	3
3051	-	Exciter Field Breaker (Trip)	1
3055	-	Primary Circuit Breaker 5218 - Generator (Trip)	1
3152	-	Primary Circuit Breaker 5214 - Generator (Trip)	1
3731	-	Lift Pumps (On)	4
3746	-	Stop Valve "A" Drain (Open)	3
3748	-	Stop Valve "B" Drain (Open)	3
3790	-	Stop Valve "C" Drain (Open)	3

Data from teams 5 and 18 could not be reproduced with annunciator times. However, information was available from a previous program output which indicated the time from the malfunction until the operator's action. The average malfunction to annunciator time was used to compute the annunciator to operator reaction time as shown.

Lined-out file numbers were invalid data for this malfunction.

Figure C-4 PMS summary printout of response times for malfunction 3

STARTING FILE NUMBER 506 TOTAL # FILES 77 FOR MALFUNCTION NUMBER 121

FILE #	MAL TIME	ANN 7158	CTE 1 680	CTE 2 682	CTE 3 684	CTE 4 686	CTE 5 688	CTE 6 692	CTE 7 694	CTE 8 696	CTE 9 698	CTE 10 700	CTE 11 702	CTE 12 1809	ANN. D.T.
510	688	699	78	201	328	****	****	70	200	327	****	****	****	240	11
521	216	217	****	****	****	****	****	****	****	****	****	****	****	****	1
522	11	21	20	200	266	****	****	20	200	266	****	****	****	****	10
524	916	923	115	****	****	****	****	130	****	****	****	****	****	****	7
526	194	205	71	153	185	229	****	33	123	****	288	****	****	268	11
533	38	47	183	64	411	****	****	184	66	411	****	****	****	****	9
537	20	31	46	138	****	****	****	49	139	****	****	****	****	****	11
543	191	200	262	447	****	****	135	389	464	****	****	157	****	****	9
546	208	218	****	****	60	****	****	****	****	85	****	****	****	****	10
553	518	527	77	135	249	****	****	63	136	249	****	****	****	****	9
556	27	38	43	140	****	****	****	122	143	****	****	****	195	****	11
616	109[illegible]	1105	130	229	301	****	****	130	229	301	****	****	****	****	9
512	[illegible]	85	231	605	793	****	****	249	617	805	****	****	****	****	11
527	322	334	120	217	275	****	****	118	218	275	****	****	****	81	12
540	68	79	****	299	160	420	****	****	300	161	423	****	****	114	11
552	11	22	243	380	643	****	****	246	382	645	****	****	668	263	11
567	55	65	45	348	****	****	****	46	350	****	****	****	****	91	10
~~601~~	~~115~~	~~126~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~11~~
614	1306	1316	****	****	****	395	191	****	****	****	403	206	343	****	10
624	43	55	75	****	****	****	****	81	****	****	****	****	****	277	12
636	78	91	100	****	284	****	****	101	250	284	****	****	****	****	13
645	352	361	38	327	****	****	****	66	345	****	****	****	****	****	9
661	130	142	299	****	****	****	****	314	****	****	****	****	****	****	12

Annunciator #7158 - Discharge Condenser Pumps Condition High
Critical Task Element - CTE

		Expected Operator Actions
680	- Condenser Cooling Water "A" Inlet North Side (Close)	2
682	- Condenser Cooling Water "A" Inlet South Side (Close)	2
684	- Condenser Cooling Water "B" Inlet North Side (Close)	2
686	- Condenser Cooling Water "B" Inlet South Side (Close)	2
688	- Condenser Cooling Water "C" Inlet North Side (Close)	2
692	- Condenser Cooling Water "A" Outlet North Side (Close)	2
694	- Condenser Cooling Water "A" Outlet South Side (Close)	2
696	- Condenser Cooling Water "B" Outlet North Side (Close)	2
698	- Condenser Cooling Water "B" Outlet South Side (Close)	2
700	- Condenser Cooling Water "C" Outlet North Side (Close)	2
702	- Condenser Cooling Water "C" Outlet South Side (Close)	2
1809	- Emergency Rod In	1

Lined-out file number was invalid data for this malfunction.

Figure C-5 PMS summary printout of response times for malfunction 121

STARTING FILE NUMBER 506 TOTAL # FILES 77 FOR MALFUNCTION NUMBER 138

FILE #	MAL TIME	ANN 2801	CTE 1 1605	CTE 2 1608	CTE 3 1609	CTE 4 1610	CTE 5 1611	CTE 6 1612	CTE 7 1615	CTE 8 1616	CTE 9 1619	CTE 10 1622	CTE 11 0	CTE 12 0	ANN. D.T.
506	21	22	160	****	156	****	****	****	158	****	****	****	****	****	1
513	13	14	40	****	162	****	****	****	164	****	41	****	****	****	1
523	141	142	183	****	185	****	185	****	189	****	183	****	****	****	1
525	527	529	212	709	216	628	215	675	194	659	209	720	****	****	2
534	18	19	109	****	111	****	110	****	112	****	106	****	****	****	1
540	38	40	155	****	158	176	158	177	158	196	155	189	****	****	2
544	12	14	66	****	****	****	109	****	110	****	66	****	****	****	2
550	14	15	127	****	129	****	129	****	131	****	127	****	****	****	1
554	683	685	69	220	71	199	73	202	75	208	70	243	****	****	2
560	31	33	119	****	121	174	121	177	122	****	119	****	****	****	2
561	29	31	285	****	287	****	287	****	288	****	286	****	****	****	2
617	431	432	68	216	73	193	73	195	75	207	65	234	****	****	1
511	1196	1215	354	****	361	****	375	****	363	****	172	****	****	****	19
525	3246	3266	78	****	88	****	89	****	73	****	83	****	****	****	20
537	501	502	86	****	112	****	111	****	72	****	102	****	****	****	1
551	642	813	201	****	****	****	****	****	195	****	205	****	****	****	171
566	242	243	****	****	47	****	47	****	40	****	****	****	****	****	1
600	471	472	220	****	231	****	****	****	200	****	207	****	****	****	1
611	463	465	70	****	73	****	74	****	75	****	71	****	****	****	2
623	394	395	105	****	108	****	110	****	****	****	77	****	****	****	1
635	1075	1101	158	****	162	****	161	****	167	****	158	****	****	****	26
644	133	135	176	****	210	****	191	****	178	****	166	****	****	****	2
660	384	387	155	****	156	****	156	****	159	****	156	****	****	****	3

Annunciator #2801 Reactor Building Containment Cooling Water Effluent Radiation High
Critical Task Element - CTE

CTE	Description	Expected Operator Actions
1605	Cleanup Pump "A" (Stop)	-
1608	Cleanup Pump "A" (Start)	2
1609	Reactor Water Cleanup Inner I.V. (Close)	1
1610	Reactor Water Cleanup Inner I.V. (Open)	2
1611	Reactor Water Cleanup Outer I.V. (Close)	1
1612	Reactor Water Cleanup Outer I.V. (Open)	2
1615	Reactor Water Cleanup Discharge to Reactor (Close)	1
1616	Reactor Water Cleanup Discharge Reactor (Open)	2
1619	Cleanup Pump "B" (Stop)	1
1622	Cleanup Pump "B" (Start)	2

Figure C-6 PMS summary printout of response times for malfunction 138

STARTING FILE NUMBER 506 TOTAL # FILES 77 FOR MALFUNCTION NUMBER 2

FILE #	MAL TIME	CTE 1 2827	CTE 2 2824	CTE 3 2828	CTE 4 0	CTE 5 0	CTE 6 0	CTE 7 0	CTE 8 0	CTE 9 0	CTE 10 0	CTE 11 0	CTE 12 0	M. OUT	OCCUR.
511	737	90	****	147	****	****	****	****	****	****	****	****	****	0	1
~~512~~	~~1921~~	~~****~~	~~****~~	~~311~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~2008~~	~~1~~
514	268	192#	****	****	****	****	****	****	****	****	****	****	****	485	1
517	1346	158	****	****	****	****	****	****	****	****	****	****	****	0	1
530	29	321	403	****	****	****	****	****	****	****	****	****	****	338	1
532	39	241	****	****	****	****	****	****	****	****	****	****	****	316	1
536	35	159#	168	****	****	****	****	****	****	****	****	****	****	196	1
~~567~~	~~327~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~345~~	~~1~~
541	153	180	****	****	****	****	****	****	****	****	****	****	****	350	1
545	228	189	192	****	****	****	****	****	****	****	****	****	****	419	1
552	100	316	****	****	****	****	****	****	****	****	****	****	****	432	1
555	495	214	****	237	****	****	****	****	****	****	****	****	****	714	1
615	293	310	314	****	****	****	****	****	****	****	****	****	****	610	1
515	32	203	221	****	****	****	****	****	****	****	****	****	****	0	1
531	184	86	****	****	****	****	****	****	****	****	****	****	****	332	1
555	50	204	****	****	****	****	****	****	****	****	****	****	****	0	1
572	30	113	129	****	****	****	****	****	****	****	****	****	****	156	1
~~604~~	~~268~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~0~~	~~1~~
~~605~~	~~520~~	~~****~~	~~****~~	~~79~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~752~~	~~1~~
613	57	385	398	****	****	****	****	****	****	****	****	****	****	64	1
626	66	100	****	****	****	****	****	****	[illegible]	****	****	****	****	229	1
641	21	****	****	****	****	****	****	****	****	****	****	****	****	0	1
650	87	****#	****	****	****	****	****	****	****	****	****	****	****	312	1
664	57	227#	****	****	****	****	****	****	****	****	****	****	****	375	1

Annunciator #7668 - Condenser Volume Low
Critical Task Elements - CTE

CTE		Expected Operator Actions
2828	Steam Jet Air Enjector Pressure Control (Close)	3
2827	Steam Jet Air Enjector Pressure Control (Open)	2
2824	Steam Jet Air Enjector Pressure Control (Close)	3

Lined-out file numbers were incorrect data for this malfunction.

The first actions for these teams were the reduction of reactor power, by reducing reactor recirculation flow, which could not be captured in the manner that other times were. The power reduction was examined for all teams but was first action for only these four.

Figure C-7 PMS summary printout of response times for malfunction 2

STARTING FILE NUMBER 201 TOTAL # FILES 70 FOR MALFUNCTION NUMBER 11

FILE #	MAL TIME	ANN 7764	CTE 1 13	CTE 2 130	CTE 3 458	CTE 4 465	CTE 5 1219	CTE 6 1336	CTE 7 1349	CTE 8 1808	CTE 9 1870	CTE 10 2019	CTE 11 3055	CTE 12 3152	ANN. D.T.
203	125	127	****	****	138	135	99	****	62	129	376	117	13	11	2
205	107	110	81	87	27	****	81	68	50	****	493	16	8	7	3
211	85	87	****	****	51	50	86	****	140	29	****	26	74	34	2
215	1859	1862	159	156	49	49	****	65	57	****	160	27	38	37	3
226	217	219	123	118	39	39	54	228	101	****	507	****	26	25	2
232	82	84	21	20	158	157	189	368	167	86	31	7	42	42	2
236	85	88	24	26	****	27	57	25	27	164	****	151	9	8	3
242	103	105	290	239	116	****	140	****	131	****	53	41	33	32	2
246	51	54	213	152	17	16	99	238	193	****	****	10	7	6	3
252	166	168	112	91	20	16	36	76	71	18	45	7	19	20	2
256	11	14	228	267	73	73	58	****	54	****	****	2	25	25	3
262	106	109	251	221	58	58	43	241	37	10	28	6	13	13	3
533	389	392	****	****	241	239	27	****	54	****	237	23	193	193	3
557	110	112	****	****	71	70	10	145	23	****	****	9	64	64	2
574	71	73	****	****	255	255	25	****	23	****	86	****	250	250	2
617	255	258	****	****	105	100	119	293	23	****	23	****	80	75	3
631	34	38	****	****	164	163	****	****	****	****	123	11	132	****	4
643	240	242	****	****	165	164	241	417	51	****	****	18	143	141	2
652	62	64	****	****	****	****	103	****	54	****	82	22	107	105	2
666	104	106	****	****	129	130	35	****	35	****	****	6	****	11	2

Annunciator - 7764 - Turbine Generator Load Reject Scram Trip.
Critical Task Element - CTE

CTE	Description	Expected Operator Actions
13	Shutdown Bus. 2 (Backfeed)	5
130	Shutdown Bus. 1 (Backfeed)	5
458	Primary Circuit Breaker 5218 - Generator (Trip)	4
465	Primary Circuit Breaker 5214 - Generator (Trip)	4
1219	HPCI Turbine Steam Supply (Open)	2
1336	RCIC System Flow (Manual)	2
1349	RCIC Turbine Steam Supply (Open)	2
1808	Control Rod Power	* Verify power to Control Rods
1870	SRM/IRM Drive (In)	3
2019	Mode Switch to Refuel	1
3055	Primary Circuit Breaker 5218 - Generator (Trip)	4
3152	Primary Circuit Breaker 5214 - Generator (Trip)	4

Data for Team 13 could not be reproduced with annunciator times. However, information was available from previous program output which indicated the time from the malfunction until the operator's action. The average malfunction to annunciator time was used to compute the annunciator to operator reaction time.

Figure C-8 PMS summary printout of response times for malfunction 11

STARTING FILE NUMBER 506 TOTAL # FILES 77 FOR MALFUNCTION NUMBER 9

FILE #	MAL TIME	ANN 2879	CTE 1 1161	CTE 2 1387	CTE 3 1399	CTE 4 1385	CTE 5 1441	CTE 6 1451	CTE 7 1464	CTE 8 2022	CTE 9 2023	CTE 10 2024	CTE 11 2025	CTE 12 3152	ANN. D.T.
507	111	117	764	327	234	530	481	263	83	644	632	552	552	579	6
~~515~~	~~86~~	~~115~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~84~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~29~~
516	179	243	****	****	190	183	167	****	14	278	277	154	154	208	64
520	15	56	340	800	180	164	166	798	542	924	923	588	603	613	41
527	18	66	****	227	244	583	586	231	****	458	451	396	396	420	48
531	196	219	****	463	225	214	265	467	104	582	559	539	537	559	23
535	719	755	234	515	495	492	502	516	92	581	580	****	****	536	36
542	18	35	****	****	322	430	457	****	81	290	289	187	187	234	17
547	56	125	****	260	168	****	690	653	140	785	786	458	458	499	69
551	157	169	764	466	262	300	350	696	****	680	679	620	620	747	12
557	41	99	****	226	63	80	****	229	264	562	669	443	443	472	58
614	43	65	****	****	118	211	294	****	167	494	493	296	295	319	22
516	461	520	71	133	91	136	****	56	****	****	****	232	232	247	59
556	571	578	****	****	****	****	****	****	****	98	98	45	45	97	7
573	215	222	****	****	33	46	25	27	21	144	145	****	****	95	7
~~605~~	~~693~~	~~726~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~33~~
616	42	102	****	****	429	****	464	****	130	251	250	170	170	183	60
627	329	364	****	280	327	****	****	252	185	594	595	433	433	472	35
~~642~~	~~66~~	~~261~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~****~~	~~14~~	~~****~~	~~****~~	~~197~~	~~197~~	~~****~~	~~195~~
651	108	178	****	225	229	276	140	139	72	260	260	121	121	172	70
665	558	603	****	****	136	164	****	****	188	300	299	267	267	373	45

Annunciator #2879 - Auto Blow [illegible] ves Temp High
Critical Task Element - CTE

CTE	Description	Expected Operator Actions
1161	RHR Pump (Start)	4
1387	RHR Pump (Start)	4
1399	Torus Cooling System Valve	4
1385	RHR Pump (Start)	4
1441	RHRSW Pump-Start	4
1451	RHRSW Pump-Start	4
1464	MSRV 1-22-OPEN	1
2022	Scram Reset (GR 1 & 4)	5
2023	Scram Reset (GR 2 & 3)	5
2024	Manual Scram (Channel A)	3
2025	Manual Scram (Channel B)	3
3152	Primary Circuit Breaker 5218 - Generator (Trip)	*

* Clearing Breaker Disagreement

Lined out file numbers were incorrect data for this malfunction.

Figure C-9 PMS summary printout of response times for malfunction 9

STARTING FILE NUMBER 506 TOTAL # FILES 77 FOR MALFUNCTION NUMBER 122

FILE #	MAL TIME	ANN 7771	CTE 1 1336	CTE 2 1349	CTE 3 1543	CTE 4 1544	CTE 5 1551	CTE 6 1552	CTE 7 1808	CTE 8 1870	CTE 9 2019	CTE 10 2887	CTE 11 3055	CTE 12 3152	ANN. D.T.
564	422	423	296	654	23	22	22	21	****	370	8	6	28	29	1
565	18	20	203	45	57	59	55	55	****	****	11	7	18	17	2
567	52	54	****	59	26	26	26	26	****	24	9	145	154	154	2
570	52	54	****	38	31	32	31	32	11	53	8	24	47	46	2
574	1614	1616	549	9	14	14	12	13	****	18	46	14	84	83	2
575	207	208	171	47	16	16	17	17	31	702	3	50	109	110	1
577	65	67	11	13	71	70	71	70	****	****	20	47	58	58	2
601	1139	1141	****	63	17	17	17	17	****	91	****	5	22	23	2
603	270	272	125	65	17	17	17	17	****	****	12	35	44	43	2
605	32	34	65	66	12	11	12	11	7	28	194	14	23	22	2
607	89	90	****	58	11	11	11	11	****	87	58	14	34	35	1
612	1906	1906	26	27	8	8	8	8	9	84	6	7	15	15	0
513	2110	2112	232	17	12	12	12	12	****	15	84	3	6	7	2
532	1019	1020	****	33	83	83	80	80	****	2	9	74	80	82	1
541	976	977	****	15	11	12	8	8	****	18	****	5	81	82	1
553	1399	1400	134	12	9	8	9	8	****	20	7	7	11	11	1
570	622	623	****	28	5	5	5	4	****	11	****	9	37	37	1
602	1254	1256	****	14	188	187	187	186	****	26	****	4	196	195	2
615	87	88	26	21	234	235	237	235	****	74	10	19	36	36	1
625	602	603	****	****	388	389	386	385	****	29	5	7	52	51	1
637	2298	2299	****	145	20	20	24	24	****	47	14	92	99	98	1
646	491	492	****	36	25	25	28	27	****	47	27	****	62	62	1
662	1240	1241	****	20	10	10	10	10	****	337	5	****	151	152	1

Annunciator #7771 - Main Steam High Radiation Scram
Critical Task Element - CTE

1336 - RCIC System Flow (Manual)
1349 - RCIC Turbine Steam Supply (Open)
1543 - Main Steam Line Inboard Isolation Valve (Close)
1544 - Main Steam Line Inboard Isolation Valve (Close)
1551 - Main Steam Line Outboard Isolation Valve (Close)
1552 - Main Steam Line Outboard Isolation Valve (Close)
1808 - Control Rod Power
1870 - Insert NI Detector
2019 - Mode Switch to Refuel
2887 - Trip Main Turbine
3055 - Primary Circuit Breaker 5218 - Generator (Trip)
3152 - Primary Circuit Breaker 5214 - Generator (Trip)

Expected Operator Actions

5
2
4
4
4
4
* Verify Controlled Power
3
1
* Verify Turbine Trip
* Clearing Breaker Disagreements
*

C-10 PMS summary printout of response times for malfunction 122

APPENDIX D

STATISTICAL ANALYSES

This appendix contains the summary tables for the inferential statistics mentioned in the body of the report. The page on which the test statistic is referenced is given in parenthesis in the title of each table.

Table 2 presents the results of F_{max} tests on the log-transformed RTs to determine if group variances were sufficiently homogenous to allow analysis by ANOVAs. Strictly speaking, the F_{max} test is valid only when the groups compared are the same size, which was not true in this study. We have used the F_{max} only for screening purposes, to identify comparisons for which the use of ANOVAs was clearly inappropriate, and do not feel that the unequal _ns_ completely invalidated the test for this purpose.

The knowledgable reader will appreciate that groups of three (or less) are less than ideal for any kind of statistical analysis. We have not simply pooled the data from Utilities B and C because the error data presented in Section 6 suggest that the two groups differ in at least on respect.

Table D-1 Within-subjects analysis of variances of ($\log_{10}$) RTs of 17 teams completing all exercises (p.26)

Malfunction	$\bar{X}$ (Log RT)	SD	MS	df	F
34	.9390[a]	.3740	(T) 5.5185	9	44.115*
91	.8035	.5725	(E) .1251	144	
25	.9429	.3716			
3	1.2481	.3312			
121	1.8547	.3827			
138	2.0671	.2303			
2	2.2926	.1617			
11	1.0776	.3376			
9	1.9493	.3424			
122	.8830	.2647			

* $p < .001$

a. $\bar{X}$ (Log RT) is the mean of the $\log_{10}$ RTs, or the (log of the) geometric mean. These differ from the means given in Table 4-3 because only 17 RTs are used to compute them.

Table D-2 Results of F_{max} tests for homogeneity of utility variances for log transformed RT data

Utility	S^2Log RT	n	df	F^a_{max}
Malfunction 34				
A	.25618	12		
B	.12112	8	3/11	2.251
C	.11379	3		
Malfunction 91				
A	.08269	11		
B	.20872	9	3/10	6.941**
C	.57392	3		
Malfunction 25				
A	.14030	11		
B	.15046	9	3/10	1.373
C	.19270	3		
Malfunction 3				
A	.11157	11		
B	.03832	9	3/10	3.829
C	.14672	3		
Malfunction 121				
A	.08741	11		
B	.07803	7	3/10	2.575
C	.20091	3		
Malfunction 138				
A	.06159	12		
B	.06610	8	3/11	275.417***
C	.00024	3		

(continued)

Table D-2 Results of F_{max} tests for homogeneity of utility variances for log transformed RT data (continued)

Utility	S^2Log RT	n	df	F_{max}^a
Malfunction 2				
A	.01867	11		
B	.06084	6	3/10	209.793***
C	.00029	2		
Malfunction 11				
A	.13102	12		
B	.03320	6	3/11	3.946
C	.09227	3		
Malfunction 9				
A	.11602	11		
B	.14178	5	3/10	3.717
C	.03814	2		
Malfunction 122				
A	.05200	12		
B	.04593	8	3/11	2.609
C	.11981	3		

a. F values for all malfunctions, are the F_{max} statistic.

* $p < .10$
** $p < .05$
*** $p < .01$

Table D-3 One-way analysis of variance summaries for RT data (p.29)

Utility	$\overline{X}$ (Log RT)	SD	n	MS	df	F
Malfunction 34						
A	1.0705	.5061	12	(B) .02785	2	
B	1.1215	.3480	8	(W) .19467	20	.143
C	.9622	.3373	3			
Malfunction 25						
A	.9513	.3746	11	(B) .27386	2	
B	.9398	.3879	9	(W) .14961	20	1.831
C	1.4041	.4390	3			
Malfunction 3						
A	1.1608	.3340	11	(B) .08993	2	
B	1.2296	.1958	9	(W) .08579	20	1.048
C	1.4367	.3830	3			
Malfunction 121						
A	1.7056	.2957	11	(B) .32847	2	
B	2.0748	.2793	7	(W) .09690	18	3.390*
C	2.0185	.4482	3			
Malfunction 11						
A	1.0072	.3620	12	(B) .09885	2	
B	1.2266	.1822	6	(W) .09954	18	.993
C	1.1253	.3038	3			
Malfunction 122						
A	.9054	.2280	12	(B) .24817	2	
B	.6532	.2143	8	(W) .05666	20	4.380**
C	1.0751	.3461	3			

* $p < .10$
** $p < .05$

Table D-4 Kruskal-Wallis one-way analysis of ranks for RT data (p.29)

Utility	n	Sum of ranks Observed	Sum of ranks Expected	H[a]
Malfunction 91				
A	11	89.5	132	
B	9	149.5	108	
C	3	37	36	7.775*
Malfunction 138				
A	12	136.5	144	
B	8	93	96	
C	3	46.5	36	.926

a. The H statistic is approximately distributed as Chi-square with 2 degrees of freedom.

* $p < .05$

Table D-5 Mann-Whitney U tests for RT data (p.29)

Utility	n	Sum of ranks Observed	Sum of ranks Expected	U	Z
Malfunction 2					
A	11	109	99	23	.9045*
B	6	44	54	43	
Malfunction 9					
A	11	102	93.5	19	.8497*
B	5	34	42.5	36	

* $p > .30$

Table D-6 One-way analysis of variance for Mean Rank Response Time (p.33)

Utility	$\overline{X}$	SD	n	MS	df	F
A	10.82	1.88	12	(B) 8.5989	2	2.119*
B	11.96	2.18	9	(W) 4.0581	21	
C	13.31	2.04	3			

* $p > .10$

Table D-7 Raw data for error probability estimates errors of omission, Class I manipulations (p.42)

Malfunction	Utility A	Utility B	Utility C	Total
	X/Y[a]	X/Y	X/Y	X/Y
11	12/1	6/1	3/0	21/2
138	48/1	32/4	12/0	92/5
121	22/0	16/2	6/0	44/2
122	12/1	8/1	3/0	23/2
9	44/0	24/5	8/0	76/5
2	22/0	14/1	--	36/1
91	99/2	81/4	27/0	207/6
34	60/5	40/5	15/0	115/10
Total	319/10	221/23	74/0	614/33

a. X = Total number of required manipulations

Y = Total number of omitted manipulations

Table D-8 One-way analysis of variance of utility demographic data (p.49)

Utility	$\bar{X}$ (Log RT)	SD	n	MS	df	F
Age						
A	36.42[a]	6.74	43	(B) 49.4766	2	.899
B	34.73	8.80	37	(W) 55.0547	88	
C	33.55	3.86	11			
Education						
A	1.37	1.63	43	(B) 2.1464	2	.843
B	1.67	1.67	37	(W) 2.5465	88	
C	1.00	1.10	11			
Control-room experience						
A	5.35	5.35	43	(B) 8.4895	2	.301
B	5.40	5.75	37	(W) 28.1819	88	
C	4.05	2.96	11			
Outside-control-room experience						
A	6.67	4.13	43	(B) 123.1930	2	8.626*
B	4.39	3.85	37	(W) 14.281	88	
C	1.77	.82	11			

* $p < .001$

a. These means are computed from the individuals' data and differ slightly from group means computed from the team average data presented in Table 7-1 due to rounding errors.

Table D-9 One-way analysis of variance of "problem" scores (p. 52)

Utility	$\bar{X}$	SD	n	MS	df	F
<u>Procedures</u>						
A	1.116	.0917	11	(B) .06996	2	
B	1.272	.2450	9	(W) .02827	20	2.474
C	1.273	.0252	3			
<u>Control Board</u>						
A	1.292	.1667	11	(B) .04482	2	
B	1.372	.2046	9	(W) .04469	20	1.003
C	1.477	.3750	3			
<u>Training Experience</u>						
A	1.244	.2990	11	(B) .16034	2	
B	1.449	.2311	9	(W) .06893	20	2.326
C	1.543	.1692	3			
<u>Indications</u>						
A	1.302	.2097	11	(B) .01461	2	
B	1.228	.1735	9	(W) .03711	20	.394
C	1.297	.1756	3			
<u>Familiarity</u>						
A	1.069	.1100	11	(B) .37720	2	
B	1.400	.2632	9	(W) .04018	20	9.388*
C	1.503	.2533	3			

* $p < .001$

APPENDIX E

CUMULATIVE RESPONSE TIME PLOTS

To construct a plot, the n RTs for each malfunction are ordered from the shortest to the longest, $X_1 \ldots X_i \ldots X_n$, where i is the position of the RT in the ordering. The estimator of the cumulative probability associated with each time, X_i, is thus

$$F(X_i) = \frac{i}{n + 1}$$

The $F(X_i)$: X_i pairs are then plotted on two- or three-cycle log-normal probability paper.

The lines on the plots were fitted by a standard regression program which returns the constants m and b for the line formula $y = mX + b$. Before the line can be fit, the data must be transformed because the original units, seconds and cumulative probability, do not have equal-interval properties in the space defined by the paper (i.e. the interval 10% - 20% is larger than the interval 40% - 50%). Units that have equal-interval properties are a) $\log_{10} X_i$, and b) the inverse normal integral of $F(X_i)$, which may be found by reference to tables of cumulative normal probabilities. In statistics texts for use in the social sciences, these tables are arranged in pairs of columns, one labeled "cumulative probability" or "F(Z)" and the other (the inverse normal integral) labeled "Z." For example, the inverse normal integral of $p = .95$ is $Z = 1.65$. These Zs have the desired equal-interval properties. The line is fit to points defined by the Z_{Xi}: $\log_{10} X_i$ pairs.

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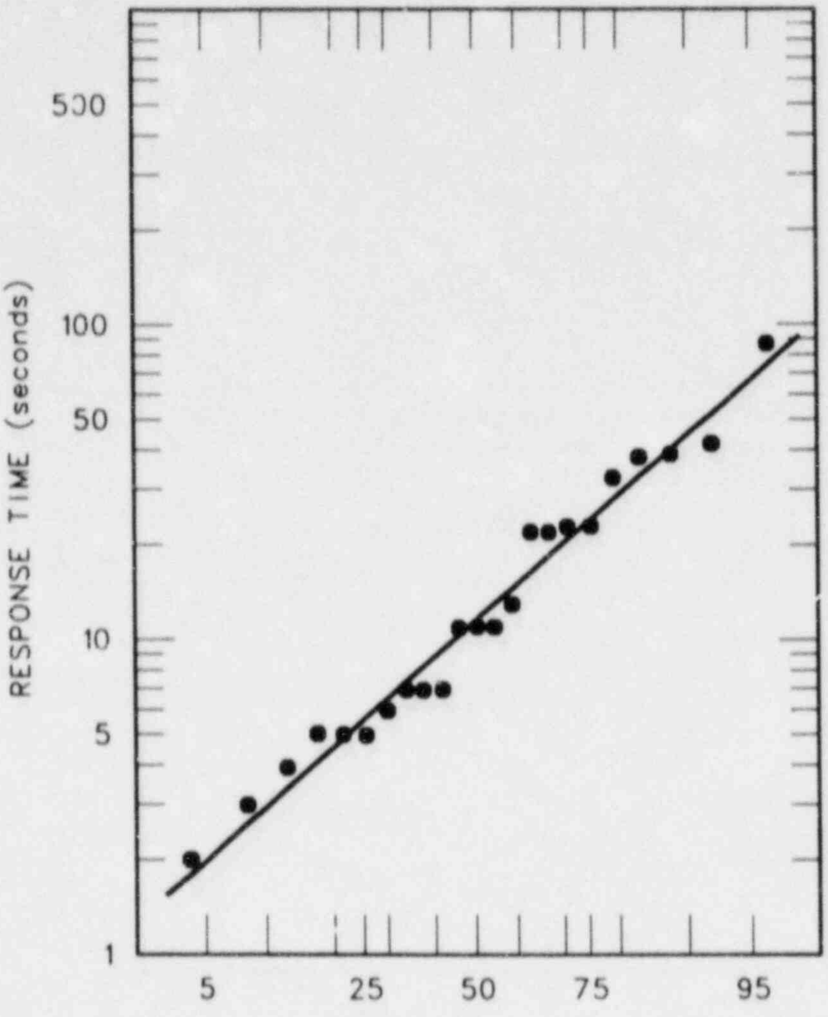

Figure E-1 Cumulative probability of operator response times to Feedwater Flow Control Failure (malfunction 34)

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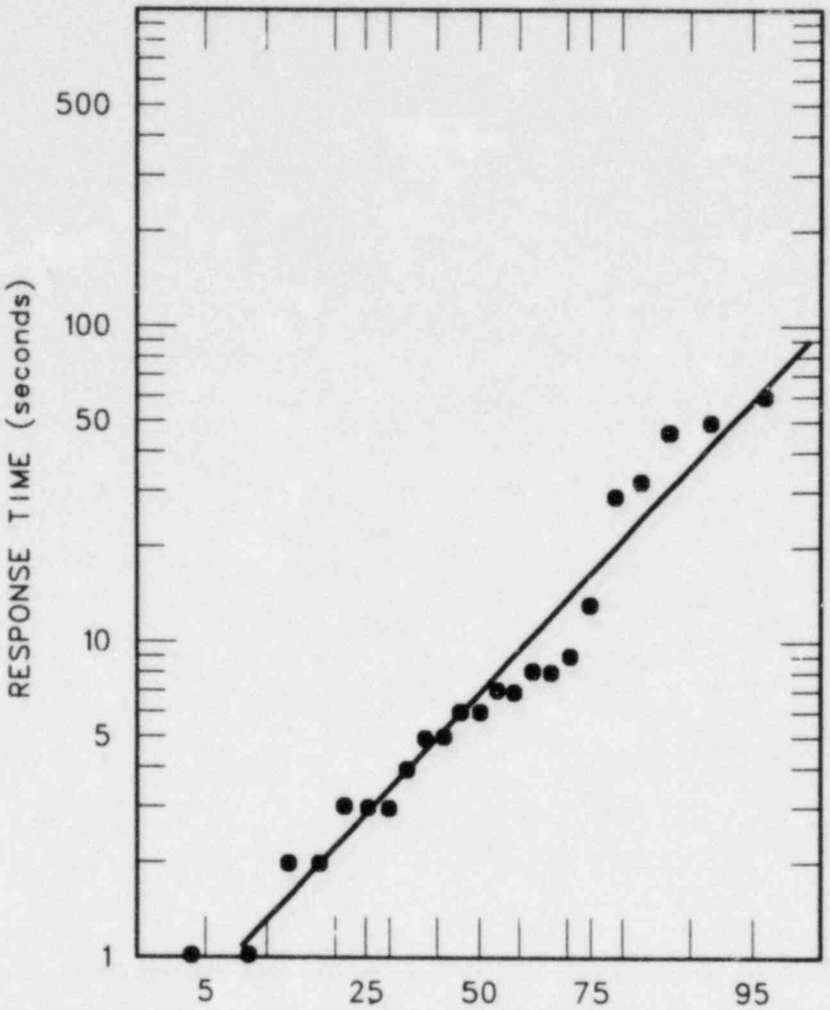

Figure E-2 Cumulative probability of operator response times to loss of shutdown cooling (malfunction 91)

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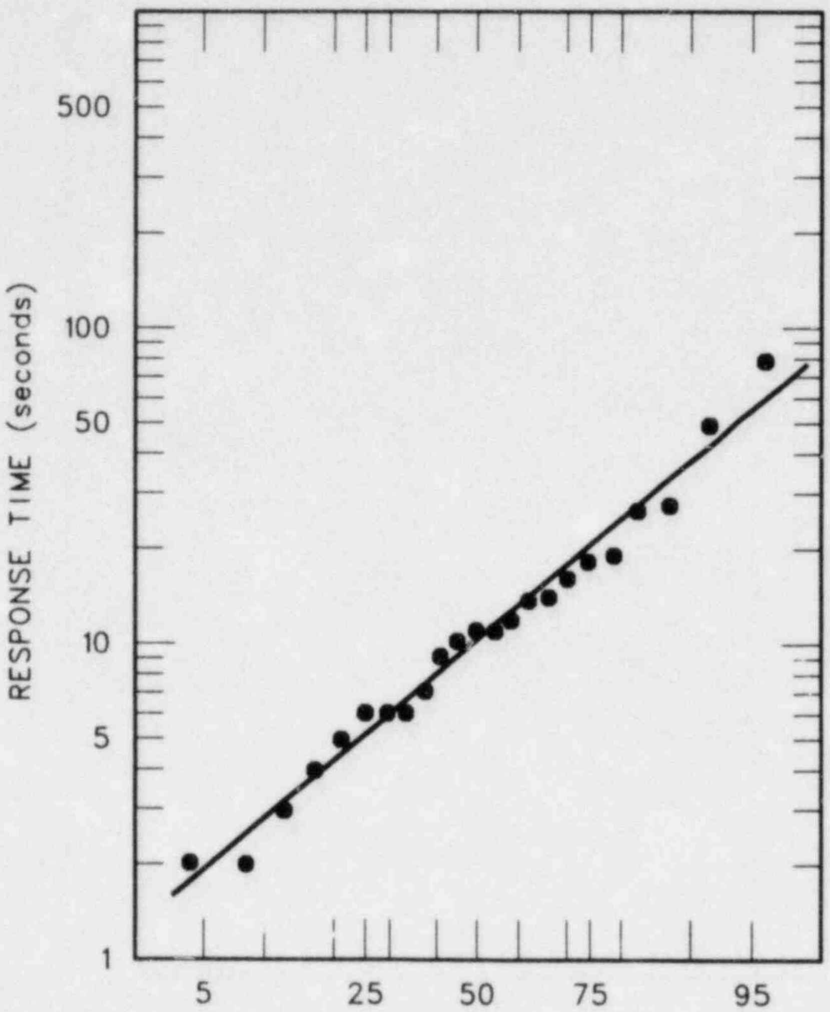

Figure E-3 Cumulative probability of operator response times to feedwater pump trip (malfunction 25)

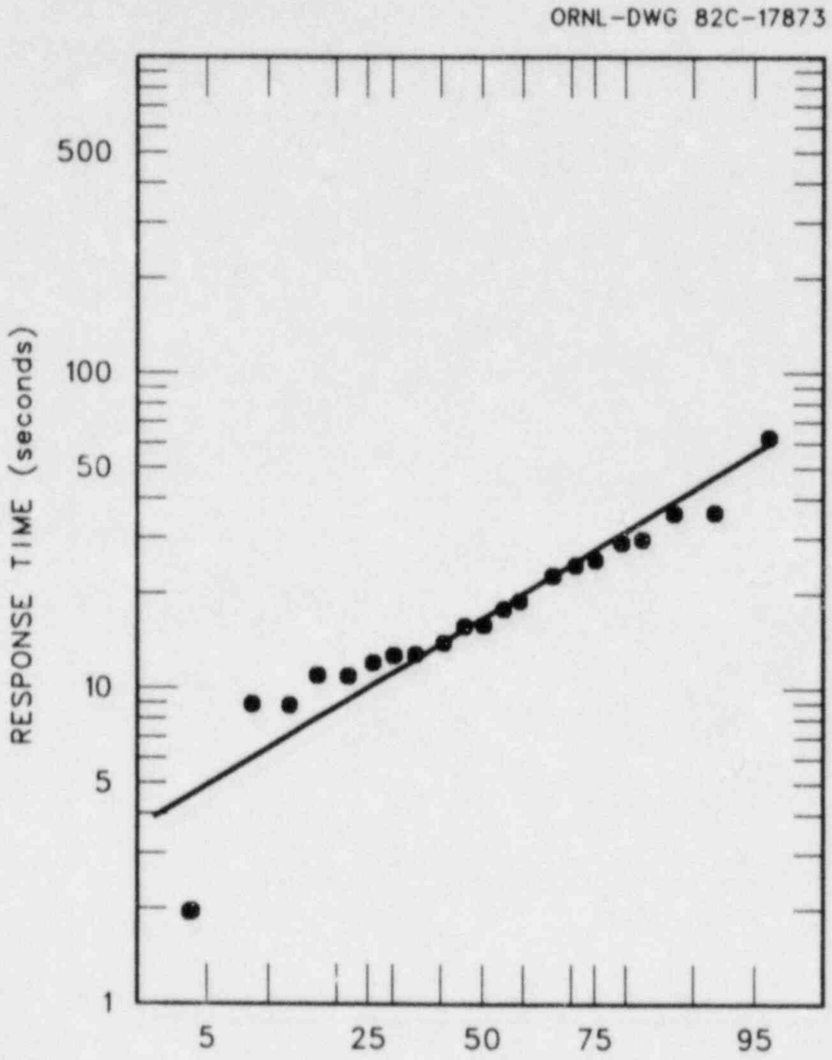

Figure E-4 Cumulative probability of operator response times to turbine trip (malfunction 3)

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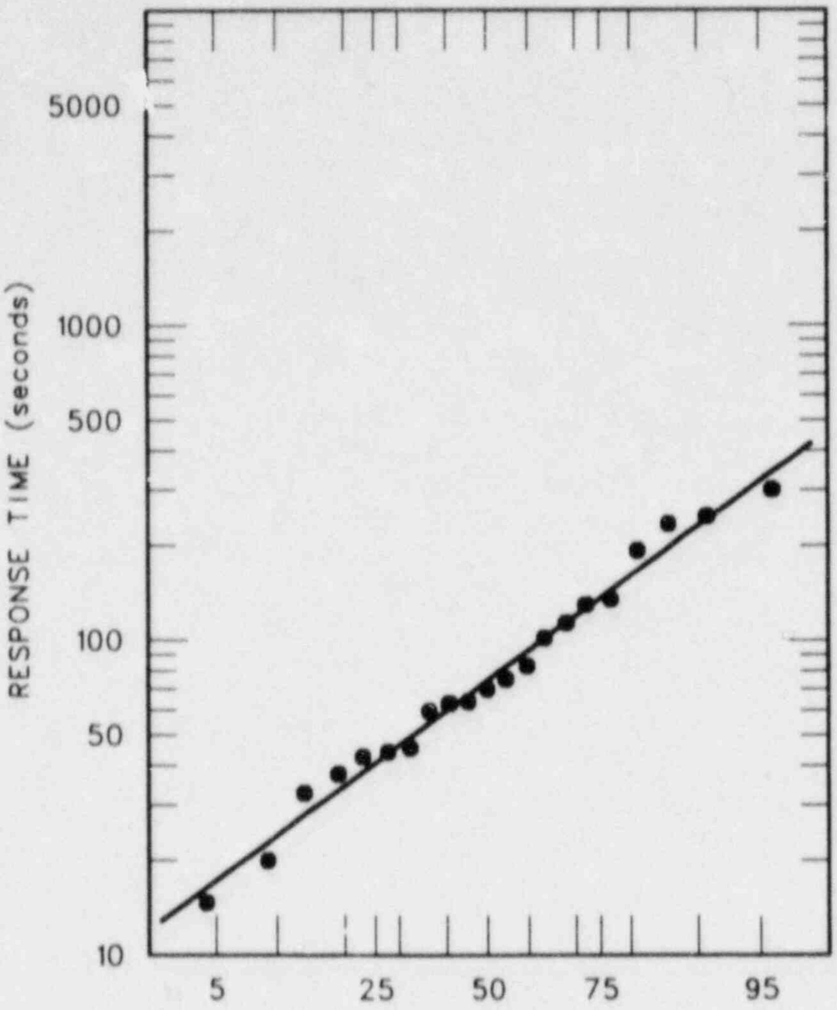

Figure E-5 Cumulative probability of operator response times to condenser tube leak (malfunction 121)

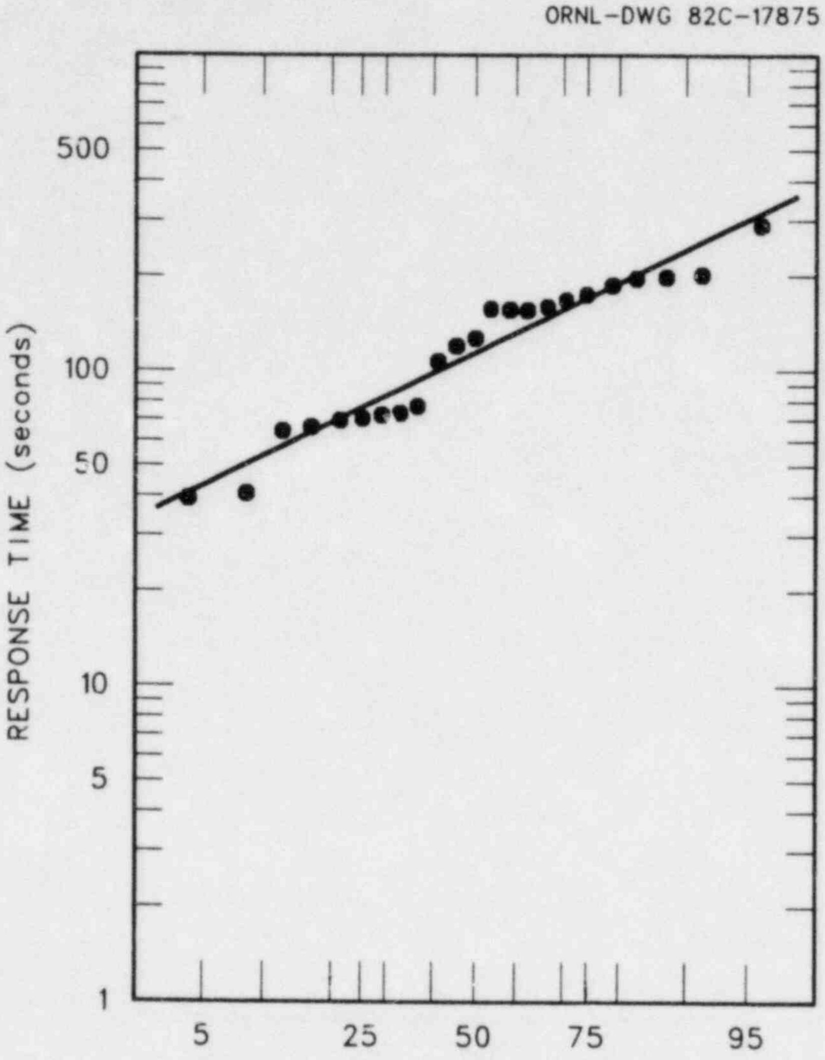

Figure E-6 Cumulative probability of operator response times to high cooling water activity (malfunction 138)

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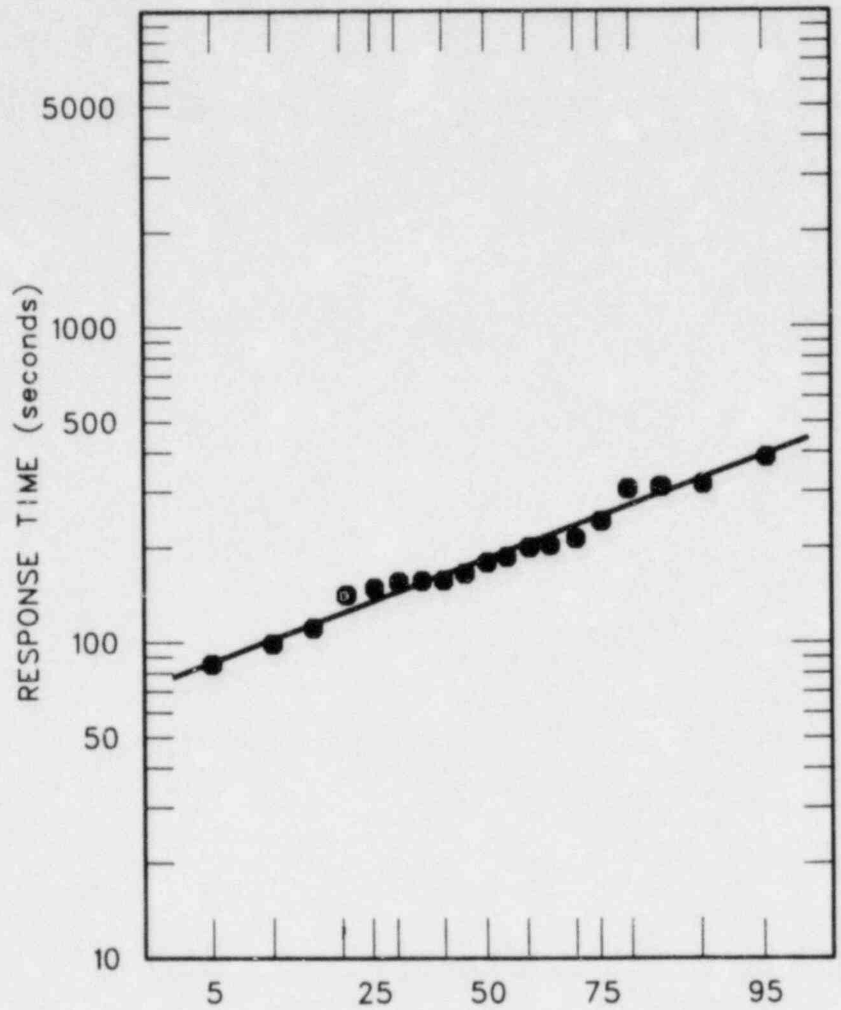

Figure E-7 Cumulative probability of operator response times to loss of condenser vacuum (malfunction 2)

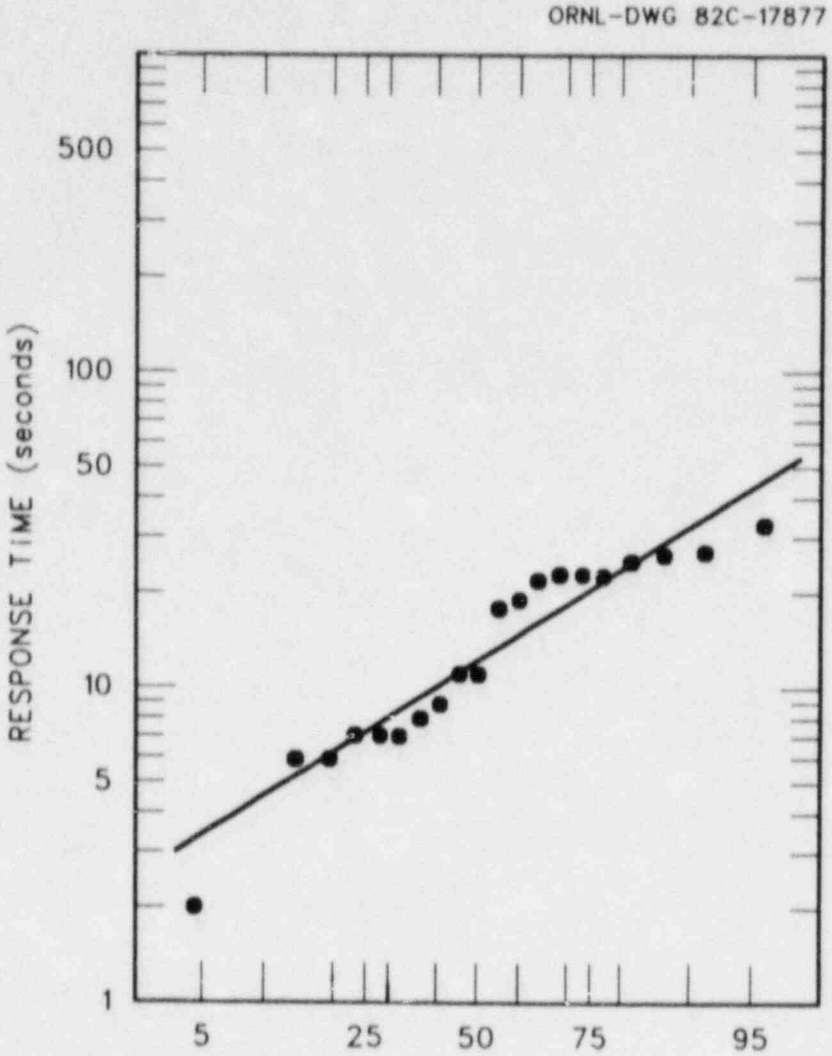

Figure E-8 Cumulative probability of operator response times to loss of offsite power (malfunction 11)

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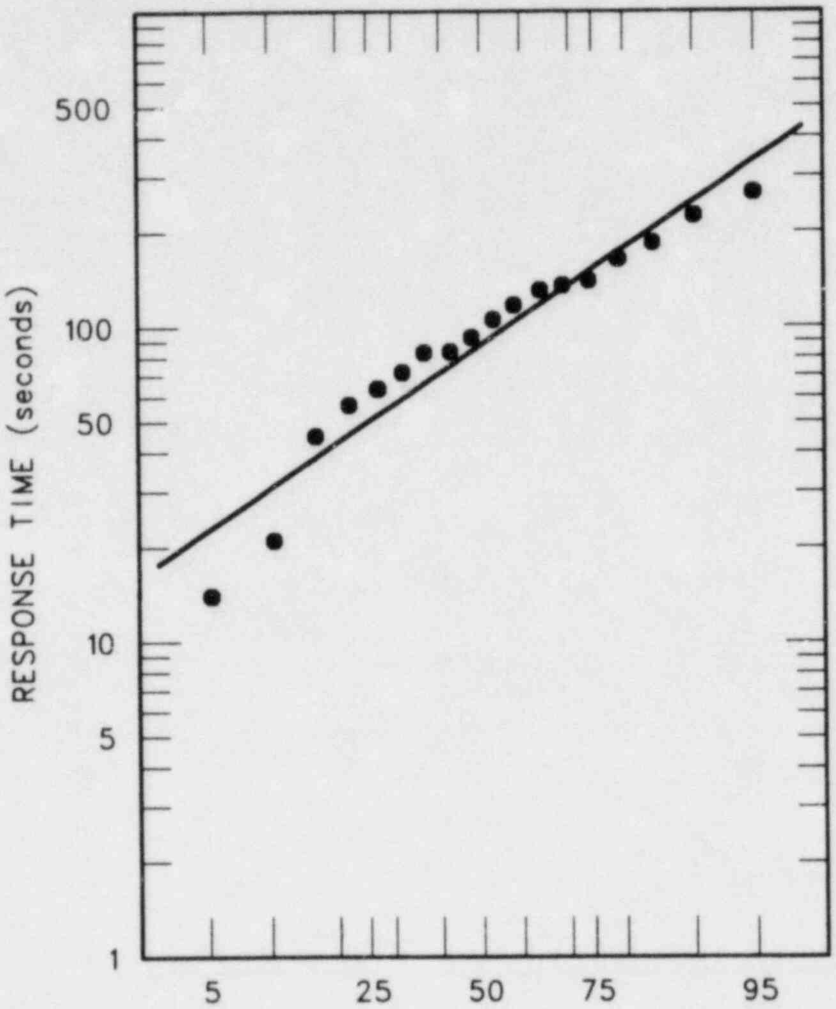

Figure E-9 Cumulative probability of operator response time to mainsteam relief valve failure (malfunction 9)

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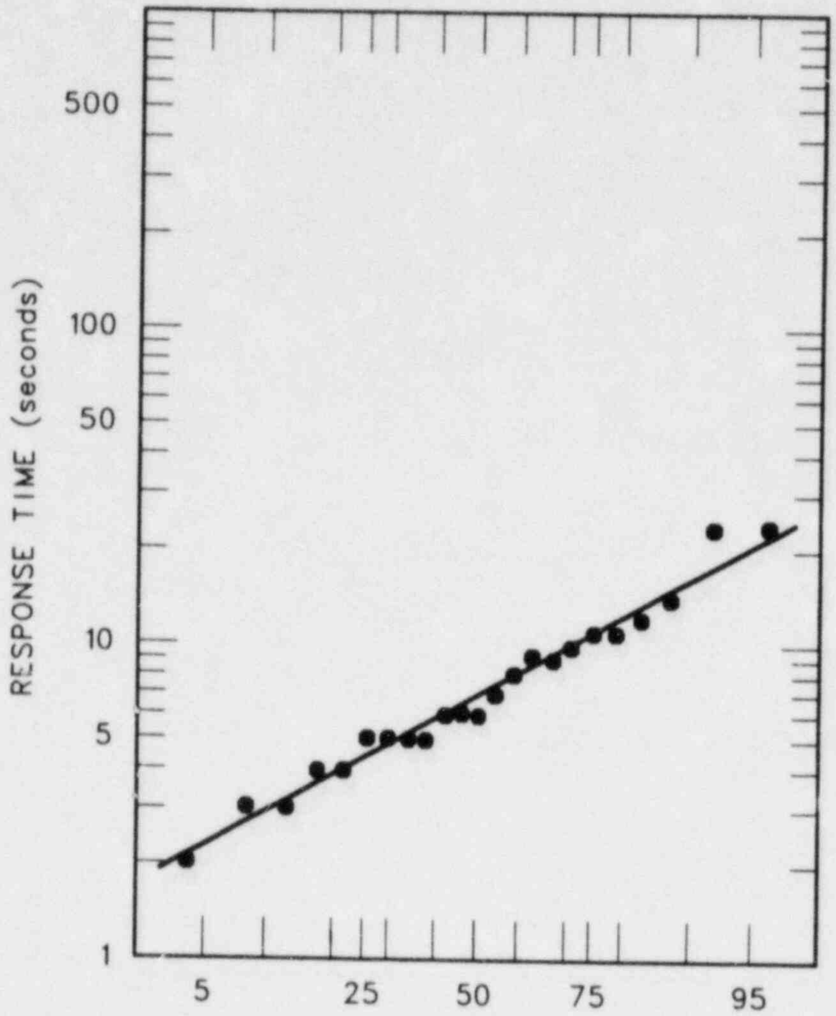

Figure E-10 Cumulative probability of operator response times to fuel element damage (malfunction 122)

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