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MODELING CONTROL ROOM CREWS FOR ACCIDENT SEQUENCE ANALYSIS

by

Y. Huang, N. Siu, D. Lanning, J. Carroll, and V. Dang
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Final Report
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"A Systems Model for Dynamic Human Error During Accident Sequences"

Project Officer: Joel Kramer

Office of Nuclear Regulatory Research
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ABSTRACT

This report describes a systems–based operating crew model designed to simulate the behavior of an nuclear power plant control room crew during an accident scenario. This model can lead to an improved treatment of potential operator–induced multiple failures, since it deals directly with the causal factors underlying individual and group behavior. It is intended that the model, or more advanced developments of the model, will be used in the human reliability analysis portion of a probabilistic risk assessment study, where careful treatment of multiple, dependent failures is required.

The model treats the members of the control room crew as separate, reasoning entities. These entities receive information from the plant and each other, process that information, perform actions that affect the plant, and provide information to the other crew members. The information retrieval, processing, and output activities are affected by the characteristics of the individual operator (e.g., his technical ability) and his relationship (measured in terms of "confidence level") with his fellow operators. Group behavior is modeled as the implicit result of individual operator behavior and the interactions bewteen operators.

The model is applied towards the analysis of steam generator tube rupture (SGTR) accidents at a non–U.S. pressurized water reactor, using the SIMSCRIPT II.5 programming language. Benchmark runs, comparing the model predictions with videotaped observations of the performances of three different crews during SGTR training exercises, are performed to tune a small number of model parameters. The tuned model is then applied in a blind test analysis of a fourth crew. In both the benchmarking and blind test runs, the model performs quite well in predicting the occurrence, ordering, and timing of key events. The model is also employed in a number of sensitivity analyses that demonstrate the robustness of the model (it generates plausible results even when the model parameters are assigned values not representative of observed crews) and the model's usefulness in investigating key issues (e.g., the effect of stress buildup on crew performance).

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1. INTRODUCTION

1.1 Objectives

The objectives of this study are to develop and demonstrate a framework for modeling dynamic crew behavior during accident scenarios in nuclear power plant operation. Interactions between individual operators as well as interactions between operators and the plant are treated. This framework is intended to provide a tool for better understanding and treatment of these dynamic interactions, which can be significant sources of common cause failures during severe accidents.

1.2 Motivation

As demonstrated by past operational experience (e.g., the TMI and Chernobyl accidents), operator performance in accident sequences is a critical factor to nuclear power plant safety. Current probabilistic risk assessment (PRA) studies also predict that a number of operator errors are extremely important to risk, but do not explicitly treat a number of issues that may greatly affect predictions of the likelihood of multiple failures. To show this, consider five simple yet potentially important observations [1]:

- Plant operators and plant components are interacting parts of an overall system that responds dynamically to upset conditions.
- The actions of operators are governed by their beliefs as to the current state of the plant.
- The operators have memory; their beliefs at any given point in time are influenced (to some degree) by the past sequence of events and by their earlier trains of thought.
- A number of operators (more than one) are involved during the accident.
- The event trees currently used in PRA to model accident scenarios are not literal simulations of the integrated plant/operating crew response, and, therefore, are not designed to formally treat the above concerns in detail.

The lack of treatment of the dynamic interaction between the crew and the plant means that the context for any given operator action is not completely specified. For example, current PRA studies generally treat operating crew behavior only in terms of successful or unsuccessful performance of specified actions (or sets of related actions). This means that any variations (e.g., in terms of timing, event order) in operator performance of the subtasks underlying each action, the resulting variations in the plant response, and the subsequent operator responses to the plant behavior (keyed through training and procedures) are also not treated. As a second example, current PRA studies do not generally provide detailed information on dynamic process variable behavior, although this can be crucial in determining the likelihood of certain operator actions (as demonstrated by the crew's response to the rising pressurizer level in the TMI–2 accident). Since the proper context for operator actions is not established, causal, "limited rationality" models for human error [2] (i.e., models in which operators are assumed to make reasonable decisions given their state of knowledge, available resources, etc.) cannot be used, and the human reliability analysis must rely heavily on limited generic data and judgment.

The second and third bullets refer to the cognitive behavior of a single operator. Neglect of this behavior greatly increases the difficulty of correctly analyzing accident scenarios in which multiple hardware failures are coupled by operator cognition. The "confirmation bias" phenomenon, in which an initially formed opinion concerning plant behavior tends to persist even if other evidence to the contrary is observed [3,4], provides one example of a potential causal mechanism for linking multiple failures. Other potential causes of scenarios involving operator–induced failures include faulty training and previous plant history. As an example of the second cause, the previous leaking history for the pressurizer pilot–operated relief valve in the TMI–2 accident inhibited a correct initial diagnosis (that the valve was stuck open); furthermore, subsequent information concerning the stuck open valve was either not noticed or noticed and ignored [5].

Current human reliability models used in PRAs (e.g., [6–8]) treat operator cognition in a largely judgmental fashion. Qualitative methods are used to help shape the analyst's judgment; these include the embedding of operator action top events in the event trees, which provides a general scenario context for the actions, and the use of supplementary models (e.g., event sequence diagrams, confusion matrices, operator task analysis). Almost by definition, "subscenarios" [9] distinguished by factors not included in the event trees (e.g., event timing, plant process variable levels, operator states–of–mind) are not treated explicitly.

As described in the next section, many of the current efforts to improve human reliability analysis are focused on treating operator cognitive behavior (e.g., [10–13]). However, these models are individual–oriented; either they treat the entire crew as a single entity, or they treat the key crew member (i.e., the decision maker). Note that current human reliability analysis models only address the issue of crew interactions through the simple mechanism of judgmentally assessed, static "performance shaping factors."

Studies on commercial aircraft crews [14] and on nuclear power plant control room crews [10] show that group interactions can have an important effect on the development of accident scenarios. For example, Ref. 14 points out that many civil aviation accidents have involved breakdowns in crew communication rather than deficiencies in operator knowledge and skills. Clearly, the characteristic time scale for aviation accidents is shorter than that for most power plant accidents. On the other hand, the flight crew has some common characteristics with nuclear power plant (NPP) control room crews: small size, a role structure dominated by authorized power, redundancy in components and in responsibility, and the need for teamwork. Ref. 10 describes a training situation in which one operator was unable to diagnose the accident until he was given key information from another operator. Moreover, the second operator did not think to look for (or already lookef for but did not provide) this information until he was queried by the first operator.

The inability of current models to simulate plant dynamics and the associated cognitive behavior of the operator and the inability of current cognitive models to simulate group behavior provide motivation for the development of an operating crew model aimed at treating these issues. The following section discusses information relevant to the development of a group model.

1.3 Literature Survey

This section briefly reviews selected work relevant to the development of a model for a nuclear power plant (NPP) control room operating crew. The review covers: a) a representative cognitive model for individual entities, b) important factors in evaluating the performance of small groups, and c) two models for small group behavior. The purposes of the review are to indicate the current state–of–the art in modeling and to identify what group and individual characteristics should be included in the crew model.

1.3.1 Cognitive Models for Individual Entities

A commonly recognized limitation of current human reliability analysis (HRA) models is that they only account for the observable surface form of human errors without considering the reasons and underlying processes (i.e., intention formation) for these errors [10]. The formation of erroneous human intentions acts as a source of common cause failure, since it can increase the likelihood of subsequent human errors and resulting system failures. Without modeling the processes of intention formation and the reasons for the formation of specific intentions, those common causes may not be identified and adequately treated.

Recognizing this, a number of researchers are developing cognitive models for individuals (e.g., [10–13]). These efforts are concentrated mostly on modeling how individuals form intentions and how these intentions are executed. At the moment, none of the models have been employed in a full–scope PRA, but this situation may change as model breadth, accuracy, and efficiency are improved.

All of the cognitive models employ an artificial–intelligence–like approach in which the operator is modeled as having a "knowledge base" (possibly subdivided) and an "inference engine" for drawing conclusions based on the information received from outside (e.g., the plant) and the information contained in the knowledge base. As a simple example, the knowledge base can contain a rule that states: if a tube in a steam generator tube ruptures, the pressurizer level will start to drop. With this rule, the inference engine can deduce that if the pressurizer level is observed to drop, a steam generator tube rupture may have occurred. The strength of the conclusion depends on an assigned strength for the rule (provided by the analyst).

The key to this approach is to construct a knowledge base that properly represents all relevant information owned by the operator (e.g., procedures, training, short cuts) and an inference engine that searches the knowledge base in a manner that properly emulates actual operator cognitive behavior. If an infinite knowledge base (covering every possible situation) and an infinitely fast and patient inference engine (allowing a complete search of the entire knowledge base) are provided, the model will represent a perfect operator. The various weaknesses in the knowledge base (e.g., incomplete coverage, incorrect rules and facts) and in the inference engine (e.g., the use of heuristics based on pattern matching or symptom likelihood [13]) need to be treated to realistically simulate operator behavior.

To exemplify current efforts in modeling actual cognitive behavior, consider the Cognitive Environment Simulation (CES) [2,10,15–16]. CES is a computer simulation that simulates operator intention formation during accident sequences. It identifies the affecting factors, the forms, and the consequences of intention formation of an operator during accident sequences. As shown in Figure 1.1, CES takes inputs from a dynamic thermal hydraulic code (e.g., a nuclear power plant simulator) and a knowledge base that represents the operator's knowledge of the plant and associated parameters. These inputs are then processed by routines simulating three major cognitive activities (monitoring, explanation building, and response management) to produce a series of intentions as outputs.

At each processing cycle (time step), the input data received from the thermal hydraulic simulation are used to decide what knowledge should be retrieved from the knowledge base. Note that the CES framework allows the treatment of situations where the operators do not observe all available information. Each plant datum from the control boards can be characterized according to its "salience" and "observability" to reflect the degree to which the content of this datum captures the operator's attention. These parameters are then compared with a user–specified filter threshold in order to determine whether the datum is actually observed by an operator.

Three types of "analysts" are used to simulate the three cognitive activities of concern. The Behavior Analyst treats an operator's activities in monitoring (and retrieving information) from the control board displays. The Situation Analyst treats an operator's activities in retrieving needed knowledge from the knowledge base and in choosing solutions from the possible alternatives. The planning activities, the scheduling of tasks to be executed, are then treated by the Response Analyst. The basic processing mechanism in CES is to create an analyst when demanded. This analyst is then responsible for a small field of concern, accessing plant data and knowledge from the knowledge base as needed.

CES allows more than one analyst of the same type to be active at a given time. In other words, the operator may perform more than one cognitive task in parallel. For example, an operator's quick survey of the control board display is modeled using several Behavior Analysts in CES. Internal communication is also allowed to occur between the various active analysts. Thus, the output of one analyst may serve as input for another analyst. For example, a Behavior Analyst may report its observations to an Situation Analyst. A Behavior Analyst may also be created by salient data or by commands from an Situation Analyst (or Response Analyst) to look for specified parameters or data.

The responsibility of an Situation Analyst created to process data obtained from a Behavior Analyst is to explain unexpected plant behavior. Usually the Situation Analyst will retrieve relevant knowledge from the knowledge base, communicate with other Situation Analysts, and/or instruct Behavior Analysts to acquire more data from control boards until a possible cause is found. It can be seen that an ideal Situation Analyst can be simulated by allowing exploration of all possible explanations and selection of the best one. This corresponds to situations where information processing resources are unlimited. Non–ideal behaviors can be treated as well. One method to simulate "confirmation bias" is to have the Situation Analyst select the first plausible explanation and then instruct the Behavior Analysts to collect information confirming this explanation [2]. The "frequency gambling" heuristic described in Ref. 13 can also be simulated. Here, the Situation Analyst selects the candidate explanation with the highest likelihood (as determined by the operator's experience).

After an explanation or a set of possible candidate explanations has been chosen by a Situation Analyst, it is sent to the Response Analyst to decide what responses should be taken. The Response Analyst must also determine the priority of a response in the event that several actions are waiting for execution. The Response Analyst's responsibility is to select among alternative responses under uncertainty and risk, to generate the expected plant behavior after a response action has been chosen and executed, and/or to command a Behavior Analyst to monitor the relevant plant responses. To do all of these, it has to interact with other analysts and with the knowledge base. The outputs (i.e., the intentions) are then executed by other means (e.g., analyst–supplied input) to simulate the feedback to plant behavior.

The knowledge base contains operational procedures, training, short cuts, and individual characteristics (e.g., skills, intelligence). Knowledge is represented in the form of "couplers," essentially production rules[1] for which conditions specifying rule applicability can be attached. For example, the coupler

Occurrence:	Adjust–rate–transaction
Subject:	Operator
Object:	Chg–flow
Direction:	Increase
Influence:	PRZR–LVL
Behavior	Increasing–Progression
Relator:	Chg–pump
State:	Operable

represents the knowledge that: a) if the operator increases the charging flow, the pressurizer level rises, and b) this only applies if the charging pump is operable [16].

The strength value associated with each production rule plays an important role in ordering the possible explanations by a Situation Analyst. Usually the explanations with higher strength values will come to the operator's mind first, given limited resources (e.g., for an operator under a high work load with no time available for further exploration). If further searching is allowed, other pertinent information may be called from the knowledge base to the operator's mind and may change the selection of possible explanations.

In CES, human intention failures result from mismatches between information processing demands made by the ongoing scenario and the operator's information processing resources. The demands can be changed by modifying the characteristics of incidents in a dynamic thermal–hydraulic code or in a simulator; for example, multiple initiating events may be simulated. The resources can be modified by changing the processing mechanisms, the structures and the strength values of production rules, or the filter threshold (used to determine what information is observed). The filter threshold can be modified using "Performance Adjustment Factors" (PAFs). The traditional performance shaping factors used in current human reliability analysis models (e.g., operator skill, time pressure) are included as PAFs; other PAFs can include the styles of human operators in handling problem–solving processes and factors characterizing the influence of stress on the operator's processing mechanisms. For example, a high stress level may narrow down the operator's field of attention; operationally this can be modeled by modifying the filter threshold.

The above discussion shows that the CES framework can represent a wide variety of human behaviors. It should be pointed out that not all of these behaviors appear to be operationalized in the working versions of CES documented in Refs. 10, 15, and 16. In particular, the filtering of available information, the impact of PAFs on the filtering process, the treatment of confirmation bias and frequency gambling, and many of the functions performed by the response analyst (e.g., selection among alternative responses under uncertainty and risk) do not seem to be implemented. Ref. 2 proposes five different styles of problem solvers: 1) the "Vagabond" (who jumps from one issue to another without

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[1]A production rule takes the form $A \rightarrow B$. In the context of declarative knowledge representation, this states that if proposition A (the activator) is true, then proposition B (the conclusion) is true. Note that A and B may be compound logical propositions (e.g., A could be of the form $\{A_1 \text{ AND } A_2\}$). Note also that a strength can be assigned to the rule, indicating confidence in the conclusion B.

finding a satisfactory solution for any), 2) "Hamlet" (who examines all possibilities too long before responding), 3) the "Garden Path Follower" (who easily fixates on a single issue), 4) the "Inspector Plodder" (a thoughtful but slow problem–solver, and 5) the "Expert Focuser" (the expert problem–solver who has all available information at his ready disposal). It appears that current implementations of CES operationalize only the last–named style.

A recent benchmark study applies CES to an interfacing systems loss of coolant accident [16]. When comparing the CES predictions with actual operating crew performances (on plant simulators), it is found that the currently implemented version of CES always performs better that the actual crew. This is because that the CES "Expert Focuser" can explore many more possible explanations for abnormal parameters, can more quickly access more information relevant to the accident, is not subject to human biases in processing information, and needs not resort to heuristics often employed by humans to deal with complicated situations.

As mentioned above, a variety of models have been proposed to deal with the cognitive behavior of operating crew members. The underlying concepts for these models (some of which have been implemented) are similar to those for CES, but some of the details/areas of emphasis vary. For example, Ref. 11 places greater importance on treating cognitive activities associated with the detailed execution of strategies (the latter are developed from the fault diagnosis process). Thus, "low level decision making" is distinguished from "high level decision making." Ref. 11 also explicitly treats uncertainties in the operators' understanding of the plant status using fuzzy logic. Ref. 13's discussion of a conceptual model for operators emphasizes the operators' use of knowledge base retrieval heuristics that are not purely logic–based. It points out that pattern–matching is the dominant cognitive process of operators responding to an accident sequence, and that operators tend to rely on pattern–matching (an automatic or nearly automatic process) rather than on laborious logical inference even when the latter style of knowledge base processing is demanded [13,17]. The laborious logical reasoning processes (performed by a concious, serial working memory) are assumed to be supplementary tools for confirming the solutions generated by pattern–matching processes (performed by an unconcious, parallel knowledge base). The SAINT/INTEROPS computer–based model described in Refs. 12, 18 and 19 implements this same distinction between "rule–based" and "knowledge–based" behavior [20]. Here, the procedures employed by an operator in dealing with a familiar situation are retrieved from the knowledge base and executed automatically. An unfamiliar situation is treated by procedures generated specifically for that situation. The process for procedure generation first involves the development of a qualitative picture representing the current plant status. This picture is then compared with that of the target state (i.e., a safe or marginally safe state). A trial procedure is represented by modifying the states of components (and, therefore, the state of plant). If the "distance" between current and target states is not reduced by the trial procedure, a different procedure must be generated.

Although their details differ, the above cognitive models do share many ideas concerning operator behaviors to be modeled and factors influencing these behaviors. The following list indicates significant issues addressed by the authors of these models. Note that many of these issues are not necessarily implemented in the reviewed models.

- An operator can neither observe all information on the control boards nor access all knowledge from his knowledge base. Furthermore, his field of attention can be narrowed during an accident, especially if he is performing in a high stress situation (e.g., when the workload is very high). More generally, stress can affect operator cognitive activity.

- The operator's cognitive processing of information is predominantly rule–based (as defined in Ref. 20). Knowledge–based reasoning is slower and more laborious, but can be performed in parallel with rule–based behavior.
- Errors in intention formation are due to mismatches between information processing demands, as determined by the characteristics of the accident, and information processing resources (e.g., the information in the operator's knowledge base).
- Knowledge stored in the operator's working memory (the volatile portion of his knowledge base) can decay over time.
- The operator can process a number of tasks in parallel. The execution of basic (indivisible) subtasks within a task is governed by the priorities assigned by the operator. Ongoing activities/processes can be interrupted by salient data or events.
- The operator continuously generates and updates his expectations regarding plant behavior; differences between these expectations and actual plant behavior will flag his attention.

These issues need to be addressed in a realistic simulation of crew performance.

1.3.2 Evaluating Group Performance

The cognitive models discussed above apply to individual entities. In order to model the behavior of an operating crew, it is important to identify the important issues and factors associated with the performance of groups of individuals. This is done by reviewing work aimed at evaluating small group performance. (Here, the term "small group" refers to the number of persons that can all have face–to–face communication with each other.)

Group performance in problem solving and decision making has long been studied by behavioral scientists interested in business and political groups. The group performance influencing factors commonly recognized can be summarized as follows:

- Characteristics of individual members:
  - behavior patterns (style)
  - ability
  - skill
- Characteristics of the group:
  - cohesiveness (level of attraction for a member to remain in a group)
  - norms (behavior standards enforced by the group)
  - distribution of ranks and status (the relative "position" of each group member)
- Social environment:
  - group's goal
- Physical environment:
  - nature of tasks
  - resources available
- Dynamic group interaction processes:
  - communication
  - group decision making and problem solving
  - coordination (teamwork)
  - influence (how group members affect the behavior of others)

Ref. 21 summarizes a collection of experimental and theoretical studies on the performance of small groups aimed at showing how a group influences individual members. Not surprisingly, individual behavior patterns can affect the group function both positively and negatively. Cooperative and efficient behavior tend to positively affect performance, while aggressiveness and high self–confidence tend to have negative impacts. Conversely, Ref. 22 discusses how the group can influence the individual members. The group can train new members to respond to situations by using the memories of older members. The group can also have a restricting influence on individuals.

Regarding group effectiveness, most references support the intuitive notion that the group structure and group processes can have positive effects on effectiveness. However, they also point out cases where the group performance can be negatively affected. Ref. 23 observes that a group produces more and better solutions to problems, but is less efficient (takes more time) than individuals. It also finds that when facing problems requiring strong concentration, the presence of others can adversely affect an individual member's performance. In other words, the group interaction processes can interfere with an individual's logical reasoning processes. Thus, Ref. 23 concludes that a decentralized communication structure is most efficient when the group must solve complex problems, whereas a centralized network is most efficient when solving simple problems. Ref. 24 cites experiments in which the pooled output of non–interacting individuals was better than that of an interacting group. Ref. 24 also notes that when a group faces a familiar task, almost no discussion between group members occurs. However, when facing an unfamiliar task, there is a tendency for group members to begin generating and evaluating solutions rather than to take time to study and analyze the task itself. Ref. 22 states that, although the group is usually better at solving problems than the average individual, it is seldom better than the best individual.

The preceding discussion is based on analyses of small groups performing in different settings than a nuclear power plant control room. Work is also being performed on the evaluation of the team skills of nuclear power plant control room crews. Assuming that team skills can be rated based on direct observations, Ref. 25 proposes the following seven dimensions for evaluating control room crews:

- Two–way communication of objectives/plant status (the team's ability to maintain plant awareness)
- Resource management (its ability to use resources, e.g., procedures, assistance from other members)
- Inquiry (the extent to which team members created an atmosphere in which all were encouraged to ask questions for clarification purpose)
- Advocacy (the team members' ability to present and defend arguments for a particular action)
- Conflict resolution and decision making (the members' ability to recognize and resolve differences of opinion related to actions required to sustain or stabilize plant status)
- Stress management (the members' ability to get the job done even when confronted with unpleasant and potentially dangerous situations, by reducing or effectively handling stress levels)
- Team spirit (the degree to which team members support one another as they perform under emergency conditions)

It can be seen that communication between operators, both informational and non–informational, is an important underlying process for all of these dimensions. For example, the second dimension, resource management, is related to the sharing of the information from the control panels and from the written procedures. This information usually is shared through communication. Inquiry, advocacy, and conflict resolution or decision making also can only be done via communication. The sixth dimension, stress management, is more individual–oriented but can be affected by communication (e.g., an effective leader can calm down a flustered subordinate). Team spirit also can clearly be affected by communication.

The above discussion shows that communication is an extremely important process in small group behavior. Thus, it needs to be treated directly in a model for operator crew behavior during accident scenarios.

1.3.3 Models for Crew Behavior

Two models designed to evaluate the performance of crews are reviewed in this section. Ref. 26 describes the Maintenance Personnel Performance Simulation (MAPPS), designed to evaluate nuclear power plant maintenance team performance at the task level. Ref. 27 describes a model developed to represent submarine crew decision making. Both models recognize that the crew is composed of individuals. However, MAPPS creates a group entity (whose characteristics are determined by the characteristics of the crew members) and treats the performance of this group entity; the submarine model treats the behaviors of the individual crew members explicitly.

MAPPS [26] is an ability–driven, group–oriented, stochastic simulation model. Although designed to treat the performance of maintenance crews, it has been proposed as a tool for analyzing control room crews during accidents. MAPPS deals with the crew as a single entity. Treating each task as a collection of subtasks, it compares the ability level required for successful subtask accomplishment to the crew's current ability and subsequently derives baseline estimates of the subtask duration and success probability. The ability level required for a subtask is obtained by considering a number of subtask–related factors (e.g., accessibility of the component to be worked on, the effects of wearing protective clothing on job performance). The current crew's ability is obtained by adding the abilities of the individual crew members. (The crew member's ability is assessed by the user.) Note that the crew members's ability is adjusted for his current physical condition (e.g., how long he has worked) and the working environment (e.g., the temperature of the work area).

The baseline estimates for subtask duration and success likelihood obtained are then modified as a function of the current stress level. The stress on individual team members is composed of four parts: stress stemming from the ability difference (between the required level of ability and the crew member's actual ability), stress stemming from radiation exposure (it increases as the amount of absorbed radiation approaches the allowable limits for the individual), stress stemming from the need for communication, and stress stemming from time pressure. The total team stress is computed as the sum of the stress on the individual team members.

In order to account for the inherent variability in the impact of the identified factors on an individual's ability and stress, MAPPS establishes upper and lower stochastic bounds and utilizes Monte Carlo sampling to choose a particular effect for a given individual. The distribution for team performance characteristics (e.g., task duration) are obtained by repeated sampling.

MAPPS incorporates a number of features to allow a realistic simulation. For example, it allows the skipping of low priority tasks when the time remaining is short. It also allows emergency events to occur during the execution of a subtask. On the other hand, it assumes that the group structure is static throughout the execution of a task. More importantly, from the standpoint of accident analysis, MAPPS does not treat the reasoning underlying crew actions, nor does it explicitly treat interactions between crew members that affect this reasoning.

A somewhat different approach to group modeling is provided in Ref. 27. This reference describes a model designed to treat the behavior of a submarine control team during emergency operations. The model deterministically simulates limited aspects of the behavior of individual crew members; the transmission of information between crew members is treated explicitly.

Figure 1.2 illustrates the submarine crew model. It can be seen that five crew members are treated. They are, order of rank: the Officer Of the Deck (OOD), the Diving Officer Of the Watch (DOOW), the Chief Of the Watch (COW), the Lee Helm, and the Helm. The OOD is responsible for all ship controls, the DOOW is responsible for the bulk of the emergency control decision processes, the COW is responsible for monitoring and operation of a number of ship systems, the Lee Helm is responsible for controlling the stern planes, and the Helm is responsible for transmitting engine orders.

The cognitive activity of each crew member is modeled using one or more of five internal cognitive processing stages: the Pre–Processor (PP), the Situation Assessment (SA), the Information Fusion (IF), the Command Interpretation (CI), and the Response Selection (RS) stages. The Pre–Processor severs as a filter for incoming information provided by the system or by other crew members and also as a decision switch to decide which algorithm (i.e., decision rule) should be utilized by the Situation Assessment stage. The Situation Assessment stage decides, using predefined decision rules, what information should be processed or transferred to other crew members. The Information Fusion stage, as its name implies, is the stage at which information from a variety of sources is consolidated; it serves as a medium for interactions among operators in the organization. Information is usually transferred from subordinates' Situation Assessment stages to the superior's Information Fusion stage for further utilization. The Command Interpretation stage is the one where a superior's command is translated into a set of goals. In the Response Selection stage, the operator then chooses the solution to be applied to the problem at hand.

To reflect realistic decision making under emergency conditions, not all operators own all five stages. For example, the superior officer, the OOD, only has the Information Fusion stage. Furthermore, he receives information and sends commands to only the DOOW. The Lee Helm and Helm only own Situation Assessment and Response Selection stages. Only the DOOW and COW have all five stages to simulate their involvement at all levels of decision making during emergencies. Note that the five internal cognitive processing stages used in this model cover the monitoring, situation assessment, planning, and execution activities discussed in Section 1.3.1.

The actual transmission of information through the model, both between the cognitive stages of a given crew member and between crew members, is treated using a Petri Net formulation [28]. This permits a precise description of the interaction between elements of discrete event dynamic systems performing concurrent processes. Figure 1.2 shows the different information flow paths in the crew model. A walkthrough of the DOOW's processing mechanisms helps to clarify the working of this crew model.

The Diving Officier Of the Watch (DOOW) is responsible for the bulk of the emergency control decision processes. In the model, he receives raw information from the ship's control panels as well as information reported from the COW. The DOOW's Pre–Processor stage processes these information and chooses one of a set of pre–defined decision rules to be used by the following Situation Assessment stage. The Situation Assessment stage then processes the information according to the selected decision rule. The output of this stage is then merged with information received from the Lee Helm and Helm (their Situation Assessment stages) to serve as inputs to the DOOW's Information Fusion stage. Again, the Information Fusion stage functions according to the predefined decision rule to generate its output; this output is sent to the OOD's Information Fusion stage and the DOOW's Command Interpretation stage. Usually, the information sent to the OOD is a subset of that processed by the DOOW. The outputs the OOD's Information Fusion stage is merged with the output of the DOOW's Information Fusion stage to produce the input to the DOOW's Command Interpretation stage. The output of this stage is then fed to the DOOW's Response Selection stage, which chooses the "best" solution. This solution is transferred to the Response Selection stages of the Lee Helm and Helm, and the Command Interpretation stage of the COW. The actual actions of the crew, which are indicated as the output Y in Figure 1.2, are identified and executed by the COW, Lee Helm, and Helm.

This model treats the different responses of the crew members to different input cues. For example, in the DOOW's Situation Assessment stage, a set of pre–established decision rules is used to determine whether a pipe rupture is severe (pipe size > 6") and whether or not it has occurred in the engine room, in which case the implications and appropriate response differ from those for other flooded areas. However, the model is deterministic; a specific input to the model will generate the same output.

It should be noted this model is designed to evaluate changes in crew performance due to changes in system design (e.g., the addition of a computer–based operator aid). Crew performance is measured in terms of crew member workload and the average change in output of the crew (Y in Figure 1.2). Estimation of the latter quantity, the average change in output, requires an assessment of the probabilities of different possible input vectors (X in Figure 1.2) and of the optimal responses to each different input vector. This is done using expert opinion.

Several assumptions have been made to simplify this model. Some of the important ones are: a) the model is memoryless, b) the processing algorithms are simplistic (e.g., they do not treat contradictory information or rejection of information) and deterministic, c) faulty behaviors (e.g., forgetting, fixation, excessive narrowing of focus) are not treated, d) changes in group structure are not treated, and e) only one–way communication is allowed (e.g., subordinates cannot question superiors). Nevertheless, this work is very useful in that it suggests that a realistic model for simulating crew performance can be constructed by linking (via communication) individual models for the crew members. This conceptual approach is expanded upon in Chapter 2.

1.4 Report Structure

This report provides the details of an operator crew model constructed to treat three key issues: a) the dynamic interaction between the crew and the plant, b) the dynamic interaction between operators, and c) the cognitive behavior of the crew members. Chapter 2 presents the detailed framework adopted for modeling crew behavior during accident scenarios. The conceptual models for the plant, the individuals, the interaction between individuals, and the interactions between the plant and the individuals are discussed. Chapter 3 describes the sequence chosen for the case study, steam generator tube rupture (SGTR) in a pressurized water reactor (PWR). The chapter also discusses crew performance data collected in a set of training exercises and the application of these data in the crew model. Chapter 4 presents the implementation of the detailed crew model for SGTR. It presents a walk–through of the model and a comparison of simulated and observed crew behavior during a set of SGTR training exercises. Chapter 5 discusses the sensitivity of the model to selected inputs. It also investigates the impact of variations in crew structure on crew performance. Finally, Chapter 6 discusses the model limitations, potential applications, and areas for future work.

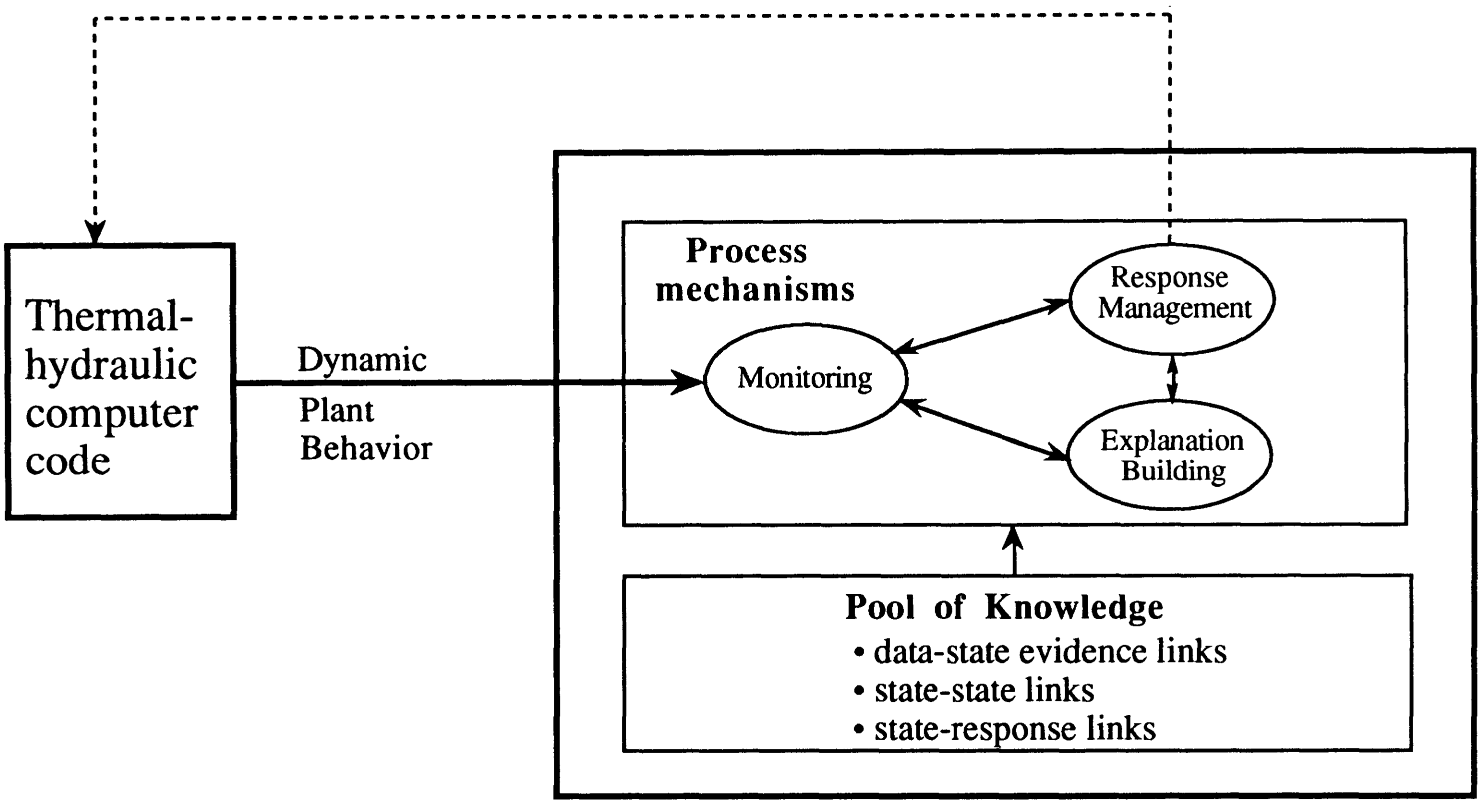

Figure 1.1 - Simplified Flow Diagram for Cognitive Environment Simulation (CES)

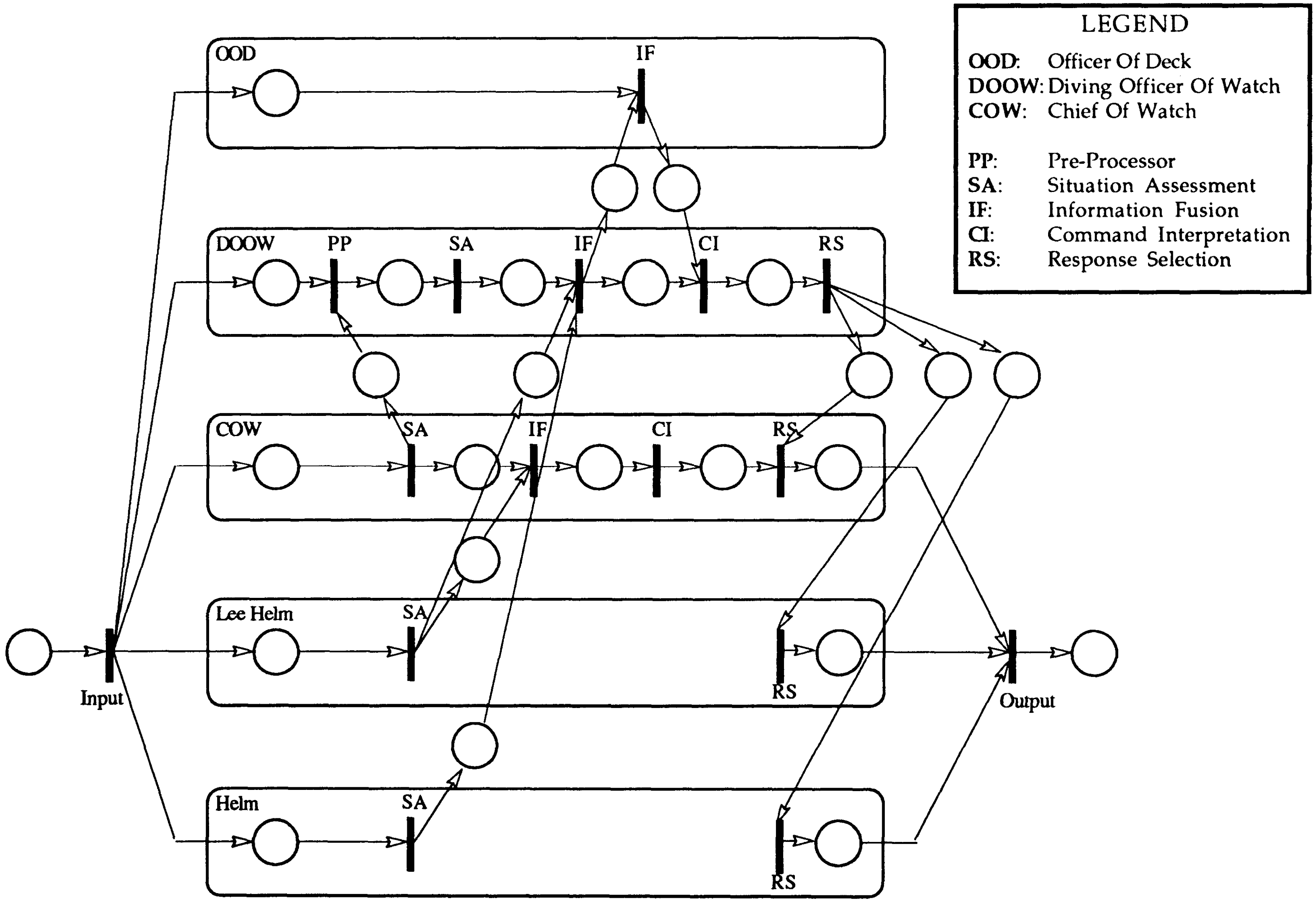

Figure 1.2 - Simplified Flow Diagram for Submarine Crew Model [27]

2. CONTROL ROOM CREW MODEL

An improved model for control room crew behavior must deal with three key issues: a) the dynamic interaction between the crew and the plant, b) the dynamic interaction between operators, and c) the cognitive behavior of the crew members. The crew model whose general features are described in this chapter, is designed to address these issues. Note that the detailed assumptions used to implement the model in the demonstration analysis are presented in Chapter 4.

2.1 Conceptual Approach

Figure 2.1 shows the basic structure of the model. It can be seen that the overall model consists of two submodels: the plant submodel (treating the plant thermal hydraulics and hardware) and the crew submodel, which responds to and interacts with the plant model. The crew submodel itself is divided into modules simulating the cognitive behavior of each individual operator. The plant submodel continuously updates information on plant parameters and alarms shown on the control board displays and receives feedback from these modules to update the plant status. Each individual operator module obtains information from the control board displays and from messages from other individual modules and then generates outputs (control manipulations and messages to other operator modules). Group cognitive behavior (e.g., group decision making) is treated implicitly as the result of coupling the cognitive behavior of each operator module via communication.

It should be noted that Figure 2.1 reflects the crew structure characteristic of a non–U.S. pressurized water reactor (PWR) at the start of an accident scenario. For other plants, or even later times in the scenario, a different crew structure may be appropriate. For example, in addition to the three operators shown in Figure 2.1, a typical U.S. PWR crew usually includes a shift supervisor and a shift technical advisor. Furthermore, later in a severe accident scenario, the control room crew can be assisted by experts in a technical support center. However, because of the modularity of this model, further expansion of the model to accommodate additional operators (perhaps even the local equipment operators working outside of the control room) is conceptually simple.

Similar to other cognitive models for operators (e.g., CES [10]), this crew model explicitly simulates changes in plant physical behavior over time, the cognitive and physical responses of the crew to these changes, and the subsequent response of the plant to the crew actions. This enables the identification and treatment of causal mechanisms for multiple equipment failures associated with operator cognition. Unlike other cognitive models, this crew model also explicitly treats the actions and interactions of the individual operators. Simulation of each operator's actions is a natural approach for dealing with both the time required to perform a series of tasks and the finite manpower resources available during an accident. Treatment of the interactions between operators is important since these interactions can affect individual cognitive behavior.

From a structural standpoint, the modeling approach used to construct this crew model has five inter–related characteristics that are extremely useful when dealing with complex dynamic processes. First, the approach is systems–oriented. Individual model entities are represented in terms of their input, their processing functions, and their output. The dynamic system behavior is the result of the interaction of the individual entities. In this case, the entities are the submodel for the physical plant and the individual operator modules. Second, the modeling approach is object–oriented in the sense that efforts are made to establish a one–to–one correspondence between model entities and physical entities in the real system. This approach sacrifices executional efficiency to some degree, but facilitates model construction and maintenance. Third, the model is modular.

Interactions between and within entities are treated in such a manner that submodels (e.g., for individual decision making) can be replaced relatively easily as long as the same input/output structure is maintained. Fourth, the approach is simulation–oriented. The overall dynamic behavior of the plant/operators system is developed during the course of the analysis as a consequence of built–in rules of behavior for the model entities. Unlike more traditional, analytically–based methodologies for treating dynamic systems (e.g., Markov system analysis), all possible system states and transitions between states need not be explicitly identified prior to the start of computations. This increases the analyst's ability to realistically deal with arbitrarily complex systems. The final characteristic, which makes this modeling approach somewhat different than that employed by other operator cognition models, is that the simulation employs a discrete event simulation framework.

In the discrete event simulation approach [29,30], notices of upcoming events (e.g., random events such as component failures) are generated, sorted by their occurrence times, and stored in a "pending list" (also called the event calendar or master schedule). The simulation clock is then advanced to the occurrence time of the next event in the pending list and that event is executed (e.g., the component is failed). Note that the execution of a given event can inject additional events into the pending list or can lead to the removal of events from the schedule. More generally, the execution of an event can lead to arbitrarily complex changes in the current system state, the pending list, or even in the rules used to model system responses to change; the only limiting factor is the ability of the analyst to encode these changes into the simulation.

Discrete event simulation is often applied in the context of Monte Carlo analysis. Although the simulation of each accident scenario is deterministic, the uncertainties associated with a stochastic process can be quantified by repeated sampling of event occurrence times. In this work, uncertainties are not treated. However, the discrete event simulation framework is employed so that, in future extensions of the work, stochastic and state–of–knowledge uncertainties can be treated in a straightforward manner.

2.2 Model Scope

The modeling structure described above is general enough to handle a wide variety of situations. However, with the addition of each new individual operator module into the analysis, a new knowledge base specific to that operator must be created. Since this work is aimed at demonstrating a new approach for modeling operating crews, a number of assumptions are made to limit the amount of work associated with this and a number of other issues.

- The operating crew consists of three individuals as shown in Figure 2.1: the senior reactor operator (SRO), the reactor operator (RO), and the auxiliary reactor operator (ARO). Other individuals (e.g., plant equipment operators, advisers in the technical support center) are not modeled.

- The emphasis of the individual operator modules is on the simplified modeling of task–related cognitive behavior. Non–task related cognitive behavior (e.g., the evolution of the crew emotional state over time) is treated in a limited manner. General knowledge based behavior for the purpose of fault diagnosis and response management is also treated in a limited manner. The models rely heavily on information collected from observations of actual crews performing steam generator tube rupture training exercises at a non–U.S. pressurized water reactor (see Chapter 3).

- Only task–related communications are modeled. Errors in communication (e.g., garbling, misunderstanding) are not treated.

- The actual actions performed by the operators are modeled only in terms of demands on operator resources and associated delay times. Errors in performing intended actions are not treated.

- Uncertainties in operator or plant behavior due to randomness or lack of knowledge are not treated.

The first, fourth, and fifth bullets deal with limitations that can be readily relaxed in later applications of the crew model. The second and third bullets can be partially addressed using more detailed, accurate models for individual reasoning, such as might be envisioned of future versions of CES. However, significant work on the treatment of emotional, non–task related behaviors (since these can affect task–related reasoning) may be required before the crew model can be confidently applied to all conceivable circumstances.

2.3 Plant Model

As shown in Figure 2.1, plant physical variables are inputs to each individual module and can be changed by the evolution of plant itself and/or by operator manipulation. Although this report emphasizes the treatment of the operators' responses during accident sequences, plant behavior must be treated explicitly to realistically reflect the situations confronted by the operators.

For the purpose of demonstrating the modeling approach, currently available thermal hydraulic codes are too complex; the computing needs of most codes exceed the capabilities of a personal computer, the hardware platform chosen for this study. Therefore, a linear regression model, based on the predictions of a PWR thermal hydraulic simulation code called PRISM [31], is used. The details of this demonstration plant model are provided in Chapter 4, which describes the application of the crew model in an analysis of a steam generator tube rupture accident.

2.4 Individual Modules: Overview and Qualitative Implementation

This section provides an overview of the models underlying the modules for individual operators shown in Figure 2.1. Although the basic structure of the individual model is similar to that of the cognitive models briefly discussed in Section 1.3.1, this model differs from those cognitive models in several aspects. First, a number of limitations in human capabilities (e.g., inability to observe all available information from the control board, inability to execute all necessary tasks simultaneously) are explicitly treated in this model. Second, operator responses to a cue are treated using the notion of "scripts" (discussed later) that can vary from operator to operator. Third, communication between operators and its effect on an individual's behavior is explicitly modeled. Furthermore, the effect of interpersonal relationships on communication are treated. Finally, a number of dynamic processes, such as the buildup of stress and the decay of short term memory are also considered.

As shown in Figure 2.2, an individual model takes input from the plant model (e.g., alarms, physical variables) or from communication (e.g., a command from the SRO). Available information is then processed in subroutines designed to emulate the four task–related cognitive activities: monitoring, situation assessment, planning, and execution. The output from the individual model can be either an action (or a series of actions) that may affect the plant behavior or a message sent to other operators. The detailed information processing mechanism of an individual model and its interactions with the plant model and with other individual models are discussed below.

2.4.1 Task–Related Cognitive Activity

Following the initiation of an accident scenario, the resulting abnormal plant conditions challenge the operating crew with two major problems: What is the root cause? and How can the plant be returned to a safe state? A review of relevant literature indicates that two major, parallel cognitive activities are initiated to respond to these questions. The first question is addressed by a laborious fault diagnosis process, which usually demands detailed logical (knowledge–based) reasoning and a structured understanding of the plant status. The second question is addressed by automatic, trained (rule–based) responses, in which a series of mitigative actions is taken by the crew in reaction to the observed abnormalities. These two major processes can interact with each other during the evolution of the accident scenario. For example, the results generated through the fault diagnosis process may serve to trigger mitigative actions in the same way that an abnormality observed in a plant parameter would. Going in the other direction, the plant behavior triggered by the mitigative actions can provide information to the fault diagnosis process.

It should be noted that the rule–based behavior of the operators is strongly influenced by the available written procedures. In this case, the relevant procedures are the abnormal operating procedures (AOPs), used until reactor trip or safety injection occurs, and the emergency operating procedures (EOPs), used after reactor trip or safety injection. In some plants, the crew members are trained to memorize all the important steps of the AOPs in order to respond quickly to abnormalities in plant status. On the other hand, the EOPs are often followed in a more formal fashion: the Senior Reactor Operator (SRO) finds and reads the appropriate EOP aloud, and the other members of the operating crew follow his instructions[2].

Based on the above discussion, and on a review of a variety of proposed and implemented cognitive models, the following assumptions are employed in modeling the task–related cognitive behavior of an individual operator:

- operators can deal with a limited number of problems in parallel,
- operator intention formation and actions associated with accident management are the result of monitoring, situation assessment, planning, and execution processes,
- decision making within each stage is the result of automatic, heuristic reasoning (i.e., rule–based behavior) or resource intensive, logical reasoning (i.e., knowledge–based behavior),
- these reasoning processes are separate and parallel, and
- most of the decision making within each cognitive process/cognitive activity stage is rule–based.

The first assumption is directly addressed by the discrete event simulation modeling approach adopted, as indicated in Section 2.1. In this approach, only one event (a change

[2]The Charles River Plant has about 30 AOPs and 50 EOPs.

in one or more properties of any entity in the system being modeled) can be executed at one time. However, the cognitive processing and actions taken by an operator in dealing with a given problem typically involve several events. By interlacing the various events associated with different problems on the simulation's pending list (which determines the timing of event executions), parallel processing of these problems can be simulated.

The last assumption follows from the procedure–based response of the operators (described above), the results of a large–scale simulator–data based study for operator reliability modeling [32], observations of crew behavior during training exercises at a non–U.S. PWR (see Chapter 3), and discussions by other researchers interested in cognitive modeling (e.g., [13]).

The implementation of these modeling assumptions is discussed in the following sections.

2.4.1.1 Monitoring Stage

The monitoring stage is used to model the information retrieval process, where the information may be obtained from the plant or from other operators. In the former case, the operator module can acquire information concerning the plant condition actively (e.g., when the module looks for a desired piece of confirmatory information) or passively (e.g., the plant submodel issues an alarm which is noted by the operator module). In the latter case, the operator module can only obtain information passively.

Information can be actively obtained from the plant by "specific monitoring" or "general monitoring." A "specific monitoring process," i.e., a process aimed at gathering specific information, can be activated[3] internally by the operator module itself, when it perceives the need to collect additional information, or externally, when it notices a new alarm[4]. With the exception of alarms, all information on the control board displays is provided passively. In other words, this information is not observed unless the operator module is actively monitoring the control board. On the other hand, because an alarm generates both auditory and visual stimuli (i.e., annunciation and flashing lights) that draws an operator's attention to it, an alarm actively activates an operator module monitoring process. After the alarm has been identified, the operator module may initiate a number of follow–on actions, such as the monitoring of related parameters to confirm the alarm. For example, following recognition of the pressurizer level deviation alarm, the operator module can check the value of the pressurizer level in order to confirm this alarm.

A specific monitoring process can also be activated by an operator module when more information from the plant is required to confirm/support information processing activities or to accomplish operator actions. For example, in real life, when the operator suspects the root cause of an alarm is related to a steam generator problem, his trained response is to monitor the status of the steam generator parameters. This behavior is emulated by the operator module by internal activation of a specific monitoring process.

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[3]In the context of this simulation–based analysis, a process can be viewed as a subroutine that is "activated" (i.e., created and initiated) on demand. The subroutine is designed to perform a particular function. When it has finished executing that function, it is "destroyed" (i.e., cleared from memory).

[4]It is important to note that the various monitoring processes discussed in this section represent actions initiated by the Execution Stage, described in Section 2.4.1.4. The Monitoring Stage covers the execution of these processes, including the filtering of incoming information.

When not engaged in specific monitoring, an operator module can be engaged in "general monitoring." Here, the module scans the control board, paying attention to those parameters that are judged to be important. More specifically, during general monitoring, an operator cannot observe all information available from the control board displays. The possibility of observing a plant parameter is dependent on the importance of this parameter (as perceived by the operator) and the operator's focus of attention. The importance of a plant parameter not only depends on the nature of the parameter but also on the evolution of the accident scenario. For example, in a steam generator tube rupture accident, the pressurizer level is quite important before reactor trip but then becomes less critical after reactor shutdown. The operator's focus of attention is dependent on the evolution of the scenario, and on his defined area of responsibility. For example, one operator may not pay much attention to primary side symptoms (e.g., pressurizer level) if he is primarily responsibile for handling the secondary side of the plant.

Modeling of the operator's limited scope of attention is done by assigning an operator-specific "priority" to each plant parameter and an overall "filter threshold" for each operator. The "priority" represents the importance of the parameter; its assigned value depends on the operator's area of responsibility, focus of attention, his perception of the relative importance of the parameter, and the unexpectedness of the parameter value. The "filter threshold" is used to represent the attention resources of the operator. If the threshold is high, e.g., when the operator is under a high level of stress such that his field of attention has been narrowed, low priority information will not be noticed. This comparison of priorities and filter thresholds operationalizes the concept of dynamic narrowing of the operator's field of attention due to stress or high workload, as discussed in Refs. 10, 12, and 13.

Note that the general monitoring process described above is implemented in the crew model. However, this capability is not exercised in the test application, since this work focuses on crew response to an accident (where the crew, in responding to a variety of cues, employs specific monitoring).

Passive information reception is treated using the same notion of priorities and thresholds. In the case of plant alarms, it is assumed that the priority is sufficiently high such that the alarm is observed regardless of the current level of the operator's filter threshold. In the case of messages from other operators, a message will be received if its perceived importance is greater than the receiver's "message reception threshold." This threshold is a function of the receiver's confidence in the sender, as further discussed in Section 2.5.

2.4.1.2 Situation Assessment Stage

The function of this stage is to generate action plans ("action scripts") in response to the information (observations on plant parameters and received messages) passing through the monitoring stage. When the situation represented by the information is familiar to the operator, responses may be generated automatically, using built-in rules. For unfamiliar situations, more laborious logical reasoning may be required. As shown in Figure 2.2, the function of this stage is represented by four substages: *concern generation*, *concern merge*, *control activity*, and *script selection.*

A "script" is defined as a pre-programmed package of rules used by operators in responding to a specific cue. An operator's scripts include responses learned from both formal and informal training, as well as those required by the written procedures. The notion of a script is a useful concept in modeling the behavior of crews because it reflects the highly trained, procedure-oriented behavior of the crew members. The concept is also useful in modeling a number of error patterns. First, it allows treatment of one form of confirmation bias, where an operator initially chooses a script and follows the script despite mounting evidence that the script is inappropriate. Second, situations where the crew members are on "different pages" can be modeled by having the crew members use different scripts. Similarly, the concept allows the treatment of situations where an operator's expectations for the behavior of his fellow crew members is not met. Observations of crew behavior during training exercises at a non–U.S. PWR indicate that the crew members do indeed follow scripts, even for actions not directly specified by procedures.

The function of the *concern generation* (CG) substage is to decide whether an input should become a "concern," i.e., an issue that must be dealt with by the operating crew. For an observed plant parameter, answers to such questions as Is the status of the parameter expected? or Does the value of the parameter approach or exceed the tolerance limit? are used to determine if a concern should be generated. For example, the input "pressurizer level is decreasing" will become a concern in the early stage of a steam generator tube rupture sequence beacause it is unexpected, but may not do so after the operator has decided that a steam generator tube rupture accident is underway because, in this case, the pressurizer level decrease is expected. As a second example, the AOPs demand that the operators trip the reactor when the pressurizer level approaches 14 percent. Thus, an observed pressurizer level of 20% is more likely than an observed level of 30% to generate the concern "should the reactor be tripped?"

Concerns can also be generated in response to received messages. If the content of a message concerns the status or value of a plant parameter, it will be treated in the same manner as an observed plant parameter. On the other hand, if the message is a command, a suggestion, or a declaration, it automatically becomes a concern. (Of course, such messages can be rejected by the receiver at the Monitoring Stage; in this case, they will not reach the Situation Assessment Stage.)

Each generated concern is assigned a "priority" by the operator to indicate its urgency when handled by subsequent stages or substages. Note that for a message, the receiver may assign a priority different from that given by the sender.

A concern generated by the *concern generation* substage is then sent to the next substage, *concern merge* (CM). The function of this substage is to merge those concerns that are related. Note that the processing represented by this stage can include a mixture of conscious and unconscious activities. Some merging processes are automatic and unconscious (e.g., when merging identical concerns); others may, depending on the training of the operator, may need laborious, conscious logical reasoning. For example, a well–trained operator may immediately recognize that the concerns "pressurizer level is decreasing," "charging flow is increasing," and "primary pressure is decreasing" practically indicate the same issue: "primary inventory is decreasing." On the other hand, a less well–trained operator may need to think about the connection between these concerns.

The *concern merge* substage, which reflects the actual grouping ("chunking") of information unconciously performed by the operator, is a useful modeling element for two reasons. First, the merging process is needed when treating limitations in the short term memory capacity of an operator (discussed further in Section 2.4.2.2). Assuming that the portion of short term memory dedicated to the storage of concerns is of finite volume, a lack of concern merging will lead to an unrealistically rapid overfilling of short term memory. Second, the creation of a single, merged concern (instead of many, related concerns) allows the efficient identification and activation of an associated action script.

Whenever the *concern merge* substage receives a new concern from the *concern generation* substage, it searches for concerns in the "concern list" (the ordered list used to store the concerns) that are related to the new concern. If related concerns are found, then this new concern is merged into an existing concern. Otherwise, the new concern will be filed in the concern list. It is assumed that the priority of an existing concern in the concern list will be increased as more (new) concerns are merged into it.

Prioritization of tasks to be executed (i.e., scheduling) is a common human cognitive activity. This is because each operator has limited processing resources and many activities are competing for these resources. Ref. 2 states that "resource competition implies that there is some agenda of processing items that could be chosen to be carried out next and a method for selecting among those competing items." The concern list is a queue ordered by priority (as assigned by the operator) that provides the first agenda for activity selection and execution. Note that the priority of a concern can change dynamically. Note also that the concern list performs, in a more limited manner, the same function as the pending list used by the entire crew simulation. The concern with the highest priority is the first concern retrieved from the list and processed.

Whenever the contents of the concern list are changed, either by the addition of a new concern or by modification of the priority of any concern already on the list, it must be decided if the most important concern in the list must be processed immediately or if the current ongoing action should be completed. Thus, the priority of the most important concern in the list is compared with that of the ongoing action being executed by the Execution Stage (see Figure 2.2 and Section 2.4.1.4). If the priority of the concern is higher, the action is interrupted and the concern is processed simultaneously by both of the next two substages (*control activity* and *script selection*) of the Situation Assessment stage. Otherwise, treatment of the concern will be delayed until the ongoing action is finished.

The *control activity* (CA) substage is used to represent fault diagnosis, the use of logical reasoning to find the root cause of the accident scenario. This substage needs information from the operator's knowledge base and the concern list. The knowledge base provides structured knowledge about the plant for logical reasoning. In this work, a set of simple, relatively high level production rules is used to represent the knowledge base. These rules often take the form

$$\{A_1 \text{ AND } A_2\} \rightarrow B$$

Here, A_1 represents an initial condition, A_2 represents any corresponding evidence, and B is the conclusion.

In the *control activity* substage, the concern is first compared with the production rules to see whether it appears as an initial condition (A_1) in the left hand side ("activator statement") of any production rules. If no match is found, then the control activity is terminated. If a match is found, the next step is to search for the corresponding evidence (A_2) in the concern list. If this is not found, the operator may passively wait (cycling the *control activity* substage) for the arrival of A_2 or actively generate a new concern to collect the necessary information. The newly generated concern, is provided as input to the *concern merge* substage.

In parallel with the logic–based *control activity* substage processing described above, the *script selection* (SS) substage performs the rule–based processing used to determine which script should be followed by the operator. The script is chosen to match the concern being processed. Different operators may have different scripts responding to the same concern. Based on the script, one or more "actions" are generated and filed in the "action list" for further processing.

2.4.1.3 Planning Stage

The Planning Stage receives actions generated by the *script selection* substage in the Situation Assessment Stage, and orders these actions according to their priorities for execution. As mentioned in the previous section, the prioritization of tasks to be executed is a common cognitive activity performed because of limited processing resources. The "action list" is the second prioritized queue proposed by this model to deal with the competition for resources among processing activities.

The actions waiting to be executed are temporarily stored in the action list. Like the concern list, whenever the contents of the action list have been changed either by the addition of a new action or by modification of the priority of any action already on the list, a competition for available resources begins. The priority of the most important (highest priority) action waiting in the list is compared with that of the currently executing action. If the priority of the waiting action is higher than that of the ongoing action, the ongoing action will be interrupted; otherwise, the waiting action will be delayed until the ongoing action is completed. If the ongoing action is interrupted, the waiting action will then become the ongoing action and the previously ongoing action will be filed back on the action list. Note that although the internal scheduling of actions is done by the Planning Stage, there are some externally generated actions that can bypass the Planning Stage and interrupt his current task. The operator's response to an alarm is one of these externally generated actions.

As mentioned in Section 2.4.1.1, an alarm generates both auditory and visual signals for the operator. Due to the salience and unexpectedness of an alarm, it is quite possible that the operator's ongoing action will be interrupted. To treat these situations, it is assumed that an alarm will always interrupt the ongoing action and lead to the activation of a monitoring process. This treatment bypasses the usual Situation Assessment Stage; an alarm generates a monitoring action directly, assigns this action the highest priority, and files it in the action list. Thus, an alarm forces the Planning Stage to deal with the alarm immediately.

After the activation of the alarm–activated monitoring process, the operator returns to his "regular" routine, as specified by the concern and action lists. Note that although the alarm monitoring action has the highest priority, the concern related to the alarm does not always have a high priority. For example, in a steam generator tube rupture accident, a safety injection actuation (SI) alarm after reactor trip will immediately attract the operator's attention. However, following acknowledgment of this alarm, no further concerns or actions will be generated because the operator expects the alarm in this accident scenario.

2.4.1.4 Execution Stage

An operator module interacts with the plant submodel and other operator modules in three ways. First, it can obtain information from the control board displays or from other operator modules. Second, it can change the plant behavior by manipulating control switches. Third, it can change the internal status (e.g., state of knowledge) of other operator modules by sending them messages.

The highest priority action in the action list is executed by the Execution Stage. As indicated above, actions can be categorized into three classes: monitoring, manipulation, message exchange, and expected message generation. Specific and general monitoring are performed as discussed in Section 2.4.1.1. Control switch manipulation is handled in a straightforward manner; after an assumed delay time, the position of the switch (which affects the predictions of the plant physical model) is changed. A message exchange is often associated with an action in one of the other two classes. For example, in responding to a steam generator tube rupture accident, an operator may be required to start a second charging pump (a manipulation action). In this case, his training requires that he initiate a message exchange with his superior to report the current status of the pump. Such a connected group of actions (a script) is treated as a single action in the Planning and Execution Stages. Note that a message exchange can also stand alone as an action. The execution of message exchanges is discussed further in Section 2.5. The last action category, expected message generation, is used to treat the fact that interactions between operators are not isolated events, but are rather parts of a continuing process that evolves over time.

After an operator executes an action, he may expect to receive some related messages from other operators. In one case, a superior may expect a response from his subordinate after he has issued a command to that subordinate. For example, the subordinate might report on the status of the equipment affected by the command. If the expected response is not received by the superior within a certain time, the superior is very likely to repeat the command. Similarly, if a subordinate makes a suggestion to his superior, he may expect a response from his superior. For example, when a subordinate observes and reports that the pressurizer level is decreasing, he may expect that the senior reactor operator will issue a command aimed at controlling this decrease in level. If this command is not received in a certain amount of time, the subordinate may make a suggestion related to the expected command.

This model deals with the message/response process by generating (within the mind of the original sender) expected messages. These expected messages are stored in a specific portion of short term memory (the "expected message set") until the characteristic delay time associated with the expected message has elapsed. The delay time is dependent on the urgency of the expected message and also on individual and group characteristics (e.g., the relative status of the sender and receiver). If this delay time elapses without a response from the receiver that matches the expected message, an intention to send a repeat message to the non–responding receiver is filed in the action list. This intention is then scheduled and executed in the same manner as all other actions. Of course, if the expected message is received before the delay time elapses, there is no need to issue a repeat message.

After the execution of an action, the operator module rearranges the contents of the concern and action list, and picks the first action in the action list for execution.

2.4.2 Memory

In order to perform the cognitive activities demanded by a problem or a task, the operator needs to retrieve knowledge from his memory. The memory representation used in this study is a simplified structure intended to emulate the human memory system; it is not intended to literally reflect how knowledge is actually stored in or retrieved from different parts of the memory system.

2.4.2.1 Knowledge Base (Long–Term Memory)

Studies in neuropsychology suggest that two major groupings of knowledge exist. These normally interacting groupings are the long–term and short–term memory systems [33]. The major differences between these two memory systems are their capacities and surviving intervals. The short–term memory system usually has a small capacity and may decay quickly with time while the long–term memory system has a large capacity and is relatively permanent. In this study, the stable long–term memory system is modeled using the "knowledge base," a concept commonly used by the cognitive models discussed in Chapter 1. The implementation of short–term memory is discussed in the next subsection.

In this study, the knowledge base of an individual operator module contains three major sets of information: a set of scripts, a set of production rules used during fault diagnosis, and a set of parameters representing the group (crew) characteristics. As mentioned earlier, scripts are used to represent the automatic, trained responses of operators to dynamic changes in plant status. The scripts include responses learned during formal and informal training, as well as those required by the written procedures. The degree to which they depend on the written procedures depends on the phase of the accident to which the operator is responding.

Prior to reactor trip, the operators may be working on the basis of memorized procedures (the abnormal operating procedures, or AOPs). Actions that are strongly related to each other and can be envisioned as an integrated action are treated as being part of the same script. To illustrate this, operator actions in starting a second charging pump and the subsequent monitoring of pump status and charging flow rate are included in the same script since they are parts of an integrated action. Note that the content of a script, which relates to a specific concern, may be different for different operators due to variations in experience, skill, operational style, etc. This is further discussed in Chapter 4.

After reactor trip, crew responses become much more formalized, and less variability in responses can be observed. Here, a step, or a group of related steps in the applied written emergency operating procedures (EOPs) are treated as a single script.

The second part of the knowledge base, the set of production rules, encode the operator's knowledge of the plant related to the fault diagnosis process. These rules represent a multitude of (perceived) facts stored in memory, including facts concerning the plant operating history and current plant status. Because they also represent the relationships between facts, they also implicitly model individual reasoning styles (e.g., the tendency to jump to conclusions). This work employs a simplified set of production rules. However, the modularity of the modeling framework adopted allows the use of a more sophisticated model of logical reasoning when such a model becomes available.

The third part of the knowledge base contains information on the parameters governing the interaction between operators. Since these parameters may change as the scenario evolves, only their initial values are stored in the operator's knowledge base. The dynamic values are stored in the short–term memory. Note that this modeling is based on the previously mentioned hypothesis that one's knowledge base and short–term memory can interact with each other.

2.4.2.2 Short–Term Memory

During an accident sequence, an operator may receive a considerable amount of information from the plant and from other operators. Due to the limitations of his cognitive resources, he cannot process all this information immediately. The concern and action lists mentioned in Section 2.4.1 are thus necessary to provide a temporary storage area for information that is waiting for further processing. This storage area is part of an operator's "short–term memory" and is distinct from long–term memory, where static and permanent knowledge is stored.

In this work, an operating module's short–term memory stores results generated by the four stages of task–related cognitive activities discussed in Section 2.4.1 (monitoring, situation assessment, planning, execution). These results include the observed status of plant parameters (from monitoring), and expected plant behavior (from situation assessment or from execution). Short–term memory is also used to store the dynamic values of parameters characterizing group interactions (e.g., an operator's confidence in each of his fellow crew members).

As mentioned earlier, an operator's short–term memory is of limited capacity. Furthermore, its contents can decay over time. Regarding the limitation on capacity, a number of experimental studies have derived a "magic number," the maximum number of items that a person can remember [34]. Ref. 34 obtains an empirical value of 7 (±2) items that can be remembered; this is used in the base case analysis (described in Chapter 4) when modeling the limited capacity of short–term memory. (Sensitivity studies investigating the importance of this value are described in Chapter 5.) Note that although they are stored in short term memory, such items as the current values of plant parameters and expectations on future plant behavior, can be observed or directly inferred from the control board displays. For example, after a charging pump has been started, the status light of the pump, which indicates that it is running, will remind the operator that primary inventory should increase. Therefore these items are not treated as being restricted by the size of short term memory.

In summary, only the number of items stored in the concern and action lists is limited; the base case analysis assumes that each list can hold a maximum of 7 items (concerns or actions). Items not high enough in priority to be placed in the top 7 of each list are dropped (forgotten).

In addition to being dropped due to the limited capacity of short–term memory, an item stored in the concern and action lists can be forgotten due to memory decay. It is assumed that the priority of an item will determine the time at which it is removed from its list. (In a stochastic model, the priority will affect the time–dependent probability of removal.) The detailed implementation of these issues will be presented in Chapter 4. The effect of other factors (e.g., stress level and workload) on short term memory size and decay are discussed in the following section.

2.4.3 Non–Task Related Activity: Stress

In addition to the task–related cognitive activities discussed in the previous sections, this model employs a simple treatmment of non–task related issues, since these can affect individual and group behaviors. In particular, a study on small group efficiency characterizes human behavior during group interactions using three dimensions: dominance vs. submissiveness, task–orientation vs. emotionality, and positivity vs. negativity [35]. The model used in this study adopts the concept of "stress" to explicitly treat the second dimension, and to cover the other two dimensions to a lesser degree.

The term "stress" has been defined in many ways that overlap in practice but are not identical [36]. Ref. 37 defines stress as "the non–specific responses of the body to any demands." Based on this definition, stress occurs when there is a substantial imbalance between environmental demands and the response capability of the individual. For the scope of this study, interest is focused on what conditions contribute to the buildup of stress and on how stress affects human responses in nuclear power plant accident scenarios.

2.4.3.1 Sources of Stress

The THERP model, commonly used to analyze human reliability in nuclear power plant risk assessment studies, defines two categories of stressors relevant to nuclear power plant emergency operations: psychological and physiological stressors [6]. The stressors are defined as "any external or internal forces that cause bodily or mental tension" [6]. The psychological stressors include surprise (unexpectedness), task load and speed, and inconsistent cueing; the physiological stressors consider the individual's physical condition – fatigue, discomfort, vibration. Thus, Ref. 6 considers stress either produced through reactions to the task environment (i.e., to changes in plant behavior) or due to the operator's physical condition. Note that, as mentioned in the previous sections, during an accident scenario, an operator interacts not only with the plant but also with other operators. In a crew model, therefore, the possibility that group interactions can induce stress on an operator should also be considered.

In this analysis, it is assumed that the stress on an individual consists of three components: "burden" stress from workload, "frustration" stress (related to confusion) from unsuccessful fault diagnosis, and "irritation" stress from group interactions (i.e., other members' messages). Furthermore, the sensitivity to each of these sources of stress (stressors) as well as the effects of stress on the operator's behavior varies from individual to individual. This classification is not intended to represent a specific psychological viewpoint; rather it provides a simplified but reasonable way to describe and quantify stress and its effects.

The burden stress component represents two psychological stressors identified by Ref. 6: "unexpectedness" and "task load and speed." As mentioned in Section 2.4.1.1, the unexpectedness of a plant parameter – its deviation from the operator's expectation for its behavior – will increase its probability of passing the operator's filter threshold and becoming a concern. Hence, the length of the concern list is related to unexpectedness through the number of plant parameters or phenomena that have become concerns. The length of the action list is related to the task load and speed. Therefore, the burden stress grows with the total length of these two lists.

The stressors "inconsistent cueing" (or confusion) can be best described as the difficulty an operator has in trying to understand why the plant behaves in a specific (but abnormal) way. In this model, the logical reasoning processes are simulated in the *control activity* (CA) substage of the Situation Assessment Stage. It seems plausible to assume that the degree of confusion or frustration is proportional to the time an operator spends diagnosing the root cause. Inconsistent cues (evidence) will generally cause an operator to spend more time in situation assessment and will therefore increase the frustration stress component.

The third stress component, "irritation" stress, results from interactions with the other operators. Messages from other crew members may irritate an operator, especially when the operator does not agree with the content of the message or when the operator perceives that the message "tone" is inappropriate. For example, when a subordinate suggests an action to his superior but is then denied, he may be irritated from the rejection. The superior may also be irritated when the suggestion made by a subordinate is made in an insubordinate manner.

Of course, different individuals may respond differently to sources of stress; one may be sensitive to certain sources but insensitive to others. The literature on stress notes that some individuals may be able to perform effectively under stressful situations that far exceed the capabilities of others, because of training, experience, conditioning, support, or other factors [38]. To reflect this fact, each operator is assigned different sensitivities to both the accumulation of stress and in responding to the accumulated stress.

This analysis does not treat physiological stressors explicitly. In principle, these stressors can contribute to an individual operator's initial stress and can affect his sensitivity to stress. For example, an operator who is fatigued before the start of the sequence may be more sensitive to stress buildup. However, from the standpoint of this model, these considerations only affect initial parameter assignments. Moreover, the accumulation of stress from physiological stressors during the sequence is not judged to be significant due to the relatively short time span of the scenario treated in this study. Thus, the effects of the physiological stressors can be considered to be treated in the parametric sensitivity studies discussed in Chapter 6.

The quantitative implementation of these concepts, including the assignment of stress sensitivity and the impact on an individual's stress level due to specific operator–plant and operator–operator interactions, are further discussed in Chapter 4.

2.4.3.2 Effects of Stress on Individual Behavior

The traditional view of stress links stress to arousal. Arousal is a concept that is related to non–specific changes in the body such as hormone secretion and brain activity due to external stimulation. Stress increases arousal. The well–known Yerkes–Dodson law relates performance and arousal [39]. This inverted U–shaped function, shown in Figure 2.3, is regarded as one of the stronger and most replicated findings in stress research [40]. Stress always causes qualitative differences in a person's ability to allocate attention to environmental cues. In a simple situation with few cues, stress will improve performance by causing attention to be focused. In a complex situation with many cues, performance will decrease due to overload or anxiety – many cues will go unattended.

During normal plant operation, while the automatic systems are functioning normally, there is little for the operator to do aside from monitoring the systems. However, when abnormal situations occur (e.g., an alarm goes on), the operators must react quickly, often within minutes, to return the plant to a desired state. Thus, an operator's job requires him to alternate between two situations: a steady state where the information load is insufficient to keep him aroused, and an emergency where his actions may be critical and the information load may be excessive. Ref. 39 states that the effect of overload on human behavior is performance degradation, especially in tasks that require selection and execution of responses, like those demanded in nuclear power plant emergency operation.

In this work, three plausible assumptions are made in applying the Yerkes–Dodson law in the evaluation of the effects of stress on operator performance during accident scenarios. First, due to the potentially severe consequences of an accident sequence (e.g., core melt) and to the high workload demands in mitigating the abnormal conditions, it is assumed that stress has no "positive" effects on performance. This assumption implies that an operator's stress level is always greater than the optimum level shown in Figure 2.3.

The second assumption is that stress not only affects the accuracy but also the speed of executing a task. This is because stress can also be envisioned as an interruption to the individual's current task [36]. Individuals have to pay some attention to remove the stress–induced interruption; hence the pace of the current task is reduced.

Finally, it is also assumed that the stress level will affect the individual operator in interactions with both the plant and the other operators. The qualitative effects of stress on each of the four task–related cognitive activity stages (Monitoring, Situation Assessment, Planning, and Execution) are discussed below. The detailed implementation is described in Chapter 4.

The narrowing effect of an operator's field of attention due to stress has been recognized by many researchers interested in modeling operator behavior during an accident (e.g., see Section 1.3.1). Studies on stress have concluded that stress reduces attention capacity and focuses it on the central task [36]. In the Monitoring Stage of our crew model, whether a plant parameter will be observed by an operator is determined by the priority of this parameter and the operator's filter threshold. To simulate the narrowing of the operator's field of attention under stress, the filter threshold is assumed to increase with the stress level.

In the Situation Assessment Stage, the generation of concerns and the selection of related scripts are considered automatic and unconscious. Stress is assumed to have no effect on this low–level cognitive behavior. On the other hand, the situation is quite different when the operator is performing fault diagnosis, a high–level cognitive activity. Under stressful situations, the time that an operator spends in searching for evidence in the concern list is assumed to increase. This increase is treated by modeling the actual elapsed fault diagnosis time as the product of a nominal search time and a multiplicative time factor. The time factor increases with increases in stress level. Note that the increased time spent in the *control activity* substage will increase the frustration stress component incrementally; thus, there is a positive feedback loop in this model.

The effect of stress on the time an operator spends on an executional task (e.g., manipulation of controls) is modeled in the same manner. The concepts of a nominal time and a time factor are also applied in computing the task execution time. Unlike fault diagnosis, however, the increased execution time is assumed to have no direct feedback effect on stress.

As mentioned earlier, short–term memory has limited capacity and its contents may decay with time. Some experimental studies have found that any kind of stress will impair short–term memory retrieval [36]. To model this impairment, the decay time of items in short–term memory, i.e., the time an item resides in short–term memory before being forgotten, is assumed to decrease with stress. Thus, increases in stress level increase the possibility of forgetting an item in short–term memory. Recall that, as discussed in Section 2.4.2.2, the assigned priority of an item also affects the item's decay time. Thus, this model treats the finding that, in stressful situations, humans generally tend to remember items perceived to be more important [36].

In addition to the effects on individual behavior described above, the current stress level affects group interactions. For example, it affects an operator's willingness to send out or receive a message. This is further discussed in the next section.

2.5 Interactions Between Operators

One of the objectives of this study is to explicitly model operating crew behavior during an accident scenario. The approach adopted, discussed in Section 2.1, treats crew behavior as the result of individual behaviors (discussed in Section 2.4) linked by task–related and non–task related communications between individuals.

In this approach, the individual behaviors define the behavior of the group. However, it is also recognized that the characteristics of the group have an impact on the behavior of the individual group members [17,24]. For example, theoretical and experimental studies suggest that certain group characteristics (e.g., a group member's confidence in his colleagues) affect the willingness of individual members to communicate. Studies of civil aviation accidents have shown that some accidents could have been prevented if crew members who possessed adequate information had provided it to others [14]. The discussions in the following sections cover the impact of group characteristics on task–related and non–task related communications, and how the group characteristics can be changed by the group interactions.

2.5.1 Task–Related Communication

Due to the partitioning of responsibilities during an emergency operation, each control room operator needs support from other crew members to acquire information regarding the plant status and to accomplish the demanded tasks. For example, suppose the senior reactor operator (SRO), who is officially in charge of plant or unit operation and hence is the authorized decision–maker, may decide to start a charging pump at a certain point in a sequence. To accomplish this task, the SRO has to issue a command to his subordinates, who have direct access to the relevant control switches. The pump startup task can be considered accomplished only after the SRO's command has been fully understood and successfully executed by the subordinates, and the appropriate feedback has been received by the SRO. Therefore, this task can be viewed as unsuccessful when any one of the following situations occurs: the SRO does not send out the command, the subordinates do not receive, understand, or execute the command, or the SRO does not receive the appropriate feedback. More generally, a failure of communication occurs when:

- the sender does not send out the message,
- the content of the message is distorted by the medium or by the receiver,
- the message is rejected by the receiver, or
- the sender does not receive appropriate feedback

This work treats the first, third, and fourth bullets; the second bullet is not treated, but can be handled within the framework of the existing model.

Regarding the first bullet, it is possible that a sender may override an original intention to send a message. This situation usually occurs when a message is perceived by the sender to be unimportant or when the sender is reluctant to initiate the communication. Studies of civil aviation accidents have shown that subordinates in a cockpit crew aware of relevant information have sometimes, for some reason, not provided this information. Ref. 14 concludes that these situations are possibly caused by the low status of the subordinates, the atmosphere created by a highly dictatorial superior, and/or extreme interpersonal relationships between crew members.

To model this mode of communication failure, it is proposed that a sender's willingness to send information to a specific receiver is related to the importance of the information (perceived by the sender) and the interpersonal relationship between them. The two parameters used to model this interpersonal relationship are the sender's self–confidence and his confidence in the receiver. The sender's self–confidence is defined as his confidence in his own capability for properly executing the tasks in his responsibility area. The sender's confidence in another crew member is defined as his confidence in the other's capability for properly executing demanded tasks and his perception of the other's trustworthiness. The operationalization of these confidence measures, and the numerical criterion used to determine if the sender does indeed send the message, is discussed in Chapter 4.

Note that this study also considers the possibility of time delays in message sending when the receiver is perceived by the sender to be occupied. For example, when a sender is ready to send a message but observes that the receiver is communicating with another operator, he will wait until the receiver has finished that communication before sending his message.

Due to the high–noise environment in the control room during an emergency operation (caused by the repeated annunciation of alarms), a message may be distorted during communication. Misinterpretation of a message by a receiver is also possible (perhaps due to high workload or inexperience). However, message garbling is not included in the scope of this study for the following reasons. First, the operators are required by training to repeat commands before executing the commanded tasks. Furthermore, the sender usually has direct visual access to the task area and will double–check the execution of the command, especially if the action is critical. As a result, the recovery of misinterpreted messages is highly probable. A second motivation for not treating message garbling within the scope of this study is that modeling its consequences (e.g., the particular way a message is distorted) is extremely difficult. Additional work is required to determine if this omission is significant.

Although it is assumed that messages are received without distortion, it is not assumed that all messages will be accepted. A message is rejected when the receiver decides to ignore its content. To model the possible rejection of a message by an operator, an approach similar to that mentioned in modeling a sender's willingness to send out a message is used. Whether or not a message will be accepted by the receiver is a function of the importance of the message, as perceived by the receiver, and of the receiver's confidence in the sender. The numerical operationalization of this concept is presented in Chapter 4. Once a message is accepted by the receiver, it is treated as a concern and its effects on individual behavior are then handled by the processing mechanism of the individual module for the receiver. (This includes the issuance of a response to the sender; here, the receiver of the original message now becomes a sender.)

As mentioned in Section 2.4.3.2, it is assumed that stress will affect the possibility of sending and receiving messages. This is operationalized by increasing the threshold values for message sending and receiving (discussed in Chapter 4) with increasing stress.

2.5.2 Non–Task Related Communication

The task–related communications discussed above are verbal and informational. Verbal, non–informational messages and non–verbal, non–informational messages can also be important. As an example of the former class, emotional messages, e.g., "shut up!" or "watch your own area," can be sent when an operator is under high stress. Such messages have been noted in civil aviation accident studies [14]. As an example of the latter class, facial expressions or body language of a senior operator under high stress could affect the behavior of his subordinates[5].

Without a general model for the emotional behavior of an individual (analogous to the artificial–intelligence inspired model for cognitive behavior used in this work), it is difficult to predict when and how an emotional message will be issued, or how this message will affect the behavior of the other operators. In this study, a highly simplified approach is used to handle the effects of negative emotional messages and non–verbal

[5]Non–verbal, informational messages are also possible (e.g., when an operator points to an indication to alert others) but can probably be treated within the framework of verbal, informational messages.

communication. (Positive messages can, in principle, be treated within the same framework. However, this is not done in this work.)

In this approach, a "tone" is assigned to each emitted message to represent the degree of stress verbally communicated, or shown, by the sender. The extent to which the receiver is affected is dependent on how sensitive he is to the tone of the message. If he is sensitive, it is assumed that his stress level will increase when the message is received. Note that if all operators in a crew are sensitive to the (negative) tone of each others' messages, increases in stress levels can rapidly propagate (there is a positive feedback mechanism). Further, one of the consequences of the quick buildup of stress levels is that the values of the thresholds for sending out and accepting messages will increase. In this manner, a breakdown in communication between operators due to a dynamic increase in stress can be modeled.

2.6 Summary

The modeling approach for treating the behavior of control room crews during accident scenarios treats each operator as a separate, reasoning entity. The behavior of the crew as a whole is simulated as the result of individual behaviors, the interactions between individuals through communication (verbal and non–verbal), and the interactions between the crew members and the plant.

Individual task–related behavior is treated using four cognitive stages: Monitoring, Situation Assessment, Planning, and Execution. Both short–term and long–term memory are used to support cognitive processing. Like other cognitive models (e.g., CES [10]), this model can treat operator limitations in cognitive processing by providing a less than complete, or even an incorrect, knowledge base (long–term memory). This model also incorporates operator limitations as part of the basic process model. Filter thresholds restricting the passage of information are used to model the operator's limited attentional resources; limitations in the size of key lists stored in short term memory (the concern and action lists) are used to model the finite size of short term memory; the requirement that an operator only deal with one concern/action at a time models limited attentional and processing resources; the use of scripts represents the operator's trained patterns of responses (which, for some complex scenarios, may not be correct).

Non–task related behavior is treated using a simple model for stress. It is assumed that the level of stress is a dynamic function of workload, the degree of success in diagnosing the scenario, and crew interactions. Increased stress is assumed to narrow the operator's field of attention, increase the time spent required in various diagnosis and executional tasks, and reduce the lifetime of items stored in short–term memory.

Interaction between individuals is treated as being the result of communication. The sending and receiving of verbal, informational messages is simulated explicitly. Negative messages of alternate forms (e.g., non–verbal, non–informational) are treated by assigning a (negative) tone to verbal, informational messages. Communication is affected by the importance of the message and a number of group characteristics: the self–confidence of the sender, the sender's confidence in the receiver, and the receiver's confidence in the sender. (Other group characteristics, such as the distribution of role and status within the group, are treated implicitly by the knowledge base, e.g., the scripts, assigned to each operator.) Note that individual stress can also affect crew interactions, since it can affect the tone of a message, irritate the receiving crew member, raise thresholds for sending and receiving messages, and therefore tend to restrict communications.

The simulation modeling framework employed is systems–oriented, object–oriented, and modular. This is a natural framework for dealing with complex, dynamic, processes involving multiple entitities. Moreover, it can be modified relatively easily to incorporate improved psychological and physical models, and to treat uncertainties in these models. This framework, because it clearly defines needed inputs and outputs, also provides structure for the collection of operator performance data. The data for this analysis are discussed in the next chapter.

Table 2.1 - Summary Characteristics of Crew Model (Page 1 of 3)

Internal Cognitive Processing	
Multiple-Stage Task-Related Processing	Treats monitoring, situation assessment, planning, and execution.
Dominance of Scripted Behavior	Treats most behavior as scripted. Scripts based on training, procedures.
Resource Intensive Logical Reasoning	Emulates logical reasoning process using high level production rules.
Parallel Problem Solving	Allows operators to be aware of multiple problems.
Memory Types	Distinguishes between short-term and long-term memory.
Limitations in Cognitive Processing	
Limited Attentional Resources	Operator does not receive all information sent (either from the plant or from other operators). Message reception depends on perceived importance of information, current focus of attention, relative confidence in sender (in the case of communication).
Limited Processing Resources	Operator can only work on one concern/action at a time. Order of processing depends on internal prioritization.
Use of Heuristics	Modeled implicitly by the scripts and production rules included in the knowledge base (long-term memory).
Processing Delays	Treats time required to process information.
Limited Short-Term Memory	Lists storing operator concerns and planned actions are limited in length. Items not high enough in priority to be retained are dropped (forgotten); important items can also be forgotten.

Table 2.1 - Summary Characteristics of Crew Model (Page 2 of 3)

Non-Task Related Behavior	
Stress	Assumed to change dynamically with workload, failure to diagnosis situation, irritation from negative interactions with other crew members. Affects field of attention, time spent in tasks, lifetime of items in short term memory. Also affects thresholds that govern communication.
Crew Interactions (Communication)	
Group Behavior, Group Decision Making	Treated as result of individual behaviors (e.g., information processing) linked by communication.
Verbal, Task-Related Communication	Simulated explicitly. Commands and suggestions are distinguished from other forms (e.g., announcement of plant status).
Non-Verbal and Non-Task Related Communication	Negative forms treated by attaching a negative tone to informational messages. This tone can add to the irritation stress felt by the receiver.
Message Filtering	Decisions to send/receive messages depend on perceived importance of message, operator self-confidence, confidence in receiver/sender, stress levels of sender/receiver, preoccupation of receiver.
Process Treatment	Treats message sending/receiving as parts of a larger process (rather than independent events). The sender may expect a certain response from the receiver; if the response is not obtained in time, the sender may choose to send his message again.

Table 2.1 - Summary Characteristics of Crew Model (Page 3 of 3)

Execution of Actions	
Execution	Not simulated explicitly. Assumes that planned actions (e.g., control switch manipulation) are correctly executed (slips are not treated).
Side Effects	Time delays in performing actions, preoccupation of operators performing actions are modeled explicitly.
Modeling Framework	
Systems Oriented	Focuses on establishing correct input/output relationships for model entities.
Object Oriented	Maintains, when possible, a one-to-one relationship between model entities and real entities.
Modular	Allows expansion to accommodate additional operators, modification to incorporate improved psychological models.
Simulation-Oriented	System behavior over time develops implicitly as the consequence of operator-operator and operator-plant interactions (which are governed by built-in rules).
Discrete Event Simulation	Synchronizes parallel, interacting processes using master calendar; encourages object-oriented modular modeling. Provides natural framework for treating uncertainties.

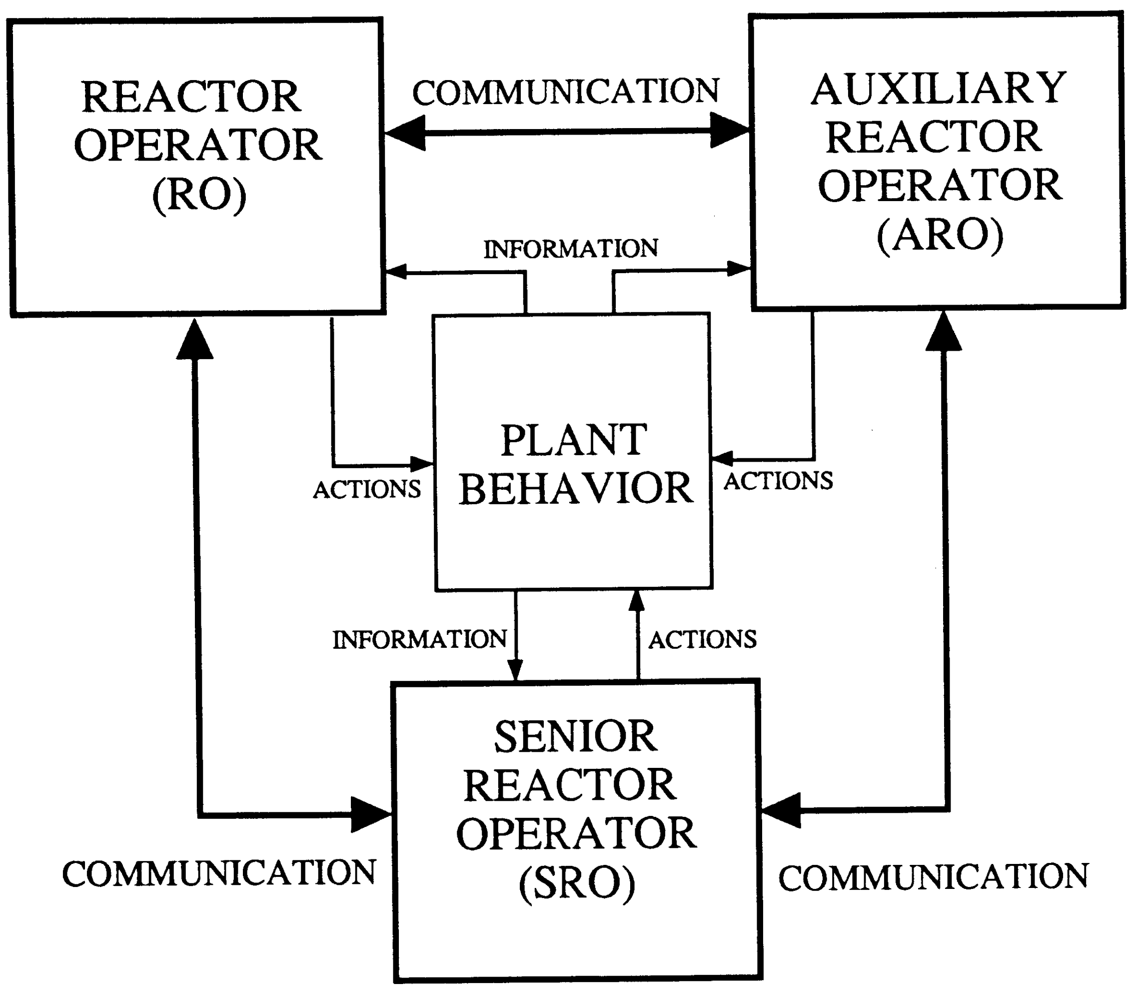

Figure 2.1 - Conceptual Model for Control Room Crew

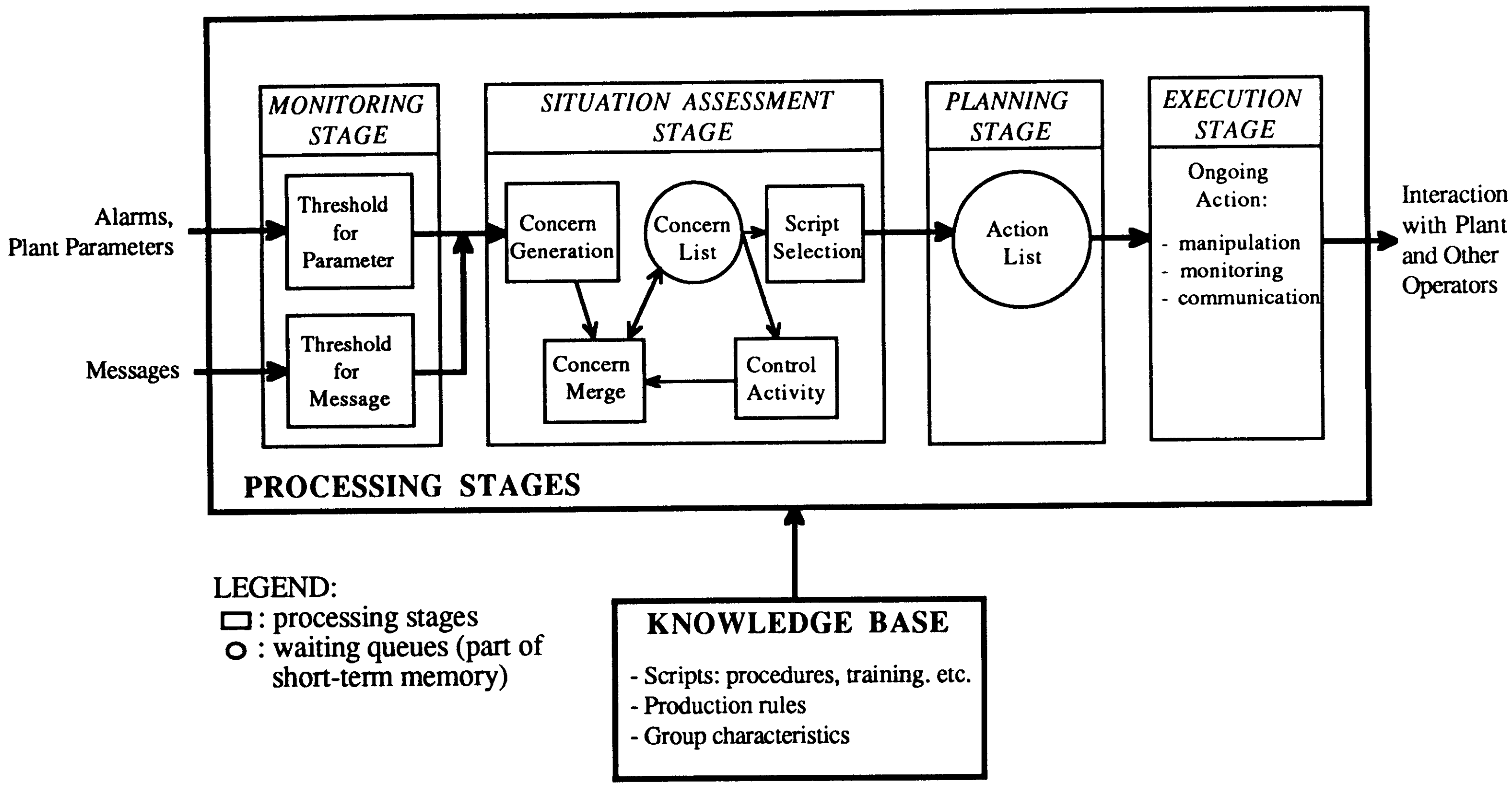

Figure 2.2 - Conceptual Modeling Framework for Individual Operator

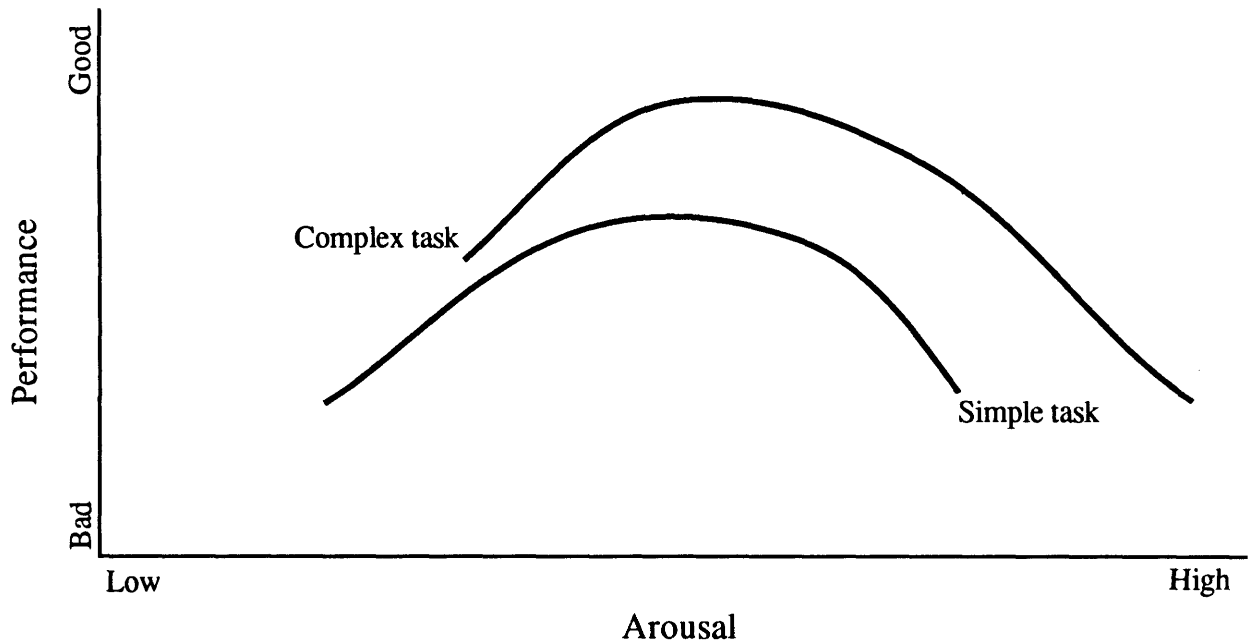

Figure 2.3 - The Yerkes-Dodson Law Relating Performance and Arousal [38]

3. DATA COLLECTION AND ANALYSIS

3.1 Introduction

Chapter 2 provides the basic framework developed in this work to model crew behavior during accident sequences. This chapter covers key data used to implement the model in an analysis of pressurized water reactor (PWR) steam generator tube rupture (SGTR) accidents. (The actual model implementation for SGTR is discussed in Chapter 4.) It also describes the process used to collect data, since this may prove useful in future studies.

The SGTR accident is chosen as a case study for a number of reasons. First, it can involve considerable interaction between the operators and the plant, and therefore is a natural situation for testing a dynamic analysis tool. Second, it can be an important contributor to early fatality risk, since it can lead to both a core melt and a direct release of radioactivity to the atmosphere (bypassing containment). Third, various forms of information on the scenario are available, including reports of actual events, a fast PC–based PWR simulation model that treats SGTR, relevant emergency operating procedures, and PRA analyses of SGTR. Fourth, and most important, videotapes of actual operating crews performing training exercises on SGTR are available. In combination with the results of interviews of the crew members and of training supervisors, these videotapes provide an invaluable source of information regarding the behavior of individual crew members and their interaction during simulated accident conditions.

This chapter is concerned primarily with the data collected from a one–month visit to a non–U.S. PWR (henceforth referred to as the "Charles River Plant") and from a detailed review of the videotapes made for that plant. Section 3.2 provides the necessary context for the data collected; it describes the control room environment, the division of responsibilities among crew members, and the SGTR operating procedures and related actions relevant to the Charles River Plant. Section 3.3 describes the general approach used to gather data. The raw data are obtained from interviews with control room operators and with training supervisors, and from observation of videotapes of SGTR training exercises. The raw data are checked for internal consistency and for usefulness with respect to the modeling framework. The data gathering and checking processes are described in Section 3.4.

3.2 Background: Control Room Work Environment and Operations

3.2.1 Crew Composition

The Charles River Plant consists of two identical Westinghouse three–loop PWR units, each of which is rated at 950 MWe. Each unit is operated by three control room operators and several equipment operators (EOs). The three control room operators are the Senior Reactor Operator (SRO), the Reactor Operator (RO), and the Auxiliary Reactor Operator (ARO). The EOs are assigned to take care of local activities in the auxiliary building, the turbine building, the sea water pump house, etc. The two units share one Shift Engineer (SE), who is in charge of station operation.

As shown in Figure 2.1, the crew model described in this report does not include the Equipment Operators or the Shift Engineer. The Equipment Operators, while important for gathering information about plant status and for manipulating/restoring equipment, do not spend a large amount of time (if any) in face–to–face interactions with the control room crew members during an emergency. Regarding the Shift Engineer, he may not be immediately available when the SGTR occurs. The Shift Engineer is assigned to take care of the operation of two units; hence, he has to "swing" between the two control rooms, which are separated by some 5-minute walk. Furthermore, at the Charles River Plant, the training policy requires that the three-operator crew be able to independently handle all accident scenarios without the supervision of the Shift Engineer. As a consequence, training exercises on plant simulators usually involve only the three operators. Finally, although the SRO usually will consult with the Shift Engineer in making important decisions, the plant operating policy recommends that the Shift Engineer not step into unit operations unless it appears that the operating crew will perform inappropriate actions. Data gathering is therefore confined to the behavior of the SRO, RO, and ARO in each crew. (In later work, the model can be expanded to treat other personnel and data on the performance of these other personnel will then be required.)

3.2.2 Control Room Layout and Areas of Responsibility

Figure 3.1 shows the layout of a unit control room for the Charles River Plant. The SRO is in charge of unit operation; he usually stands or sits at a desk located between the RO's panel (Nos. 1–3) and the computer keyboards. The RO is in charge of Panels 1–3, while the ARO is in charge of Panels 4–12.

The primary side controls and indications are located in Panels 4–6. Panel 1 provides redundant primary side controls and indications, and may be described as a concentrated version of Panels 4–6. Feedwater (both main and emergency feedwater) indications and control switches are located both in Panels 2 and 7. Other indications and controls for the secondary side are located in Panels 3 and 8–12.

Note that the control room layout and division of responsibilities among crew members differ from those for many U.S. plants. In the latter, there are no separate panels for the RO; one operator typically deals with the primary side of the plant and another deals with the secondary side. Another difference is that crews in the U.S. plant usually include a Shift Technical Advisor (STA). This difference arises partly because the control room operators at the Charles River Plant are required to complete a minimum of two years of college.

Panels 4–12 contain an upper panel, a middle panel, and a lower panel. The upper panel contains the flashing lights for all available alarms. When a particular physical variable exceeds the predefined set point, an alarm is activated and both auditory and visual stimuli (an annunciator and a flashing light) are provided . The annunciator can be reset ("acknowledged") by the operator by pushing the reset button. The light will keep on flashing until the physical variable is again restored to its normal operational range. The flashing lights serve as indicators in identifying the nature of an alarm, and then as reminders when the alarms persist. Indicators and meters for plant parameters are provided in the middle panels for ease of monitoring. The lower panels house control switches related to plant equipment and systems whose statuses are shown on the indicators and meters.

If all operators stay in their nominal positions as shown in Figure 3.1, they are separated by some 10 feet. Based on this distance and the size of the indicators, it is judged that the SRO cannot directly monitor the plant parameters unless he changes his position. On the other hand, the flashing alarm panels (lights) are designed to be visible to all operators. Thus, it is assumed that all operators have direct visual access to them. These assumptions are confirmed by informal discussions with the control room operators at the Charles River Plant.

The structure of an operating crew is highly centralized: the SRO is the only authorized decision–maker. At the Charles River Plant, each SRO has a senior operator's license, while each RO and ARO has at least an operator's license (some ROs have a senior operator's license). Due to differences in seniority and in the type of license held by each operator, official "status" is naturally arranged in the order of SRO, RO, and ARO. This group structure may affect crew behavior in a number of ways. For example, in all of the videotaped exercises, no ARO ever made a suggestion to the SRO. The effects of group structure on crew behavior are further discussed later in this chapter.

3.2.3 Crew Actions During Steam Generator Tube Rupture

This subsection describes the general characteristics of the steam generator tube rupture (SGTR) accident and the crew actions required to mitigate this accident. These actions are governed by the plant operating procedures. The manner in which the operators implement the procedures, in turn, depends on the current phase of the accident. Before reactor trip (RT) or the initiation of safety injection (SI), the Abnormal Operating Procedures (AOPs) are in effect. At the Charles River Plant, the operating crew is required to memorize these AOPs and to rely on memory when implementing them. After RT/SI, the operating crew uses the Emergency Operating Procedures (EOPs). The Charles River Plant SRO is required to find the relevant EOP in his set of procedures and to read the procedure aloud, ensuring that his subordinates follow the instructions provided by the procedures.

3.2.3.1 SGTR Response Prior to Reactor Trip/Safety Injection

A steam generator tube rupture accident breaks the barrier between the primary and secondary sides of the steam generator (SG)[6]. The difference in pressure between the primary and secondary sides causes the radioactive reactor coolant to flow into the secondary side of the steam generator. The immediate results of this accident are drops in pressurizer level and pressure, an increase in the level of the faulted steam generator (the steam generator with the ruptured tubes), and an increase in the radioactivity level in the secondary side.

The decrease in pressurizer level soon actuates the "pressurizer level deviation" alarm. The set points for this alarm are 5% above and below the normal operating value. (At rated power, this operating value is approximately 59%.) The nominal crew responses to this alarm are to monitor and maintain the pressurizer level. Some actions that can be taken by the decision maker (the SRO) to maintain the pressurizer level are: to increase charging flow, to isolate letdown flow, and to start up a second charging pump. The last action is the most effective of the three to slow down the rate of level decrease. In the case of an SGTR accident, these actions (taken by the RO) may not stop the pressurizer level from dropping, especially if more than one tube is ruptured. If the level continues to decrease, the SRO should order the RO to reduce the reactor power. The purpose of this action is to reduce the degree of thermal shock on the reactor pressure vessel when a manual or automatic reactor trip is anticipated.

On the secondary side of the plant, the increased radioactivity level will activate the "secondary radiation high" alarm. This alarm will be activated whenever any group of sensors located in the steam generator blowdown lines, steam lines, or condensers detects a high radiation level. Depending on the size of break and the sensitivity of the sensors, this alarm may activate before or after the "pressurizer level deviation" alarm is activated.

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[6]See Ref. 41 for a description of plant behavior during a tube rupture accident.

The nominal response of the SRO is to command the ARO to check the radiation monitor. In most SGTR cases, the sensors located in the steam generator blowdown line are the ones that actuate this alarm, due to their proximity to the location of the rupture. However, because the sensors are located downstream of the common header for all steam generator blowdown lines, the alarm does not tell the operator which steam generator is faulted. Following the radiation alarm activation, the SRO should take further actions to check which steam generator is faulted (if he suspects that the root cause of the alarm is SGTR).

The two major tasks for the crew in dealing with an accident scenario are: to diagnose the root cause and to take the actions necessary to mitigate the scenario. Observations of operating crews performing simulation exercises and interviews with these operators indicate that the operators perform these two tasks in parallel. The actuation of a "secondary radiation high" alarm, combined with the decreasing pressurizer level, should be sufficient evidence for the SRO to infer, at least preliminarily, that an SGTR accident is underway.

With the suspicion that an SGTR accident is underway, the SRO should look for further evidence to confirm this preliminary conclusion. Two nominal actions that can be taken are: calling the chemistry department to sample the steam generator water, and commanding the ARO to check for any mismatches between the steam generator levels and feedwater flow rates. The performance of a water sample check usually takes about 20 minutes, and is only important for scenarios involving small size breaks. For larger breaks, the leakage of primary coolant into the faulted steam generator will lead to a higher steam generator level and a lower feedwater flow rate, as compared with those of the intact steam generators. (The decrease in the feedwater flow of the faulted steam generator is due to the compensation of the automatic level controller for the increased level.) The degree of mismatch between the level and feedwater flow rate for the faulted steam generator depends on the number and size of the ruptured tubes. For small breaks, the indications of a mismatch may be somewhat ambiguous, and detection of the mismatch may therefore require the judgment of the ARO. Note that if the ARO reports to the SRO that it is not clear if there is a mismatch, the SRO may repeatedly ask the ARO to check until it can be clearly determined that there is a mismatch.

If the existence of a mismatch is confirmed (which, in combination with the falling pressurizer level, tells the SRO that an SGTR accident is underway), the SRO should come back to check the pressurizer level. Plant training recommends that the SRO manually trip the reactor when the pressurizer level approaches 14% (this is stated in the AOPs). Thus, even if the SRO decides that an SGTR is underway, he is supposed to wait until the pressurizer level approaches this set point before ordering the RO to manually trip the reactor.

Table 3.1 summarizes the important nominal operator actions during a SGTR sequence before reactor trip. A nominal action is defined as the most appropriate response to a specific cue, based on the judgments of training supervisors and control room operators. The dashed arrows represent the command flows from the SRO to the RO and ARO. Note that not all operator actions are included in this table. For example, the ARO may check the status of the steam generator following the initial alarms and report his observation to the SRO before he is requested to do so. Similarly, the RO can proactively report the status of the pressurizer level.

Two general characteristics of the early operator response to the SGTR scenario are worth noting. First, since the SGTR affects both the primary and secondary sides of the plant, both the RO and ARO are kept busy in their areas of responsibility (the RO is mainly responsible for the primary side, while the ARO is mainly responsible for the secondary side). Second, although there is a nominal "textbook" response to the SGTR scenario, actual crew responses during the early part of the scenario can vary. This is because: some of the key indications (e.g., steam generator level/feedwater flow mismatch) may be ambiguous, the crew is reacting on the basis of memorized procedures (and these may be improperly memorized), the procedures allow some latitude in response selection (recall that the SRO has three options in responding to the decreasing pressurizer level), and the operators can take proactive measures that anticipate the textbook responses. These characteristics are factored explicitly into the model, as discussed in Chapter 4.

3.2.3.2 SGTR Response After Reactor Trip/Safety Injection

Following reactor trip, the crew follows the emergency operating procedures (EOPs). Two EOPs of particular interest are the E–0 procedure, titled "post–reactor trip/SI," and the E–3 procedure, titled "steam generator tube rupture." E–0 covers generic plant parameter and system status validation steps intended to identify both the current status of the plant and the second, more event–specific procedure to be followed next. E–3 covers specific actions required to identify and isolate the faulted steam generator and to start cooldown and depressurization of the primary system[7]. A portion of the E–0 EOP is shown in Table 3.2; the contents of E–0 and E–3 are summarized in Tables 3.3 and 3.4, respectively.

In executing the EOP steps, the SRO is responsible for giving instructions (commands) to his subordinates; he does this by reading each individual step. Due to the control panel layouts and the division of responsibility between the RO and ARO, each step usually is executed by one operator. The other operator may double–check the step execution, if he himself is not engaged.

As shown in Table 4.3, most of the steps in E–0 are designed to check/validate system or component status. Several steps require the SRO to acquire information from a subordinate and to choose an appropriate response. The steps requiring the SRO's judgement are Steps 15, 16, 21, 25, and 26. Step 26 is the branching point for procedure transfer. In this step, the crew is asked to check the presence of the radiation alarm. Given that the radiation alarm is on, the procedure requires the crew to leave E–0 and transfer to E–3. It is unlikely that the SRO will miss this obvious branching point if the alarm is on; however, the transfer may be missed if some adverse event has occurred (such as a malfunction of the radiation alarm). Even in this case, the E–0 procedure will instruct the crew to transfer to E–3 later in Step 33.

The major tasks required by E–3 are the identification and isolation of the faulted steam generator. These tasks are essential to prevent the release of radioactive coolant outside the containment building. The increasing level and pressure of the faulted steam generator may challenge the steam generator relief valve if isolation is not performed in time. The faulted steam generator can be identified by an abnormal increase in its level. The ease of identification depends on the difference in levels between the faulted and intact steam generators, hence it depends on the leakage rate, which itself depends on the rupture size. Once identified, isolation of the faulted steam generator requires closing of the feedwater supply valves, blowdown isolation valves, sample and drain valves, and the related main steam isolation valve and its bypass valve.

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[7]In order to terminate the flow of primary coolant to the steam generator through the ruptured tubes, the primary system must be depressurized. Cooldown of the primary system is required during depressurization in order to ensure that sufficient subcooling margin is maintained.

After the isolation of the faulted steam generator, the crew must initiate cooldown and depressurization of the primary system. The main objective of this task is to equalize the primary and the faulted steam generator pressure and thus reduce the leakage rate to the faulted steam generator. The cooldown will be executed first to ensure that the primary coolant does not reach saturation during depressurization. This process is accomplished by dumping the steam generated in the intact steam generators to the condensers via the steam dump valves. The depressurization process involves the use of pressurizer sprays and pressurizer relief valves. Once cooldown and depressurization has been accomplished, the crew initiates long–term cooling to stabilize the reactor to cold shutdown.

Because of the detailed guidance provided by the EOPs, the actions required after reactor trip do not require extensive logical reasoning by the operators. The EOPs help the crew organize the available information for diagnosis and also provide instructions to deal with critical component failures (e.g., loss of radiation alarm). The crew training for the plant studied, due to regulatory requirements, demands that crews precisely follow the EOPs. In this study, it is assumed that variations of operator behavior in following the EOPs are limited. Possible variations are further discussed in Chapter 4.

3.3 Field Study

A visit was paid to the Charles River Plant (a non–U.S. PWR) during the month of January 1990. The primary purpose of the visit was to gather information on crew behavior (e.g., the pattern of communication between operators under a variety of circumstances, adherence to procedures, and cooperation between crew members) relevant to a steam generator tube rupture accident. Data were collected via interview and videotape observation.

3.3.1 Interviews with Control Room Operators

The station's operating crew staff can be divided into five groups. Each group consists of a Shift Engineer (SE), two control room crews, and several Equipment Operators (EOs). Interviews were done with all control room crew members (the SRO, RO, and ARO) and Shift Engineers. In total, 35 control room operators were interviewed.

Each crew member's interview lasted from 45 minutes to an hour. Questions were asked concerning the individual's responsibilities during normal operation and during an SGTR scenario, and the key indications for these two phases. The interviewees were also asked to rate the technical ability of their crew, the quality of teamwork for their crew, their confidence in their fellow crew members, and the confidence that they believe their crew members would have in them. Of these questions, the most important ones from the standpoint of the crew model are those regarding confidence, since the answers directly affect the model's treatment of interactions between the crew members. The questions regarding crew technical ability and teamwork provide background information; they also provide a means to check the judgments of the crew members against those of experts (the five former Shift Engineers, whose responses are discussed in the next section).

Regarding the questions concerning an operator's confidence in another crew member, these were of the form:

> In your experience, with what percentage were you right regarding technical problems? With what percentage was your SRO (or RO or ARO) right regarding the same problems?

The answers to these questions are judged to reflect some of the interviewee's feelings concerning the other's trustworthiness, as well as his technical ability. Appendix A provides additional details on the questions asked of the operators during the interviews.

Table 3.2 presents each operator's ratings of his own crew's technical ability and teamwork quality. Noting that each operator was told to assume that the average score over all crews for both technical ability and teamwork quality should be 60, it can be seen that only two operators (the SRO for Crew #6 and the ARO for Crew #3) scored their crews as being below average. Some crews gave very high marks, providing at least an outward indication of strong confidence in themselves.

Table 3.3 presents each operator's ratings of: a) his confidence in his other crew members, and b) the confidence that he thinks his fellow operators have in him. The scores given in this table are used to compute "relative confidence levels" for the interviewee with respect to the other crew members, as discussed in Chapter 4.

3.3.2 Interviews with Former Shift Engineers

Five former Shift Engineers (three of them are currently simulator supervisors) were interviewed, with each interview lasting from one to two hours. The interviewees ("experts") were asked to rate the technical ability of each control room operator and the teamwork quality of each control room crew, and to comment on team leadership and on the effectiveness of training for an SGTR sequence.

In the case of technical ability, it was found that there was considerable variation between the experts' ratings, due to their differing interpretations of the rating scale employed during the interview. (For example, the experts apparently differed as to the meaning of a "90" rating for technical ability.) To compensate for this difference, the raw scores provided by the experts were re-scaled: the operator with the worst score was assigned a new rating of 60, the operator with the best score was assigned a new rating of 100. Linear interpolation was used to assign the ratings for operators with intermediate scores. Table 3.4 provides an example of this re-scaling, as applied to one expert's ratings of the technical abilities of the SROs. A similar procedure was employed to treat the experts' ratings of crew teamwork quality.

Table 3.5 presents the re-scaled technical ability and teamwork ratings averaged over all five responses. For comparison, the teamwork quality ratings provided by the current Shift Engineer for each group of two crews is provided in Table 3.6.

Because of the re-scaling procedure employed, the ratings provided in Tables 3.5 and 3.6 only reflect relative differences between crew members (and crews). It should be noted, however, that none of the experts provided a raw score less than 60 for any crew member or crew. Thus, the experts seemed to feel that the crew members and crews were better than average, i.e., they had confidence in the crews.

3.3.3 Videotaped SGTR Exercises

For each of the ten operating crews (where a crew consists of an SRO, an RO, and an ARO), a taped simulation exercise for a SGTR sequence was reviewed. This study uses the tapes to characterize the responses of the different crews to the simulated accident (e.g., what procedure is being followed and when). It should be noted that the tapes were made in support of the Electric Power Research Institute program to gather event timing data for the Human Cognitive Reliability (HCR) model; operators were instructed to respond to the simulated accident as realistically as possible.

Each sequence begins with a stuck-open pressurizer relief valve; following restoration of the relief valve, a tube rupture scenario was initiated. Each exercise was terminated when the operators initiated primary system cooldown and depressurization. The key actions during each exercise were generally performed within about thirty minutes. No additional hardware failures were simulated as part of the exercise.

The exercises were filmed using two cameras. The primary camera was located behind the SRO and covered the majority of the control room; the secondary camera covered the actions of the ARO and RO from the side. Due to the angles of the cameras, the facial expressions of the operators cannot be clearly observed. The SRO and RO each wore a microphone. Thus, most of the communication between operators can be clearly heard on the videotapes.

The data collected from the reviews of videotapes includes: individual variations in responding to a specific cue, the times required to accomplish specific actions, the pattern of communication, degree of adherence to procedures, and cooperation between operators. The normalized occurrence times of key events are provided in Table 3.7. It can be seen that the variation in event timings among the different crews is not great[8]. This lack of variability can be at least partially attributed to the simplicity of the scenario, the crew training and operating procedures aimed specifically at the scenario, and the correlating influence of the plant's physical behavior.

Other interesting observations can be summarized as follows:

- Written procedures were not followed before the reactor was tripped and/or safety injection was initiated. However, most crews employed similar responses during this period (recall that they are working on the basis of memorized Abnormal Operating Procedures). For example, most crews manually started up a second charging pump and tripped the reactor when the pressurizer level approached 14 percent.

- The SRO was the only decision maker during the simulation exercise. Although the SRO occasionally conferred with the RO, no formal group decision-making was observed.

- Almost all of the observed communication occurred between the SRO and his subordinates (i.e., the RO and the ARO). Less than 5 percent of the message exchanges occurred between the subordinates. This situation may be attributed to the centralized structure of the operating crew; the SRO is the only decision maker and, hence, all information goes to him.

- Variations in SRO behavior in responding to a specific cue were observed. For example, in responding to the secondary radiation alarm, several SROs went to check the radiation monitor themselves instead of commanding the ARO to do this task. Also, several SROs did not respond to the cue "pressurizer level still decreasing" after they had commanded an increase in charging flow to counteract the observed decrease. (The nominal response should be to command the RO to start up a second charging pump.)

[8]In the case of SGTR diagnosis, the relative variation in the normalized diagnosis time appears to be large, but the average absolute diagnosis time is less than five minutes. Thus, the absolute variation in diagnosis time is also small.

- When the SROs did not respond to the cue "pressurizer level still decreasing," several ROs suggested starting up the second charging pump. The suggestion was usually made 1–2 minutes after the cue had been observed, and always accepted by the SRO. Other suggestions to reduce power and manually trip the reactor were also observed when the SRO either did not or hesitated to take the action.

- Variations in subordinates' behavior in proactively responding to a cue were also observed. For example, all AROs monitored the steam generator and pressurizer statuses (after alarms), but not all of them made proactive reports to the SRO.

- In no case did an operator misunderstand a message or reject a command. However, SROs occasionally ignored/rejected suggestions coming from ROs.

- Following reactor trip, the primary source of variability in crew response was the speed with which each crew followed the written procedures.

- Only one crew committed a "slip" error in procedure following. This occurred at Steps 25 and 26 of E–0. Judging from the dialog between operators, it appears that this crew understood that there was a SGTR problem, but went to procedure E–2, "Faulted Steam Generator Isolation," which should only be applied when a steam generator vessel rupture occurs. The RO's suggestion of isolating the faulted steam generator, which was appropriate but premature (according to procedural requirements) for the SGTR sequence, may have misled the SRO to make the incorrect decision. Note that the title of E–2 can be confusing.

Although the limited sample size may not be strong enough to confirm (or deny) detailed hypotheses, the observations do provide useful suggestions for potential trends and relationships concerning crew behavior. The application of the data gathered from the videotape reviews is discussed in Chapter 4.

3.4 Data Analysis

A limited analysis of the data collected from the interviews and videotape reviews is performed to check the consistency of the data and to test some simple hypotheses regarding the relationship between crew ratings and performance. This section shows that the interview data exhibit fair internal consistency, and also are consistent with an alternate scale for rating crews. This section also shows that there is poor correlation between crew technical ability/teamwork quality and the time taken to perform key actions.

3.4.1 Data Consistency

Because of uncertainties in the interview process, it is important to check the consistency of the data gathered to quantify the technical ability of the operators and their confidence in their fellow crew members. These consistency checks involve comparisons across interview groups (e.g., between the operators and the former Shift Engineers), across variables [e.g., between "technical ability" (TA) and "teamwork quality" (TQ)], and between the interview results and a separate assessment performed by the authors.

Most of the data used in the consistency checks are denoted as follows:

$$Variable_{\text{rater}}$$

For example, $SRO\text{–}TA_{exp}$ denotes the technical ability of the SRO, as judged by the experts (the five former Shift Engineers). The variables treated in this analysis are:

C–TA	crew technical ability
SRO–TA	SRO technical ability
RO–TA	RO technical ability
ARO–TA	ARO technical ability
C–TQ	crew teamwork quality

The following subscripts indicate the rater(s):

exp	"experts" (the five former Shift Engineers)
se	the current shift engineer for a group/crew (SEs)
sro	the senior reactor operator
ro	the reactor operator
aro	the auxiliary reactor operator

For the case where the operators are asked to provide the ratings of their own technical ability that they believe their fellow crew members would assign them, the following notation is employed:

$$Variable_{selfrater,rater}$$

The first subscript indicates the operator while the second indicates the fellow crew member. For example, $SRO\text{–}TA_{sro,aro}$ represents the rating of technical ability that an SRO believes his ARO would give him.

To investigate the degree of consistency within the data, five sets of data comparisons are performed:

1) $C\text{–}TQ_{exp}$ vs. $C\text{–}TQ_{se}$, i.e., a comparison of teamwork quality ratings by two sets of assessors familiar with the crews.

2) Two comparisons of expert–assessed teamwork quality ratings vs. technical ability ratings:

   a) $C\text{–}TQ_{exp}$ vs. $SRO\text{–}TA_{exp}$
   b) $C\text{–}TQ_{exp}$ vs. a weighted sum of $SRO\text{–}TA_{exp}$, $RO\text{–}TA_{exp}$, and $ARO\text{–}TA_{exp}$

   These comparisons test if the experts distinguish between teamwork quality and technical ability.

3) Four comparisons of crew technical ability and teamwork quality ratings (provided by crew members) with those provided by the experts:

   b) $\dfrac{C\text{–}TA_{sro} + C\text{–}TA_{sro} + C\text{–}TA_{sro}}{3}$ vs. $C\text{–}TA_{exp}$

   b) $\dfrac{C\text{–}TQ_{sro} + C\text{–}TQ_{sro} + C\text{–}TQ_{sro}}{3}$ vs. $C\text{–}TQ_{exp}$

   c) $C\text{–}TA_{max}$ vs. $C\text{–}TA_{exp}$, where "max" denotes the crew member with the highest technical ability (as rated by experts) in the crew. Operationally, this is the operator in a given crew whose technical ability is furthest above the average for all operators in his class (i.e., SROs are compared with the average SRO, ROs with the average RO, etc.)

   d) $C\text{–}TQ_{max}$ vs. $C\text{–}TQ_{exp}$

These tests determine if the operators and the experts view crew technical ability and teamwork quality in a consistent manner.

4) A comparison of individual technical ability (as rated by experts) with individual technical ability (as rated by the operators). This is based on two sets of three variables:

$$\{(SRO{-}TA_{exp} - <SRO{-}TA_{exp}>),\ (RO{-}TA_{exp} - <RO{-}TA_{exp}>),\ (ARO{-}TA_{exp} - <ARO{-}TA_{exp}>)\}$$

and

$$\{[(SRO{-}TA_{ro} - RO{-}TA_{ro,sro}) + (SRO{-}TA_{aro} - ARO{-}TA_{aro,sro})],\ [(RO{-}TA_{sro} - SRO{-}TA_{sro,ro}) + (RO{-}TA_{aro} - ARO{-}TA_{aro,ro})],\ [(ARO{-}TA_{sro} - SRO{-}TA_{sro,aro}) + (ARO{-}TA_{ro} - RO{-}TA_{ro,aro})]\}$$

To explain these comparisons, consider the first variable in each set. The first variable in the first set

$$(SRO{-}TA_{exp} - <SRO{-}TA_{exp}>)$$

is the SRO's technical ability (as rated by experts) scaled by the average SRO technical ability (again as rated by the experts). The first variable in the second set,

$$[(SRO{-}TA_{ro} - RO{-}TA_{ro,sro}) + (SRO{-}TA_{aro} - ARO{-}TA_{aro,sro})]$$

represents the confidence in an SRO's technical ability as expressed by his fellow crew members. The first term (in parentheses) is the difference of the rating of the SRO assigned by the RO and the rating of the RO that he believes he is given by the SRO. The second term is similar, but applies to the ARO. This comparison checks the degree of consistency between the judgments made by the crew and by the experts.

5) A comparison of scores derived from the experts' qualitative comments on each SRO (also collected during the interviews) and the overall teamwork score for that SRO's crew (i.e., $C{-}TQ_{exp}$). This comparison provides a consistency check for the experts' assessments.

6) A comparison of team performance scores, based upon each crew's observed performance in the SGTR exercises, and $C{-}TQ_{exp}$. The team performance scores are developed using the methodology described in Ref. 25. This comparison also provides a consistency check for the experts' assessments.

To perform Comparison #1, Table 3.6 shows the teamwork quality ratings of the crews, as provided by the experts and by the current Shift Engineers (the former ratings represent averages of the ratings provided by all five experts). It can be seen that for three of the five groups, the relative orderings of each crew are in agreement. Note that two crews are included in a group, whose leader is an Shift Engineer. For Group 5, the Shift Engineer assigns the same rating to the two SROs, whereas the experts believe that Crew 7 is somewhat better. Note that Table 3.5 shows that the margin of 6.1 points is not very large, compared with the difference between the highest and lowest rated teams. The assessment of the Shift Engineer for Group 2 does not match the experts' judgment. (Unfortunately, steps were not taken to ensure that each Shift Engineer used the same scale to rate his two crews; therefore, the data for the different groups are not combined, as is done in the following cases.)

To perform Comparison #2, Table 3.5 shows the average rating of technical ability for each operator and the average of these scores for each type of operator, as provided by the experts. Analysis of these data shows that there is a strong correlation between the experts' ratings of technical ability and their ratings of teamwork quality. For example, Line 1 of Table 3.8 and Figure 3.3 show that the technical ability of the SRO ($SRO{-}TA_{exp}$) correlates well with the crew teamwork quality ($C{-}TQ_{exp}$). It is interesting to observe that, as shown in Line 2 of Table 3.8, the maximum correlation ($r = 0.96$) between $C{-}TQ_{exp}$ and a weighted sum of $SRO{-}TA_{exp}$, $RO{-}TA_{exp}$, and $ARO{-}TA_{exp}$ is obtained when

$$\text{weighted sum} = 0.50 * SRO{-}TA_{exp} + 0.35 * RO{-}TA_{exp} + 0.15 * ARO{-}TA_{exp}$$

Although the weights (0.50,0.35,0.15) are based on a small sample, they may indicate the relative importance of each crew member, in the eyes of the experts.

These results indicate that the experts, taken as a group, consistently relate "teamwork quality" and "technical ability."

In Comparison #3, the perceptions of the crew are compared with those of the experts. Table 3.2 presents the ratings of crew technical ability and teamwork quality (C–TA and C–TQ) as rated by the crew members. Line 3 of Table 3.8 shows that the correlation between crew technical ability (the average of the crew members' scores) and the expert–rated crew technical ability is fairly low. Line 4 provides a similar result for teamwork quality. On the other hand, Lines 5 and 6 show that the technical ability and teamwork ratings given by the "best" operator in the crew compare much better with those provided by the experts. In this case, the best operator is the one whose technical ability as rated by the experts, is furthest above the average for all comparable operators. Thus, for example, the ARO is the best operator in Crew #1, since Table 3.6 shows that

$$ARO{-}TA_{exp} - \langle ARO{-}TA_{exp} \rangle > RO{-}TA_{exp} - \langle RO{-}TA_{exp} \rangle > SRO{-}TA_{exp} - \langle SRO{-}TA_{exp} \rangle$$

Comparison #4 also compares the perceptions of the crew with those of the experts. Table 3.3 shows the results when each crew member is asked to rate the technical ability of his fellow crew members and to provide the score he thinks the other crew members would give him. For example, the SRO of Crew #1 thinks that the RO will give him a score of 85, whereas he himself scores the RO at 80.

It can be seen that these scores can be used to indicate the confidence that other members of the crew have in a given operator. Consider again the SRO of Crew #1. Measuring the relative confidence that the RO has in the SRO by the difference

$$SRO{-}TA_{ro} - RO{-}TA_{ro,sro} = 95 - 85 = +10$$

and the relative confidence that the ARO has in the SRO by the difference

$$SRO{-}TA_{aro} - ARO{-}TA_{aro,sro} = 70 - 92 = -22$$

the relative confidence in the SRO as expressed by the members of his crew can be measured by the sum of these scores: $10 + (-22) = -12$. To compare this confidence rating with the rating given by the experts, note that

$SRO\text{–}TA_{exp} - \langle SRO\text{–}TA_{exp} \rangle$

indicates the relative ability of SRO (as compared with the other SROs) as judged by the experts. The average SRO score is subtracted to make the score more comparable to the RO and ARO scores.

Table 3.9 shows the crew confidence and the technical ability scores for each operator, and the correlation between these variables for each operating crew. For six out of the ten crews, the crew judgments correlate reasonably well with those of the experts. In the most extreme of the four cases with poor correlation (Crew 3), the ordering provided by the crew opposes that provided by the experts. In this crew, the ARO is very highly rated by the experts, but not highly rated by his SRO, possibly reflecting his official status within the crew. Further, the SRO is highly rated by his RO, yet he is not highly rated by the experts.

Table 3.3 shows that the ratings of the Crew 3 ARO are uniform. In a number of other cases as well, some of the operators assign uniform scores for their fellow crew members and for themselves, possibly because they may not wish to reveal their true feelings on the subject. In the case of Crew 5, the responses are all uniform, and no correlation with expert opinion can be shown.

Table 3.9 indicates that the crew opinions are fairly consistent with those of the experts. Of course, the degree of correlation is not always strong. Furthermore, it should not be forgotten that the correlation coefficients are computed on the basis of only three data points.

The first four data set comparisons employ on numerical scores provided by the experts. Comparison #5 checks the consistency of the expert scores (for the SROs) with qualitative comments provided by the experts. During the interviews, each expert was asked to comment on each SRO. The qualitative comments were categorized into four classes: relation with crew members, i.e., the leader/member relationship (LM); personality (P); technical (T); and leadership (L). Each comment is quantified by assigning a score (ranging from –2 to 2) according to its strength and positiveness/negativeness. For example, the comment "willing to learn" will score +1 in technical and "often complains" will score –1 in personality. The scoring assignments for various comments are provided in Table 3.10.

Table 3.11 shows the rating for each SRO. Table 3.12 shows the correlation between these ratings, crew teamwork quality ($C\text{–}TQ_{exp}$), and the SRO's technical ability ($SRO\text{–}TA_{exp}$). It can be seen that the degree of correlation between $C\text{–}TQ_{exp}$ and the comment–based rating is not extremely strong. However, the comment–based rating correlates reasonably well with $SRO\text{–}TA_{exp}$. This indicates that the experts' quantitative judgments regarding the SROs are fairly consistent with their qualitative comments, but the nontechnical comments do not seem to translate well into crew teamwork ratings. This may mean that the scoring system used is not representative of that used by the experts, that the experts do not consider all of the factors included in the comment–based rating when assessing teamwork quality, or that there are a number of other important factors not queried that have an impact on teamwork quality.

Comparison #6 has an objective similar to that for Comparison #5; it is aimed at checking the experts' assessments of teamwork quality. In this case, the comparison is made based on a rating of the actual crew performances during the videotaped SGTR exercises[9].

Ref. 25 describes a set of seven "behaviorally anchored team performance rating scales" (mentioned previously in Section 1.3.2). These scales measure performance along seven dimensions: two–way communication of objectives/plant status, resource management, inquiry, advocacy, conflict resolution and decision making, stress management, and team spirit. Team performance along each dimension is rated anywhere from 1 to 7, where 4 represents the average performance level (examples used to scale the ratings are given in Ref. 25 for each dimension).

Using the methodology provided in Ref. 25, the Charles River Plant crews are rated for their (videotaped) performance during the SGTR simulations. Table 3.12 provides the rating for each crew. Note that if any item is not observed, the average value (i.e., 4) is assigned to that item. These items are denoted by an asterisk in Table 3.12.

Using the scores given in Table 3.12, it can be shown that the correlation between the total scores (the sum of all scores for a crew) and expert–rated teamwork quality ($C\text{–}TQ_{exp}$) is found to 0.77. Thus, the scaling procedure of Ref. 25, which employs observed team performance, appears to be consistent with the judgment of experts (which rates the crew for their performance over a wide range of possible scenarios).

In general, the above six data comparisons indicate that the results from the various interviews exhibit a fair degree of external as well as internal consistency. The Shift Engineer ratings correspond with those of the "experts" (the Training Supervisors and former Shift Engineers), the expert ratings are internally consistent, and the crew ratings correlate to some degree with the expert ratings. Furthermore, the expert quantitative ratings correlate both with their qualitative comments and with an independent assessment of actual crew performance during simulations. However, the correlations are not always very strong, and are generally based on a very limited set of data points. Further, there are some inconsistencies (e.g., the above weak correlation between nontechnical scores and teamwork quality); these require further investigation for resolution.

3.4.2 Correlation Between Teamwork Quality and Time

At first glance, it might be expected that the operating crew teams more highly rated by experts in terms of teamwork quality will be the quickest to diagnose the cause of an accident and to perform required actions. In order to test this hypothesis, four key times observed from the SGTR videotapes are correlated against the expert–assessed crew teamwork quality ($C\text{–}TQ_{exp}$). (As shown in the preceding section, $C\text{–}TQ_{exp}$ correlates reasonably well with a number of other observed variables.) The times are as follows:

- time to diagnose the accident as an SGTR scenario (T_1)
- time to isolate the faulted steam generator (T_2)
- time to initiate the SGTR procedure (T_3)
- time to cool down and depressurize the primary side (T_4)

Data for T_1 was developed based on an analysis of the dialogue among operators during the simulation. Data for T_2, T_3, and T_4 were directly observed from the videotapes.

[9]As will be shown in the following subsection, the timing of key events does not correlate well with $C\text{–}TQ_{exp}$. This comparison is also useful for exploring the degree of correlation between alternate measures of team performance and $C\text{–}TQ_{exp}$.

A scatter plot showing a rescaled T_1,

$$T_1^* \equiv \frac{T_1 - T_{1,min}}{T_{1,max} - T_{1,min}}$$

is presented in Figure 3.4. This variable is the only one to correlate reasonably well with the crew teamwork ($r = -0.68$). Table 3.13 shows that the other times do not correlate well; indeed, T_4 shows virtually no correlation with teamwork quality ($r = -0.03$). Clearly, the experts' rating of teamwork quality includes other factors than the speed at which the crew performs the necessary tasks.

The lack of correlation between most of these key times and the expert ratings is interesting because time plays a crucial role in many current human reliability assessments. As a caveat to this observation, it should again be emphasized that the sample is small; further, teamwork quality may work in concert with other "performance–shaping factors" to affect event timing (as visualized in the HCR model [7]). Nevertheless, the data indicate that teamwork quality may not be the key performance–shaping factor in determining event timing. If a rigid set of procedural steps must be performed, the timing may be more established by the procedure writer than by the operating crews.

3.5 Summary

The operating crew modeling framework described in Chapter 2 can be used to model quite general behaviors of operators during accident scenarios. To limit the scope of the model in a realistic pilot application, it is important to use data from actual operating crews. This project employs data collected from an extended visit to a non–U.S. three–loop Westinghouse PWR (the "Charles River Plant").

In addition to a study of SGTR and related plant operating procedures, the data collection effort involved interviews of 35 control room operators and 5 former Shift Engineers, as well as a detailed review of videotapes recording the performance of 10 operating crews during SGTR training exercises. The data collected from the interviews allow an assessment of the differing abilities of the crew members and of the relationships between the crew members. These assessments are used directly in the model for communication between operators, as discussed in the next chapter. The data collected from the videotape reviews allows the development of the "scripts" followed by each operator (including the key plant parameters monitored and the related criteria used to make operational decisions), an assessment of the time required to perform key actions, and the benchmarking of a physical model used to simulate plant behavior during the early stages of SGTR. The videotapes also provide justification for a number of assumptions limiting the scope of the model. Four key assumptions employed in the crew model application discussed in the next chapter are:

- The SRO is the sole decision maker, even when he has a relatively low technical ability (as compared with other SROs) and his subordinates have relatively high technical abilities.

- Scripted, rule–based behavior is dominant during the scenario. The demands on an operator's higher level logical reasoning ability are limited.

- The crew structure remains unchanged during the scenario. (This assumption is relaxed slightly in the sensitivity analyses discussed in Chapter 5.)

- The likelihood of significant message garbling is insignificant.

It should be noted that the scope of the data collection effort and, hence, the crew model application, is limited to the early phases of an SGTR scenario only. Thus, the gathered data do not allow general conclusions for operator behavior during all accident scenarios, or even for the later phases of an SGTR scenario. Other limitations on the data collected are due to the small sample size, and to weaknesses in the questionnaire and interview techniques employed (these are briefly summarized in Appendix A). Future data gathering efforts concerned with the elicitation of opinions on crew relationships might usefully employ the questionnaire presented in Appendix B. This questionnaire, developed for a field study that never took place, is intended for the study of relationships between operators; it is based upon a more general questionnaire designed to study interpersonal communications within a small group [42].

Table 3.1 - Operator Nominal Responses During SGTR Scenario

Cue (Source)	SRO's Nominal Response	RO's Nominal Response	ARO's Nominal Response
PZR level deviation alarm (panel)	Command RO to check PZR status ---►	Check PZR status	
PZR level still decreasing (RO)	Command RO to start up second charging pump ---►	Start up second charging pump	
PZR level still decreasing after second charging pump has been started (RO)	Command RO to reduce reactor power ---►	Reduce reactor power	
Secondary radiation high alarm (panel)	Command ARO to check radiation monitor	---------------------------►	Check radiation monitor
S/G blowdown line radiation high (ARO)	Command ARO to check S/G mismatch	---------------------------►	Check S/G mismatch
S/G mismatch clear (ARO) and PZR level decreasing (RO)	Declare SGTR! Consider manual trip		
PZR level approaches 14% (RO/ARO & panel)	Command RO/ARO to manually trip reactor	---► Trip reactor ---------------------------►	Trip reactor

PZR = pressurizer
S/G = steam generator

Table 3.2 - Operator Assessments of Crew Technical Ability and Teamwork Quality

Parameter	Rater	CREW #1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Average (μ) and Standard Deviation (σ)
Crew Technical Ability	SRO	90	80	65	85	90	58	70	80	80	85	$\mu = 78.4$ $\sigma = 10.7$
	RO	80	80	70	75	80	61	75	80	75	85	$\mu = 76.1$ $\sigma = 6.70$
	ARO	60	65	50	80	80	70	75	80	60	80	$\mu = 70.0$ $\sigma = 10.8$
Crew Teamwork Quality	SRO	80	92	60	80	90	58	70	85	85	85	$\mu = 78.5$ $\sigma = 11.9$
	RO	80	80	60	70	85	80	80	80	60	85	$\mu = 76.0$ $\sigma = 9.40$
	ARO	60	65	50	85	90	70	85	90	80	70	$\mu = 75.0$ $\sigma = 13.1$

Table 3.3 - Operators' Confidence Levels in Fellow Crew Members (Raw Scores)

Parameter	Rater	CREW #1	#2	#3	#4	#5	#6	#7	#8	#9	#10
SRO's Confidence Level	RO --> SRO*	85	90	80	80	85	90	80	90	80	90
	ARO --> SRO	80	90	80	80	80	90	80	90	80	90
	SRO --> RO**	80	95	70	60	90	60	80	70	70	90
	SRO --> ARO	85	95	60	60	90	75	80	80	75	90
RO's Confidence Level	SRO --> RO	85	80	50	80	85	50	90	60	80	80
	ARO --> RO	75	90	90	80	85	70	80	60	90	90
	RO --> SRO	95	80	90	80	85	85	70	60	90	90
	RO --> ARO	92	90	100	80	85	60	65	60	90	80
ARO's Confidence Level	SRO --> ARO	92	90	80	80	90	85	80	85	75	70
	RO --> ARO	90	90	80	80	90	85	80	85	75	80
	ARO --> SRO	70	88	80	90	90	85	100	80	75	90
	ARO --> RO	80	90	80	90	90	85	90	75	75	80

* The confidence level that the SRO **thinks** the RO assigns the SRO.

** SRO's level of confidence in the RO.

Table 3.4 - Example Rescaling of Expert-Rated Individual Technical Ability and Crew Teamwork Quality (Expert #1)

Parameter		CREW #1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Average (μ) and Standard Deviation (σ)
Individual Technical Ability (Original)	SRO	68	68	68	75	72	78	75	75	72	80	$\mu = 73.1$ $\sigma = 4.0$
	RO	68	78	75	76	80	68	80	70	78	68	$\mu = 74.1$ $\sigma = 4.8$
	ARO	80	75	80	68	72	78	72	80	80	75	$\mu = 76.0$ $\sigma = 4.1$
Individual Technical Ability (Rescaled)	SRO	60	60	60	83	73	93	83	83	73	100	$\mu = 77.0$ $\sigma = 13.4$
	RO	60	93	83	87	100	60	100	67	93	60	$\mu = 80.3$ $\sigma = 16.1$
	ARO	100	83	100	60	73	93	73	100	100	83	$\mu = 86.6$ $\sigma = 13.6$
Crew Teamwork Quality (Original)		74	72	65	72	72	75	80	70	78	76	$\mu = 73.4$ $\sigma = 4.0$
Crew Teamwork Quality (Rescaled)		84	79	60	79	79	87	100	73	95	89	$\mu = 82.4$ $\sigma = 10.7$

Table 3.5 - Expert Rating of Individual Technical Ability and Crew Teamwork Quality

Parameter	Operator	CREW #1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Average (μ) and Standard Deviation (σ)
Individual Technical Ability	SRO	66.6	67.2	73.8	76.4	79.6	84.3	84.8	88.4	89.3	96.4	$\mu = 80.7$ $\sigma = 9.80$
	RO	68.0	78.0	77.3	83.3	84.0	65.3	98.0	80.9	81.3	71.3	$\mu = 78.7$ $\sigma = 9.30$
	ARO	90.0	82.4	98.0	70.7	74.7	79.3	78.7	83.7	92.0	82.0	$\mu = 83.1$ $\sigma = 8.20$
Crew Teamwork Quality		67.3	65.9	71.7	71.7	80.5	70.0	96.7	87.1	87.8	90.6	$\mu = 78.9$ $\sigma = 11.0$

Note: Experts are 5 former shift engineers (3 of them are training supervisors). The score shown is the average of the expert scores.

Table 3.6 - Comparison of Crew Teamwork Quality Ratings Provided By Experts and Current Shift Engineers

Rater \ Crew	Group 1		Group 2		Group 3		Group 4		Group 5	
	#1	#4	#6	#5	#8	#2	#9	#3	#7	#10
Experts	67.3	71.7	70.0	80.5	87.1	65.9	87.8	71.7	96.7	90.6
Shift Engineer	80	85	85	85	80	70	80	70	85	85

Note: Experts are 5 former shift engineers (3 of them are training supervisors). The score shown is the average of the expert scores.

Table 3.7 - Normalized Times to Key Crew Actions in SGTR Simulation Exercises

Parameter	CREW #1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Average (μ) and Standard Deviation (σ)
Time to diagnose SGTR (Judged from dialog among operators)	0.74	1.0	0.31	0.48	0.46	0.42	0.28	0.42	0.34	0.31	$\mu = 0.48$ $\sigma = 0.23$
Time to initiate SGTR procedure (E-3)	0.68	1.0	0.52	0.78	0.87	0.83	0.56	0.82	0.77	0.78	$\mu = 0.76$ $\sigma = 0.14$
Time to isolate the faulted steam generator	0.68	1.0	0.59	0.75	0.84	0.88	0.46	0.96	0.82	1.0	$\mu = 0.80$ $\sigma = 0.18$
Time to initiate primary side cooldown and depressurization	0.74	1.0	0.59	0.71	0.88	0.86	0.64	0.89	0.79	0.98	$\mu = 0.81$ $\sigma = 0.14$

Note: All times have been normalized; the longest time taken by crews in each category is assigned a value of 1.0.

Table 3.8 - Correlation of Crew/Individual Ratings with Crew Teamwork Quality As Rated By Experts

Rater Group	**Variable**	Correlation
Experts	SRO's technical ability ($SRO\text{-}TA_{exp}$)	0.81
	Weighted sum of crew members' technical abilities ($0.5 * SRO\text{-}TA_{exp} + 0.35 * RO\text{-}TA_{exp} + 0.15 * ARO\text{-}TA_{exp}$)	0.96
Crew Members	Equal- weighted sum of crew members' grades for crew technical ability ($(C\text{-}TA_{sro} + C\text{-}TA_{ro} + C\text{-}TA_{aro})/3$)	0.31
	Equal- weighted sum of crew members' grades for crew Teamwork qualities ($(C\text{-}TQ_{sro} + C\text{-}TQ_{ro} + C\text{-}TQ_{aro})/3$)	0.38
	Highest-rated individual's grade for crew technical ability	0.73
	Highest-rated individual's grade for crew teamwork quality	0.78

Table 3.9 - Correlation Between Expert-Rated Individual Technical Ability and Crew Member Relative Confidence Level

Parameter		CREW #1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Expert Rating of Technical Ability (Minus Average for all Operators)	SRO	-14.1	-13.5	-6.9	-4.3	-1.1	3.6	4.1	7.7	8.6	15.7
	RO	-10.7	-0.7	-1.5	4.6	5.3	-13.4	19.3	2.2	2.6	-7.4
	ARO	6.9	-0.7	14.9	-12.4	-8.4	-3.8	-4.4	0.6	8.9	-1.1
Sum of Confidence Level Ratings for Operator (Provided by Team Members)	SRO	-12	-2	40	10	0	35	0	-5	10	30
	RO	-15	5	-10	-10	0	-30	10	-35	-10	0
	ARO	22	5	-10	-20	0	-25	-15	-10	-5	-10
Correlation		0.98	1.0	-0.69	0.30	0.0	0.86	0.96	0.45	0.66	0.87

Table 3.10 - Scoring for Expert Comments on SRO

Category	Score	Expert's Comment on SRO
Leader-Member Relationship	+2:	Very easy to get along with; often go out together after duty.
	+1:	Easy to get along with; sometimes go out together.
	-1:	Relation limited to working hours; not respected by others.
Personality	+1:	Industrious; actively helps others; active.
	-1:	Easily makes others unhappy; subjective; often complains; selfish; arrogant; won't let RO/ARO see control room log; too eager; less social experience.
Technical Ability	+1:	Expected to behave well in an SGTR scenario; willing to learn; technically good.
	-1:	Expected behavior doubtful in an SGTR scenario; inexperienced; technically not so good; less willing to learn.
Leadership	+1:	Negotiates with others before taking action; careful; handles things officially; always gives details; responsible; actively helps RO/ARO; hope others will learn something from him.
	-1:	May not be the actual leader; prefers to do superficial things; does not want RO/ARO to see control room log; cannot take full responsibility; easily makes others unhappy.

Table 3.11 - SRO Ratings Based on Expert Comments

Category	CREW									
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Leader-Member Relationship (LM)	4	-2	2	1	1	3	3	-1	2	2
Personality (P)	-1	0	0	-2	-1	1	1	-1	-1	-1
Technical Ability (T)	-3	-2	0	1	-2	0	0	0	1	3
Leadership (L)	-1	-3	-3	0	1	1	0	0	0	2
Total	-1	-7	-1	0	-1	5	4	-2	2	6

Table 3.12 - Crew Performance Ratings Based On Team Performance Scale [25]

Category	CREW									
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Two-Way Communication of Objectives/Plant Status	5	3	2.5	5	5	3	5	5	5	4
Resource Management	5	4	4	3	4	4	5	4.5	3	4
Inquiry	3	4*	2	4	4	4*	4*	4*	4*	4*
Advocacy	3	5	4	4	3	4	4	5	4	3
Conflict Resolution and Decision Making	3	4*	4*	4*	3	4*	4*	4*	4*	4*
Stress Management	5	2	4	3	4	4	3	5	5.5	4
Team Spirit	3	2	3	4	4	3	5	5	5.5	5
Total	27	24	23.5	27	27	26	30	32.5	31	28

* Not observed - assigned nominal (average) value of 4

Table 3.13 - Correlation of Event Timings with Crew Teamwork Quality (C-TQ_{exp})

Basis	Parameter	Correlation
Dialog among operators during exercise	Time to diagnose SGTR	-0.68
Direct observation (videotape)	Time to initiate SGTR procedure	-0.16
	Time to isolate the faulted steam generator	-0.13
	Time to initiate primary side cooldown and depressurization	-0.03

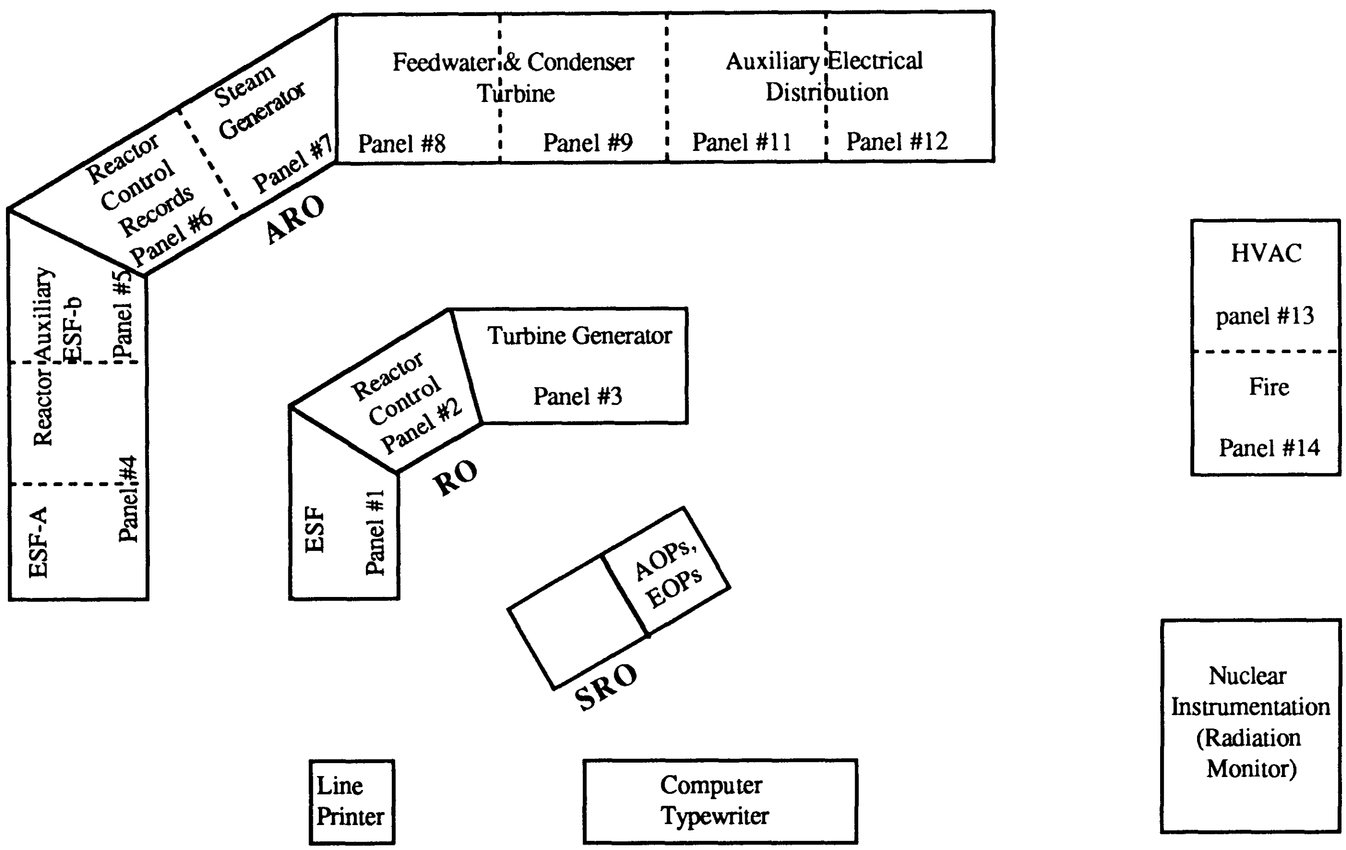

Figure 3.1 - Charles River Nuclear Power Plant Control Room Layout

Figure 3.2 - Procedure Steps in EOP E-0

Steps	Contents	Respon-sibility
1	Validation of reactor trip: all control rods at bottom, all reactor trip breakers open	RO
2	Validation of turbine and generator trip: all related valves closed, all related breakers open	ARO
3	Validation of emergency power supply: at least one AC bus energized	ARO
4	Check SI status	RO
5	Validation of main feedwater isolation: all related valves closed	ARO
6	Validation of containment isolation phase A	ARO
7	Validation of emergency feedwater pumps: all ON	ARO
8	Validation of SI pumps: all ON	RO
9	Validation of component cooling water pumps: all ON	ARO
10	Validation of nuclear service water pumps: all ON	ARO
11	Validation of containment fan coolers: at least two ON	ARO
12	Validation of containment ventilation: isolated	ARO
13	Validation of boron recirculation pumps: all stopped	RO
14	Validation of control room ventilation: isolated	ARO
15	Check status of main steam line isolation valves: if T-avg < 292 c, isolate MSIVs and all bypass valves	ARO
16	Check containment spray: if containment pressure > 0.15 Mpa, initiate spray	ARO
17	Validation of SI flow	RO
18	Validation of emergency feedwater flow (EFW)	ARO
19	Validation of EFW valve alignment	ARO
20	Validation of SI valve alignment	RO
21	Validation of T-avg: if < 292 c, stop steam dump	RO
22	Validation of PZR relieve valves: all valve closed	ARO
23	Validation of PZR safety valves: all closed	ARO
24	Validation of reactor coolant pumps: at least one is running	RO
25	Check is there any S/G with level or pressure in a uncontrolled decreasing manner	ARO
26	Check is there a secondary radiation alarm: if yes, go to E-3	ARO
27	Validation of RCS integrity	RO
28	Check is it necessary to reduce SI flow	RO
29	SI termination	RO
30	Monitor critical safety function (CSF)	RO
31	Reset SI signal	RO
32	Reset AFS signal	ARO
33	Check S/G level: if any S/G level is uncontrolled increasing, go to E-3	ARO

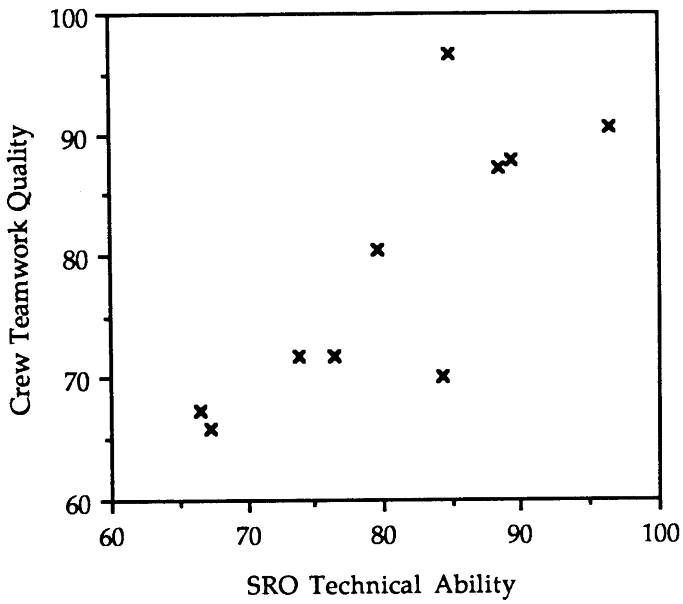

Figure 3.3 - Correlation of Technical Ability and Teamwork Quality Ratings

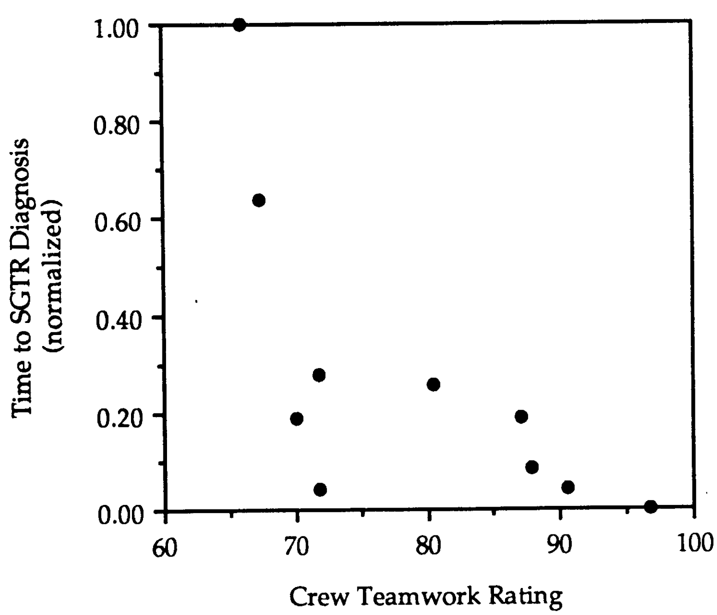

Figure 3.4 - Correlation of Teamwork Quality and Time-to-SGTR-Diagnosis

4. APPLICATION OF CREW MODEL TO SGTR

4.1 Introduction

Chapter 2 describes the detailed modeling framework developed to simulate operating crew behavior during an accident; Chapter 3 describes relevant data collected from a non–U.S. PWR (the "Charles River Plant"). This chapter describes the application of the framework and data to the early phases of a steam generator tube rupture (SGTR) scenario. The purpose of this application is to demonstrate the capability of the modeling approach in handling individual operator cognition and the interactions between operators. The model is benchmarked by comparing its predictions with crew behavior observed during SGTR training simulator exercises.

The crew model is implemented using the SIMSCRIPT II.5 simulation language; key features of this language are briefly described in Section 4.2. Section 4.3 describes the plant model used to simulate the physical behavior of the plant during the accident. Section 4.4 covers the implementation details for the modules representing the individual operators, and Section 4.5 discusses the interactions between these modules. Section 4.6 compares the predictions of the simulation model with observed crew behavior in a number of benchmarking calculations.

4.2 Simulation Language: SIMSCRIPT II.5

The modeling framework described in Chapter 2 requires the treatment of four entities (the SRO, RO, ARO, and the plant) that perform actions, change state, and interact over time. More generally, it requires the scheduling and execution[10] of subroutines ("routines") representing events (system changes occurring at a discrete points in time) and processes (linked sets of related events occurring over finite time intervals)[11].

A number of programming languages are available to fulfill these requirements. This work uses the SIMSCRIPT II.5 language [43]. SIMSCRIPT II.5 is a commercial, general programming language which is similar to FORTRAN but has additional facilities to model events and processes. Recent extensions allow treatment of continuous simulation problems (involving the solution of time–dependent differential equations) [44]. Because of the simplicity of the physical plant model used in this report (see Section 4.3), this continuous simulation capability is not exercised in this analysis; it might be useful in later efforts when more detailed physical models are integrated into the analysis.

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[10]Scheduling is the modeling process in which "event notices" (pointers to specific event routines) are placed in the simulation's pending list (briefly discussed in Section 2.1). The event notices are placed in the order in which their respective event routines are to be executed. Execution of an event routine involves the advancement of the simulation clock up to the execution time for the event, as well as the performance of actions specified by the routine. Note that these actions can include changes in the pending list (e.g., the deletion or addition of pending event notices).

[11]Because process routines are used only to structure the execution of a number of events, the notion of a process not as fundamental to the model as the notion of an event. However, from the standpoint of object–oriented modeling, processes are useful entities because they naturally represent situations where the sequence of events/actions/decisions is, barring interruptions, largely predefined (e.g., when following a written procedure). Note that the concept of "interruption" is meaningful when discussing processes, and not when discussing events.

In comparison with FORTRAN, SIMSCRIPT II.5 has a number of features to aid the modeling of a complex, dynamic system. First, as mentioned above, it is specifically designed to treat events and processes. For example, the user needs to specify such details as the time to initiate a process and the duration of portions of the process, but does not need to create the scheduling routines that use this information. Second, the syntax of SIMSCRIPT II.5 is very English–like; this makes the coding easier to understand (especially by people who are not the original code authors) and enhances code maintainability. Third, SIMSCRIPT II.5, like other advanced programming languages (e.g., C) allows the user to create hierarchial data structures relatively simply (FORTRAN only allows the use of arrays). These data structures are useful for representing an operator's short–term memory and static knowledge base.

To enlarge on the last point, every model entity in a SIMSCRIPT II.5 program is represented using a data structure (illustrated schematically in Figure 4.1). The data structure can include scalar parameters (termed "attributes"), subscripted arrays (as in FORTRAN), and lists (termed "sets"). Arrays can be used to store information about related scalar parameters. Sets are used to indicate relationships between the model entity "owning" the set and the model entities "belonging" to the set (alternatively, being a "member" of the set). A particular version or state of the model entity is defined when its attributes, arrays, and sets are assigned particular values (members, in the case of sets). Section 4.4.1 discusses the particular attributes and sets used in modeling the characteristics and knowledge of each individual operator.

Appendix C provides a simple SIMSCRIPT II.5 program designed to illustrate these features. The program was created, compiled, debugged, linked, and executed within the SIMLAB programming environment [45] on a 25 MHz PC/386–class computer. Along with the program, the appendix provides a number of figures that show the dynamic development of the pending list; this serves to illustrate how the SIMSCRIPT II.5 coding is used in scheduling and executing independent events and events within processes.

4.3 Plant Model

For the purpose of demonstrating the crew modeling approach, currently available thermal hydraulic codes are too complex; the computing needs of most codes exceed the capabilities of a personal computer, the hardware platform chosen for this study. Therefore, a simplified physical model, which uses linear regression to correlate a physical variable with other related variables, is used. The data used to develop the necessary correlations are mainly derived from a PWR thermal hydraulic simulation code called PRISM [31].

PRISM is a sophisticated, graphical interface simulation code that has many of the physical models and control algorithms built into the Seabrook plant simulator. It allows users to interact with the simulation while running on a personal computer. Users can halt a simulation, key in desired hardware status changes and operator actions, and resume the simulation. In a steam generator tube rupture (SGTR) sequence, which has been chosen for the demonstration case study, some operator actions that can be treated by PRISM are: starting up a second charging pump, reducing reactor power, tripping the reactor manually, and opening or closing the steam generator relief valves and steam dump valves.

To develop a simple but realistic plant model for the analysis, a series of runs of PRISM on the SGTR sequence, with and without operator actions, was done. The output data were then carefully compared with the data collected from the Charles River Plant to which the crew model is applied. Some discrepancies between actual and predicted values were found for two plant parameters: the pressurizer (PZR) level before reactor trip, and the steam generator level after reactor trip. (Note that these discrepancies are not unexpected because there are physical differences between the 4–loop Seabrook plant, to which PRISM is benchmarked, and the 3–loop Charles River Plant). In this study, therefore, the PRISM predictions for these two parameters are modified to reflect the observed plant status confronted by the actual crew.

Appendix D presents the plant model equations employed in this analysis. As shown in that appendix, thirteen important physical variables are included in the simplified plant model. They are:

- charging flow rate
- steam generator pressure
- main feedwater flow rate of the faulted steam generator before reactor trip
- main feedwater flow rate of the intact steam generators before reactor trip
- steam flow rate of the faulted steam generator
- steam flow rate of the intact steam generators
- pressurizer level
- primary pressure
- safety injection flow rate
- hot leg temperature
- level of the faulted steam generator
- levels of the intact steam generators
- reactor power

The linear regression equation used to predict a physical variable has the form:

$$y = B_0 + B_1 * x_1 + B_2 * x_2 + \ldots$$

where y is the dependent variable, the B_i are the coefficients obtained from the linear regression analysis, and the x_i are the related physical variables. In addition to the thirteen physical variables mentioned above, the x_i also include the following:

- the number of ruptured tubes
- how long the pressurizer relief valve has been manually opened
- how long the pressurizer spray valve has been manually opened
- how long the steam dump valves to the condenser have been manually opened for cooldown and depressurization

The calculated results compare quite reasonably with the corresponding PRISM outputs, as shown in Table 4.1. Note that the PRISM data for the pressurizer level and steam generator level have been modified to reflect the real values facing the crew. In Table 4.1, the largest discrepancy is found for pressurizer level after reactor trip, which is not critical to crew responses. Therefore, no efforts have been made to obtain a better correlation.

Note that the plant model is capable of activating an alarm when a variable exceeds its set points, of accommodating the effects of operator actions on plant behavior, and of handling the failures of some critical systems or components. An alarm will be actuated when the physical variable is higher or lower than the built–in set points. For example, a pressurizer level deviation alarm will be activated when the pressurizer level is 5 percent lower (or higher) than the normal operating value. An operator action that will affect plant behavior is simulated by converting this action into a "boundary condition" governing the behavior of the directly affected variables. For example, the operator action "start up a second charging pump" will change the status of the charging pumps and hence increase the rate of the charging flow. The effects of this operator action on other physical variables (e.g., pressurizer level and pressure) is then obtained through the dependencies of these variables on the updated value of the charging flow. The failure of a system or component (e.g, failure of all emergency feedwater pumps) is treated in the same manner. In this deterministic model, the time for equipment failure is treated as one of the external code inputs. The boundary conditions for the physical model can also be found in Appendix D.

The physical model is an integrated part of the overall crew model. The model provides information to the operator modules via output to the control board displays. Three sets are used to simulate the control board displays: the PARAMETER.SET[12] (containing the current values of key parameters), the ALARM.SET (containing the current status of key alarms), and the SYSTEM.STATUS.SET (containing the current statuses of key systems). Information from these sets is obtained by the operator modules through a variety of monitoring processes, as described in Section 4.4.2.1. The operator modules can also affect the plant model; this is discussed in Section 4.5.1.

4.4 Individual Operator Modules

In the modeling framework discussed in Chapter 2, an individual operator module receives input from the plant module and from other operator modules. This input and relevant information from the module's knowledge base are processed in four stages: monitoring, situation assessment, planning, and execution. The situation assessment stage is further divided into concern generation, concern merge, control activity (i.e., fault diagnosis), and script selection substages. The output from an individual operator module can be either an action that affects the plant behavior or a message for one or both of the other operators.

This section describes how the modeling framework is implemented in an analysis of the early phases of a steam generator tube rupture (SGTR) accident. Section 4.4.1 describes the manner in which information is stored in the operator module's short term memory and static knowledge base. Section 4.4.2 provides a functional description of each of the stages or substages of task–related cognitive activity (excluding the planning stage). Due to the distribution of responsibilities among the crew members, the function of each (sub)stage may be different for the different operators (i.e., the SRO, RO, and ARO). Section 4.4.3 describes the implementation of the planning stage, i.e., the control mechanisms of the implemented model. These control mechanisms are implemented by two levels of "managers." Variations in operator knowledge and behavior treated in this study are summarized in Section 4.4.4. Possible variations include the selection of alternatives in responding to a cue, the time spent in executing a task, the degree of short term memory decay, and an operator's responses to increases in stress level. A simplified flow diagram for the individual operator module is shown in Figure 4.2.

4.4.1 Operator Module Characteristics

In this study, the individual operator modules employ the same information processing mechanisms (discussed in Section 4.4.2 below). Differences between operators

[12]In this chapter, the program names of particular model constructs, e.g., the PARAMETER.SET, are referred to using capital letters. Lower case letters are used for related entities and concepts. Note that because SIMSCRIPT II.5 allows a very English–like naming convention, the program names are often nearly identical with the entity/concept names.

are modeled by modifying the operator's individual characteristics (e.g., the operator's technical ability), the contents of the modules' memory (short–term and long–term) and the specific rules used during fault diagnosis control activity.

The operator's individual characteristics are stored as attributes of the associated operator module. Table 4.2 lists the attributes used. Note that most, if not all, of these attributes can change over the course of the accident.

To allow treatment of the dynamic nature of memory and of some of the complexity of the information stored in memory, an operator's short–term and long–term memory are modeled using a variety of sets. Each set is owned by an operator module; each set can contain data structures related to specific pieces of information. For example, the operator's set of scripts stored in the static knowledge base (the SCRIPT.SET), contains the scripts used by the operator in responding to different cues. Each script is a data structure (with its own attributes). Table 4.3 lists the different sets owned by an operator module. Note that two sets, the MESSAGE.SET and the PHENOMENA.NOTICED.SET, are "recorders." These sets are useful for model execution, but do not necessarily correspond to or emulate any actual psychological entities. The following section discusses how the sets listed in Table 4.3 are used in modeling the behavior of individual operators.

4.4.2 Functional Description of Individual Model Stages

4.4.2.1 Monitoring Stage

As discussed in Section 2.4.1.1, the operator module receives information from the plant via general or specific monitoring processes. The purpose of general monitoring is to determine if the plant is in an abnormal condition; the purpose of specific monitoring is to gather information needed to respond to an ongoing scenario. Section 2.4.1.1 also recognizes that the information retrieval process can be passive (e.g., when an alarm notifies the operator of an abnormal situation).

To implement these ideas, three monitoring process routines are employed: general monitoring, specific monitoring, and alarm monitoring. General and specific monitoring are processes activated[13] by an operator module as a result of its earlier planning and decision making. Note that, because of his specific responsibilities, it is assumed that the SRO never performs either general or specific monitoring. Alarm monitoring is a process activated by the occurrence of an alarm. All monitoring process routines represent actions (or sets of actions) to be performed by the operators. Like any other actions, they can be interrupted by higher priority events and processes.

An operator module can execute a general monitoring process only when there are no other tasks to perform, i.e., when the module's concern list and action list (introduced in Section 2.4.1) are both empty. The process can be terminated if any new tasks need to be performed. During general monitoring, an operator module monitors all plant parameters until an interesting one is found. The order with which the operator monitors the parameters is determined by the dynamic priority of each parameter and the operator's dynamic filter threshold for the different parameters.

Initially, a parameter's priority assignment is affected by an operator's area of responsibility and training, and by the plant's operating history. The priority can increase

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[13]Recall that, in a simulation analysis context, "process activation" refers to the creation of a process – a set of linked actions/events – and the scheduling of that process.

when the system with which the parameter is associated is being currently monitored by the operator[14]. For example, the occurrence of a "pressurizer level deviation alarm" will direct the operator's attention to the pressurizer; this, in turn, can increase the priorities of the pressurizer level, pressurizer pressure, and charging flow (which affects level).

As discussed in Section 2.4.1.1, the concept of a "filter threshold" is used to model the limited attentional resources of the operator. In this analysis, the operator's filter threshold (whose value is carried by the attribute FILTER.THRESHOLD – see Table 4.2) is treated as a function of his stress level. This is further discussed in Section 4.4.4.3.

During general monitoring, the operator module only monitors those parameters with priorities higher than the filter threshold, starting with the parameter with the highest priority. The status (e.g., increasing or decreasing) and value for each monitored parameter are compared with the operator's expectations for this parameter[15]. Whenever the parameter status is expected and the value is within a tolerance band (the degree of tolerance is specified by the user), the operator module updates its expectations (as represented by the PLANT.PROPERTY.SET) and goes on to the next parameter; otherwise, the parameter is noted as being interesting[16] and the monitoring process is stopped. The module may also send a message to the other operator modules related to the unexpected status/value of the observed parameter.

It should be noted that this filtering based on unexpectedness of parameter behavior does not, strictly speaking, belong in the Monitoring Stage. Instead, as discussed in Section 2.4.1.2, it belongs in the *concern generation* substage of the module's Situation Assessment stage. In this work, unexpectedness filtering is performed concurrently with legitimate Monitoring Stage filtering to simplify model implementation. The threshold for all Monitoring Stage filtering is represented by the heavy bar in Figure 4.2. This indicates that some parameters may not be observed by the operator during general monitoring.

A specific monitoring process can be initiated by the ARO or RO when specific information from the plant is demanded. For example, in responding to an SRO's inquiry concerning pressurizer level, the RO is required to specifically monitor the pressurizer level. Due to the characteristics of this monitoring process, the concepts of priority and filter threshold are judged to be inapplicable. Thus, a specific monitoring process is assumed to be always successful. (Note that "success" means that the desired information is not filtered; it does not guarantee that the trend or deviation of interest is detected.) The observed information is treated as a "phenomena noticed" and may also be treated as a message to be sent to other operators.

An alarm monitoring process is activated by a plant alarm. An alarm is assumed to always interrupt an operator's ongoing actions due to its salience and unexpectedness. Following the interruption, each operator will start the process of alarm identification.

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[14]Systems being monitored are filed in the SYSTEM.ATTENTION.SET.

[15]The expected statuses and values of the different parameters are stored in the module's PLANT.PROPERTY.SET. Note that since each operator can have different expectations, each module has a separate PLANT.PROPERTY.SET.

[16]In this model, noteworthy parameters and alarms are termed "phenomena noticed." Associated data structures, called PHENOMENA.NOTICED (see Figure 4.3 for the general form of this data structure), are created and stored in the operator module's PHENOMENA.NOTICED.SET. This set acts as an artificial recorder and is not meant to necessarily correspond to any actual psychological entity.

This is done by creating a "phenomena noticed" for the alarm; later processing (in the *concern generation* substage of the Situation Assessment stage) will deal with the phenomena noticed.

The monitoring stage is used to represent the receipt of messages from other operators, as well as information from the plant control board displays. Incoming messages are assumed to be received if their importance exceeds the listening module's associated threshold (the MESSAGE.RECEPTION.THRESHOLD), which is assumed to be a function of the receiver's confidence in the sender. As mentioned in Section 2.5.1, the task–related information contained in received messages is assumed to be undistorted. Any non–task related information contained in a message that may affect the receiver's emotional state (e.g., a negative tone) is treated separately. Received messages, like noteworthy parameter values and alarms, are treated as phenomena noticed. Unlike general and specific monitoring, no particular process routine must be executing to allow message reception. Unlike alarm monitoring, not all messages are assumed to be received, nor is a process routine dedicated to message handling activated when a message is received.

In general, communication between operators is modeled explicitly, since a review of the SGTR exercise videotapes indicates that the set of possible messages during the exercise is fairly limited. One exception to this rule arises in the treatment of alarm monitoring. During this process, for example, the SRO may ask the ARO to provide information needed to confirm his guess about the nature of a given alarm. (He cannot obtain this information himself without moving closer to the alarm panels.) For ease of implementation, the time delay in these information exchanges is considered, but the communication process itself is not explicitly modeled. Each operator's alarm monitoring process is assumed to yield the same information.

The output of all monitoring processes can be a "phenomena noticed" (i.e., a PHENOMENA.NOTICED data structure which is stored in the PHENOMENA.NOTICED.SET), a message to be sent out later, or both. Section 4.5 discusses the message exchange process; the processing mechanisms for phenomena noticed are described below.

4.4.2.2 Situation Assessment Stage – *Concern Generation* Substage

Whenever a new "phenomena noticed" is recognized, a routine to generate an associated "concern" is activated. Recall that a "concern" is defined as an issue that the operator believes needs to be dealt with; a CONCERN data structure (see Figure 4.4) is used to provide information to the operator module that identifies the nature of the concern. Activation of the concern generation routine is controlled by the control mechanisms discussed in Section 4.4.3.

There are two major types of phenomena noticed: plant parameters (including alarms) and received messages. Since a phenomena noticed of the first type is either the information needed by the operator or information judged to be interesting, a CONCERN data structure related to it will be immediately generated.

In the case of received messages, a concern may or may not be generated. If the message is related to a plant parameter, a concern will be generated only if the message is unexpected (by the receiver). Note that a plant parameter value unexpected by the message sender may not be unexpected by the receiver; this is treated in the model by allowing different operators to have different criteria for unexpectedness. Whether or not a concern is generated, the receiver's knowledge of the status/value of the plant parameter related to the received message (this parameter is stored in the PLANT.PARAMETER.SET of the receiving operator module) is always updated.

For a message not related to a plant parameter, a different threshold is used to decide whether a concern will be generated. This threshold (the module's MESSAGE.TO.CONCERN.THRESHOLD) is compared with the receiver's willingness to handle a message to decide if a concern should be generated. The receiver's willingness is a function of the priority of the message (put in the form of a phenomena noticed) and the relative confidence of the receiver in the sender. The higher the message priority and the relative confidence are, the higher the value of the willingness will be. The priority represents the importance that the receiver assigns to the message; this can differ from that assigned by the sender. The implementation of this filtering process is further discussed in Section 4.5.

When a new concern is generated, several attributes are assigned to it (see Figure 4.4). For example, the PRIORITY attribute of a concern represents its importance in competing with others for processing resources; this priority is defined in the model input file. Different priorities may be assigned to the same concerns by different operators. The attribute FILE.TIME stands for the time a concern is generated and is used for estimating when the concern will be forgotten by the operator (i.e., dropped from short–term memory). Table 4.4 shows how a number of different model entities share the same types of attributes.

After the assignment of attributes, the new concern is filed in the concern list (called the CONCERN.LIST in the program), which is assumed to be contained in short–term memory. The concerns are filed in the order of their priorities. Barring future modifications of the concern list, they will later be processed in that same order.

4.4.2.3 Situation Assessment Stage – *Concern Merge* Substage

The function of this substage is to merge concerns that are related to the same system or issues, as discussed in Section 2.4.1.2. Whenever a new concern is filed in the concern list, this substage searches for other concerns in the concern list that are related to the new concern. If a related concern is found, then the new concern can either be subsumed by the existing (already filed) concern, or a new, merged concern can be created. As an example of the latter case, if the new concern is "pressurizer level is decreasing" (perhaps as the result of a message sent by another operator) and if this concern is already in the concern list, the new, merged concern is "pressurizer level still decreasing."

The rules used to implement the merging process are summarized in Table 4.5. This table lists the new concerns (to be merged), the existing concerns in the concern list, and the new, merged concern. If the new, merged concern is identical to an existing concern, the priority of this concern is increased. The priority of each concern ranges from 0.1 to 1.0. When a new concern is merged into an existing concern, the priority of the new, merged concern is increased by 0.1 over that of the existing concern until the maximum value is reached. Note that Table 4.5 reflects some of the differences in concern merge processes, due to the distribution of responsibilities among the operators.

4.4.2.4 Situation Assessment Stage – *Script Selection* Substage

The concern list provides a prioritized list of concerns to be dealt with by the operator. After the concern list has been updated (in the *concern merge* substage), the operator module must decide if the most pressing concern should be processed immediately (by interrupting processing of the current concern or current actions) or if it can wait.

(The control mechanisms governing this decision are discussed in Section 4.4.3). Concern processing involves the selection of appropriate automatic (i.e., trained) responses, as performed by the *script selection* substage of the Situation Assessment stage. It can also involve the initiation of the *control activity* substage for performing fault diagnosis, as described in the following section.

The *script selection* substage treats two types of automatic responses. The first type is appropriate to the response of the Charles River Plant crew when Emergency Operating Procedures are not being used. This applies largely to events occurring before reactor trip or safety injection actuation; it involves the use of scripts based on the Abnormal Operating Procedures as memorized by the operators. The second type is appropriate especially to events occurring after reactor trip or safety injection actuation; it involves the use of Emergency Operating Procedures that are read aloud by the SRO during the accident. The appropriate script or procedure[17] is selected by the operator module by matching the name of the concern being processed with the names of the various scripts and procedures stored in the operator's knowledge base.

A script may consist of one or more actions to be executed by an operator. It is represented by a SCRIPT data structure. (Figure 4.5 illustrates this structure.) Possible SCRIPT structures are stored in the operator module's SCRIPT.SET. The priorities of the actions indicated by a particular script are assumed to be equal to that of the concern sharing the script's name. For each action, several alternatives may be included. The choice of a specific option among alternatives is dependent on the operator's characteristics, including his technical ability and his self–confidence. These selection mechanisms are further discussed in Section 4.4.4. The actions are represented in the model by ACTION process routines; these routines are filed in the ACTION.LIST until they can be processed. Action execution is further discussed in Section 4.4.2.6.

The operator module's static knowledge base contains all of the Emergency Operating Procedure steps to be applied after reactor trip/safety injection actuation, as well as the scripts described above. (By including the procedure steps in the knowledge base, the program avoids the need to explicitly model the SRO reading the procedure steps aloud). Each step is represented using a PROCEDURE.STEP data structure (see Figure 4.6). Unlike a SCRIPT structure, no alternatives for an action are allowed in a PROCEDURE.STEP structure. This is because operator training at the Charles River Plant stipulates that the operators are to follow the Emergency Operating Procedure steps as precisely as possible; this work does not investigate situations where the operators do not adhere to their training. In the case of the SRO, he is limited to reading the written procedure steps; usually his judgment is not required unless a procedure step is related to the branching point or is ambiguous. Those steps that require operator judgment are treated using scripts; this allows treatment of SRO decision making among alternatives. In the case of the RO and ARO, a procedure step is actually a command from the SRO. Thus, no alternative is generally allowed. (Scripts are developed for those procedure steps where some variations are possible.)

Although the procedure steps are stored separately in the knowledge base, procedure following is a continuous process. In the case of the SRO, this continuous execution is facilitated by ensuring that each PROCEDURE.STEP structure (owned by an SRO) contains the names of the previous and the current steps. A particular step is chosen by matching the name of a concern, generated from a received message, with the name of the

[17]Although procedure following is a form of scripted activity, this discussion uses the term "script" only for activities prior to reactor trip/safety injection actuation.

appropriate procedure step. (Note that training requires that the operators announce when a step has been completed). Once matched, an action related to the current step (in this case, a message exchange of a command type) is filed in the action list. On the other hand, a subordinate's PROCEDURE.STEP structure indicates the name of the current procedure step being followed and the operator responsible for executing that step and for sending a message to the SRO after execution. (The attribute RESPONSIBILITY is used to identify the responsible operator.)

Not all of the operator activities in processing a concern lead to immediate filing of actions in the action list. (Recall that the action list is used to organize actions that are to be executed as soon as attentional resources are available.) In two cases, involving: i) suggestions made by a subordinate to the SRO, and ii) repeated messages from the SRO to his subordinates, the associated actions may be intentionally scheduled for execution at a later time by an operator. Unlike other actions, these scheduled actions, shown in Figure 4.2, can be generated and scheduled during the execution of certain actions, as well as during the *script selection* substage.

Regarding suggestions, the highly centralized structure of the Charles River Plant crews and the data collected from the field study (discussed in Chapter 3), indicate that that the ARO is unlikely to make suggestions. The likelihood that the RO will voice a suggestion depends on the RO's personal characteristics and his relationship with the SRO. It is assumed in this model that a suggestion may be "brewed" (but not immediately voiced) by the RO after a script is selected or after certain actions have been executed (e.g., the operators observe some unexpected values of a given plant parameter). The bold threshold bars crossing the links between the Script Selection and Ongoing Action processes and the Scheduled Action storage area in Figure 4.2 represent the points in the program where the RO module decides if a suggestion will be brewed. The criteria used to make the decision are discussed in Section 4.4.4.

Regarding repeated messages, it is assumed that the SRO always expects a return message from his subordinates when he has sent them a command or inquiry. If a response is not received in a certain amount of time, the SRO is assumed to repeat his original message. The SRO module, therefore, always brews a repeat message as soon as a command or inquiry has been issued.

The brewed suggestions and repeated messages are stored in the operator module's EXPECTED.MESSAGE.SET (treated in this model as being identical to the Scheduled Action storage area shown in Figure 4.2). A time delay is assigned to each scheduled action. This represents the time at which a scheduled action will be filed in the action list. During this time period, if the expected response is received by the operator, the scheduled action is cancelled. (This is implemented by generating a concern associated with the responding message, checking to see if this concern matches any scheduled actions, and cancelling the associated scheduled action.) Based on data collected in the field study, a nominal value of 1.5 minutes is assigned to all scheduled action time delays.

4.4.2.5 Situation Assessment Stage – *Control Activity* Substage

As mentioned in Chapter 2, logical reasoning processes for fault diagnosis and rule–based behavior are performed in parallel by an operator during emergency operations (conscious and subconscious activities can be processed simultaneously). In this model, rule–based behavior is treated by the *script selection* substage and subsequent processing; fault diagnosis is represented by the *control activity* substage.

The fault diagnosis control activity uses logical reasoning to find the root cause of the accident scenario. It needs structured information from the knowledge base and also evidence on the current status of the plant (some of the latter is obtained from the concern list). Sophisticated knowledge base representations have been developed in other work (e.g., [10,15,16]). Such representations may be mandatory for treating atomistic reasoning of operators when confronted with highly unfamiliar situations (for which they have decided that their scripts/procedures are inadequate). This application of the crew model deals with a well–defined and well–understood scenario, and therefore can use a much simpler representation of the knowledge base.

Figure 4.7 illustrates in logic tree format the small number of production rules used to emulate (at a fairly high level) the operator's knowledge related to the diagnosis of a steam generator tube rupture accident. The left–hand side tree represents the operator's reasoning processes starting from the primary side abnormalities, while the right–hand side tree represents the reasoning processes starting from secondary side abnormalities. Each tree has a three–level logical reasoning process, that is, three production rules.

The production rules represented in the two trees take the form

$$\{A_1 \text{ AND } A_2\} \rightarrow B$$

where A_1 is a proposition (a logical statement that is either true or false) related to an initial condition, A_2 is a proposition related to any corresponding evidence, and B is a conclusion. For example, the first production rule on the primary side tree has the "PZR (pressurizer) level deviation alarm on" as A_1, "PZR level still decreasing" as A_2, and "primary side leakage" as B. This intermediate conclusion serves as the A_1 for the next logical level in the same tree and also functions as A_2 in the second level of the secondary side tree.

To implement these production rules, the model employs two process routines: CONTROL.ACTIVITY.1 and CONTROL.ACTIVITY.2. These correspond to each of the two lines of reasoning shown in Figure 4.7. These processes are activated whenever the name of a concern matches the name of any of the initial boxes (e.g., "PZR (pressurizer) level deviation alarm on") in Figure 4.7. Once a control activity process is activated (the activating information acts as A_1), it searches for corresponding evidence (A_2) in the concern list. Once the related A_2 is found, the conclusion B will be generated and filed in the concern list. If A_2 can not be found, this level of control activity will either cycle until A_2 is found or generate another concern to look for A_2. For example, in the second level of the secondary side tree, the "SG problem" may generate a concern called "check SG mismatch" if the concern "SG mismatch clear" is not found in the concern list. The control activity is terminated when the root cause (SGTR) has been reached.

Due to the nature of the crew structure, and also based on data collected from the field study, it is judged that these logical reasoning processes only need be implemented for the SRO and RO operator modules. Furthermore, due to the division of responsibilities among crew members, the RO is assumed to respond differently when a conclusion is reached. For example, the RO may not declare that an SGTR event is underway when he obtains this conclusion. The model also allows interruption of the RO's fault diagnosis process due to messages received from the SRO. For example, the SRO's declaration that an SGTR is underway, when received and processed by the RO, will stop the RO's fault diagnosis process.

In this model, it is assumed that the two control activities associated with the two logic trees in Figure 4.7 can proceed in parallel (i.e., that they are part of a general fault diagnosis activity aimed at identifying SGTR). These activities use available information to generate intermediate conclusions; the conclusions, in turn, will generate new concerns (perhaps related to the need to gather specific information) that are filed in the concern list for further processing. The time delay associated with the operator's reaching a conclusion at each level of a tree is discussed in Section 4.4.4.

4.4.2.6 Execution Stage

The output of the *script selection* substage of the Situation Assessment stage is a set of actions to be executed. These actions are represented in the model by ACTION process routines. Each different type of action is associated with a different ACTION routine; a new instance (copy) of a particular ACTION routine is activated whenever an operator is required to perform the given action. The event notices for the ACTION routines are ordered in the ACTION.LIST by priority. Execution of actions is controlled by the operator module control mechanisms, as discussed in the next section. These control mechanisms are called into play when the action list is changed; this can be due to the addition of new actions or by an updating of the priorities of existing (already filed) actions. (Recall that the merging process performed by the *concern merge* substage can change the priority of a concern and, hence, the priority of the action related to that concern.) Once an action is chosen for execution, it becomes the operator's "ongoing action," as shown in Figure 4.2.

The use of process routines to model actions is important. Each "action" in the model actually represents a group of related events that are performed by the operator over a finite time interval. As indicated in Section 4.2, the SIMSCRIPT II.5 process routine provides a simple mechanism for executing these events in the proper sequence. Since processes can be interrupted, the process routine also provides a simple modeling mechanism for interrupting the operator's ongoing actions whenever a higher priority problem arises, and for resuming these actions when the interrupting problem has been resolved.

Each ACTION process routine has a number of attributes in addition to priority (see Figure 4.8). The FILE.TIME is the time the action is filed in the action list. It is used to determine when the action is forgotten by an operator due to the memory decay. The duration of an action is denoted by the attribute WORK.TIME. This time can change as the scenario progresses. It is also dependent on the operator's individual characteristics, as discussed in Section 4.4.4.

Actions executed can be categorized in three classes: manipulation, monitoring, and message exchange. The implementation of manipulation–class actions and their effects on the plant behavior are discussed in Section 4.4.3. Monitoring–class actions are discussed above in Section 4.4.2.1. A message exchange is usually attached to an action belonging to one of the other two classes. Such a linked set of actions is treated as a single action when executed. However, a message exchange can also stand alone as an action. The execution of these actions will cause an operator to interact with the plant and the other operators. Communication between operators is further discussed in Section 4.5.

4.4.3 Control Mechanisms

The preceding discussion shows how this study's implementation of the conceptual individual operator model gathers information, generates concerns, selects scripts, and performs actions. This section provides an overview of the control mechanisms needed by the model to schedule these activities. These mechanisms can be viewed as implementations of the Planning Stage (shown in Figure 2.1), where planning, in a broad sense, can include unconscious as well as conscious processing.

Two levels of manager functions are used to control the order of execution of the different routines comprising the individual operator module. The general manager, called the "action/concern manager," is in charge of overall program control. This manager decides when the two lower level managers should be activated. The first lower level manager, the "concern manager," is in charge of all activities that occur between the phenomena noticed recorder and the action list (going counter-clockwise in Figure 4.2). The "action manager" controls the activities that occur between the action list and the phenomena noticed recorder, as well as the message exchanges with other operators.

4.4.3.1 Action/Concern Manager

An "action/concern manager" is activated whenever one of the following events occurs:

- An alarm is activated.
- A "scheduled action" (a delayed action associated with either a suggestion or a repeated message, as discussed in Section 4.4.2.4) is filed in the action list.
- An intermediate or final conclusion is reached during control activity.
- An action (modeled as a process) has been completed.
- A message is received by the operator.

Regarding the first bullet, Section 4.4.2.1 states that an alarm is assumed to always interrupt any ongoing action and activate an alarm monitoring process (an alarm monitoring process, when filed in the action list, is always assigned the highest priority). This monitoring process then becomes the operator's ongoing action. Regarding the second bullet, a scheduled action is filed in the action list (see Figure 4.2) when the brewing time for the scheduled action has elapsed. In these two situations, only the contents of the action list are changed. Thus, the action/concern manager only needs to activate the action manager, discussed in Section 4.4.3.3 below.

The third bullet involves changes in the concern list, since a conclusion reached in the fault diagnosis processes leads to the generation of a new concern (see Section 4.4.2.5). The other two bullets involve situations where the contents of the operator's phenomena noticed recorder (the PHENOMENA.NOTICED.SET). Since these situations may eventually cause changes in the action list, as well as in the concern list, both the "concern manager" and the "action manager" are activated by the action/concern manager.

4.4.3.2 Concern Manager

The concern manager controls the processes involved in the identification of potential concerns, based on available data, and the selection of actions to deal with these concerns. Whenever this manager is activated, it first calls the routine to generate concerns (called CONCERN.GENERATION). The concern generation routine searches for new "phenomena noticed" and applies any applicable thresholds (see Section 4.4.2.1) to those items to decide if a related concern should be generated. Note that, as discussed in Section 4.4.2.1, received messages are treated as phenomena noticed. Note also that when this manager is activated by a conclusion resulting from the fault diagnosis process, no new phenomena noticed will be found; the new concern is generated directly from the fault diagnosis conclusion. Figure 4.7 shows, for example, that one possible early conclusion in the fault diagnosis process is that there is leakage on the primary side. This conclusion is translated into a concern which now must be dealt with in the same manner as any other concern.

After concerns are generated, the concern manager next calls a routine to merge related concerns. This routine may generate new concerns, reflecting the combination of the merged concerns, or update the priorities of concerns already filed in the concern list. If the priority of an already filed concern is updated and actions related to this concern have already been filed in the action list (through script selection), the priorities of these actions are also updated.

At this point, the concern list has been updated with new concerns; the priorities of all of the concerns in the concern list may also be updated. The concern manager next calls a routine modeling a portion of the operator's planning activities. This routine determines if the operator's ongoing action should be interrupted by a new, more important concern. The decision is made by subtracting the priority of the operator's ongoing action from that of the new concern. If the difference is large, the script selection routine is called. If not, the concern manager terminates.

The priority difference required to interrupt the ongoing action is specified by the user for each operator using the attribute INTERRUPT.FACTOR. This factor is used to model the degree to which an operator tends to interrupt ongoing actions when a new issue comes up. A large interrupt factor implies that an operator can easily become fixated on a single issue (the "garden path" style of response [10]). A small value for this factor represents an operator who easily jumps from one issue to another. A negative value implies that the operator prefers to jump from issue to issue (this is related to the "vagabond" style of response [10]). Clearly, the value to be assigned to the interrupt factor depends on the basic personality of the operator. It also might vary with the operator's emotional state and with the absolute importance of the ongoing action. Thus, the interrupt factor could be, in principle, a dynamic parameter. In the SGTR application performed in this study, these personality– and time–dependent issues are not explored, and the interrupt factor is assigned a (steady) zero value.

If the concern manager decides to interrupt an ongoing action and handle a concern in the concern list, it simultaneously activates a control activity process (see Section 4.4.2.5) and a script selection routine (see Section 4.4.2.4). This ends the responsibility of the concern manager.

4.4.3.3 Action Manager

An action manager is activated whenever the contents of the action list are changed. These changes may be caused by the actions of the concern manager, by an alarm, or by the addition of a "scheduled action" to the action list. Note that, in the case of an alarm, the action manager will generate an associated action (alarm monitoring) and file this action in the action list with the highest priority. This is one of the two types of actions that bypass the other activities shown in Figure 4.2 (e.g., "concern generation" and "script selection"). The other activities are also bypassed by the message exchange processes for the receivers.

Upon activation, the action manager first compares the priority of the first action in the updated action list with that of the ongoing action. (Note that the action list is ordered by action priority.) The manager also determines the amount of time required to finish the ongoing action. If the difference in priorities and the completion time are large (as compared with the attributes INTERRUPT.FACTOR – discussed in the previous section – and INTERRUPT.TIME.CRITERIA, which is specified by the user), the action manager interrupts the ongoing action. As in the case of the interrupt factor, the time criterion can be used to reflect the personality of the operator, his current emotional state, and the absolute importance of the ongoing action. In this study, however, the time criterion is set equal to zero. Thus, execution of an ongoing action will always be interrupted by a more important concern or action.

When the action manager decides to interrupt an ongoing action[1], the ongoing action is filed back to the action list. Its associated "work time" (the time needed to complete the action) is readjusted to reflect the amount of time already spent on execution. The action manager then selects the first action in the action list and begins to execute it. This ends the duty of the action manager.

After an ongoing action has been completed, the action/concern manager is activated to survey the contents of the phenomena noticed set, the concern list, and the action list. This starts another cycle of cognitive processing.

4.4.4 Modeling Variability Among Individuals

The preceding sections describe the implementation of a general model for the behavior of an individual operator. This section discusses a number of areas where individual behaviors can differ, and the simple models used in this study to represent these variations.

4.4.4.1 Individual Response to Cues

When faced with a concern, an operator module needs to select an appropriate script or procedure to deal with the concern. However, the script/procedure selection process is not deterministic. A review of the Charles River SGTR simulation videotapes indicates a number of differences in operator responses to important cues during the SGTR scenario; these are summarized in Table 4.6.

As mentioned in Section 2.2, the model created in this study is deterministic. In order to treat variability in operator responses to cues, rules linking operator and crew characteristics to observed behaviors are needed. The rules listed in Table 4.7, developed by trial–and–error, appear to provide a reasonable explanation of the observed data. These rules employ the technical ability and self–confidence of the individual operator and the confidence levels between crew members. Note that all of these measures are relative; they measure ability and confidence relative to the abilities and confidence levels of other operators at the Charles River Plant.

Table 3.5 provides the rating of each operator's technical ability, as provided by five former Shift Engineers (the experts). For the ease of implementation, these numerical ratings are categorized into one of the five qualitative levels: high, high–medium, medium, medium–low, and low. The categorization is based on the distance between an individual's rating and the average of ratings over all 10 operators in the same class. For example, the rating of each SRO is compared with the average for all SROs. Translation to qualitative, relative ratings is done by dividing the total observed range of variation into five equal segments. In general, two operators fall into each qualitative level. Table 4.8 provides the technical ability ratings for operators in 4 of the 10 crews considered in this study.

Similar to the development of technical ability ratings, the self–confidence rating for each operator is developed in two steps. First, a quantitative rating is developed based on the raw scores provided in Table 3.3. Second, a qualitative rating is developed based on

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[1]Received alarms and messages are assumed to always interrupt the ongoing action, but do so without invoking the action manager. They also are assumed to always interrupt any ongoing control activity.

this quantitative rating.

Table 3.3 is used to develop the quantitative self–confidence ratings. It is assumed that each operator's self–confidence rating is proportional to the ratio of the sum of confidence ratings that he believes other members would assign him, divided by the sum of his confidence ratings for his fellow crew members. For example, Table 3.3 shows that the ARO in Crew #1 assigns ratings of 70 to the SRO and 80 to the RO. It also shows that he thinks that the SRO would assign him a rating of 92, and that the RO would assign him a rating of 90. The quantitative self–confidence level of the ARO is then taken to be proportional to (92 + 90)/(70 + 80).

It should be cautioned that the ratings provided in Table 3.3 are not guaranteed to reflect each operator's true beliefs concerning his fellow crew members. Issues of personality, status within a group, fear of negative reactions, etc. may affect the ratings provided to the interviewer. In particular, Table 3.3 shows a number of cases where an operator provided uniform ratings for his fellow crew members, possibly indicating a reluctance to express his true feelings. In these cases, judgment is employed to assign self confidence ratings. These judgments are based largely on the expert rating of the operator's technical ability, adjusted by the average technical ability for all operators of the same class, as indicated in lines 1–3 of Table 3.9. However, they are also influenced by the official status (within the crew) of the operator in question.

A three–level qualitative classification is used to categorize the quantitative ratings obtained using the above procedure. For each operator, if the quantitative rating is greater than 1.0, a "high" self–confidence level is assigned, while a "low" level is assigned to a ratio less than 1.0. Others are assigned as "medium" levels.

Lines 4–6 of Table 3.9, which are developed from the raw scores provided in Table 3.3, are used to develop the relative confidence levels between operators. An operator's relative confidence level in another crew member is "high" when his own score in Table 3.9 is five points (or more) lower than that of the other operator. Similarly, his relative confidence level in the crew member is "low" when his score is five points (or more) higher than that of the other. In between these two situations, it is assumed that the operator has "medium" relative confidence in the other operator. For example, in Crew #1, this approach indicates that the ARO has low confidence in the SRO and the RO; the RO and SRO have medium confidence in each other; and the RO and SRO both have high confidence in the ARO.

4.4.4.2 Time Spent in Task Execution

The time spent in executing any given task is likely to vary from individual to individual and from situation to situation. The following simple model is used to treat these variations:

$$\text{task duration} = (\text{nominal work time}) * (\text{time factor}) \tag{4.1}$$

The nominal work times for a number of observable tasks (e.g., monitoring, control manipulation, message exchange) are estimated using the videotaped SGTR exercises as a basis. Table 4.9 presents the values obtained by averaging the observed task durations over all 10 crews. The time factor, which has a nominal value of 1.0, can be used to model individual variability due to personality characteristics. It can also be used to model changes in task duration as the scenario progresses, e.g., as stress increases. Section 4.4.4.3 presents a simple model for modeling the effect of increasing stress on task duration.

Nominal work times for other tasks are not as easily developed. Ref. 46, for example, indicates that the human response time to an existing cue is extremely short (i.e., on the order of milliseconds or microseconds). Based on this information, it is reasonable to assume that the time spent in generating concerns, merging concerns, developing intermediate conclusions during fault diagnosis, and selecting scripts is also short.

Considering the fault diagnosis process, it is assumed that the nominal time required to perform a single step deduction, e.g., to decide that, as shown in Figure 4.7, "PZR level deviation alarm on" (A_1) and "PZR level still decreasing" (A_2) imply "primary side leakage" (B), is constant over all deductions, given that the information (A_1 and A_2) are available. This time required is called the "control activity cycle time." Benchmarking calculations comparing operator behavior by the crew model simulation with behavior observed in the SGTR exercise video tapes indicate that a nominal value of 0.1 minutes for the control activity cycle time yields reasonable results. The same series of calculations also shows that a value of 0.5 minutes may be appropriate for cases when an operator's technical ability is low. Note that this control activity cycle time represents the total time spent in matching the activator (A_1), in searching for the corresponding evidence in the concern list (A_2), and in generating a conclusion (B).

The time spent in generating a concern, in merging related concerns, and in selecting an appropriate script are treated in the same way as the control activity cycle time. The nominal work time for all these processes is assumed to be 0.1 minutes[19].

As a side note, Table 4.9 shows that the time an SRO spends in understanding (interpreting) a procedure step is not treated separately from the time required fo execution of that step (where the SRO reads the procedure aloud to his subordinates). The delay due to interpretation is assumed to be included in the time interval that the SRO is looking at the next procedure step while the subordinates are executing the current step. This assumption is confirmed by the videotaped SGTR exercises and in interviews with the SROs. Thus, the SRO's reading out of the procedure step is treated as an ordinary message exchange.

4.4.4.3 Stress Accumulation and Its Effects

As mentioned in Section 2.4.3, this study hypothesizes than an operator's stress level may be increased by an increased workload, by lack of success in fault diagnosis, and by received messages with negative tones. Data are lacking to prove this hypothesis, or to quantify the effect of stress on operator performance. To demonstrate how stress effects can be treated in the operator crew model, an extremely simple and flexible model is used. The parameters of this model can be varied to reflect differences in individual stress buildup and reactions to stress.

In this model, three components contribute to the dynamically changing stress level of an operator. These are the "burden" stress, the "frustration" stress, and the "irritation" stress. The initial stress level of each operator, representing the operator's state at the time the first abnormality is detected, is usually assigned as "medium" (assigned a nominal value of 3.0 on a 5–point scale). This value can be modified by the user to account for such factors as fatigue.

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[19]Due to the manner in which SIMSCRIPT II.5 treats non–process routines, this time cannot be directly assigned to the related routines. Instead, it is assigned in the concern manager routine. Thus, whenever the concern manager is activated, 0.1 minutes elapse before the routines called by the concern manager are allowed to execute.

The burden stress component is computed as follows:

$$S_b(t) = B_1*(\text{no. items in short–term memory}) \tag{4.2}$$

where $S_b(t)$ is the burden stress at time t and the coefficient B_1 is called the burden factor. This represents the sensitivity of an operator's stress level to his workload. The second item on the right–hand side models the operator's workload. As indicated in Figure 4.2 and further discussed in Section 4.4.4.4, the concern list, action list, and the set of scheduled actions (the EXPECTED.MESSAGE.SET) are all stored in short term memory. Thus, the sum of the lengths of these lists is used in Eq. (4.2). Note that since the operator's short–term memory is updated every 0.25 minutes (as discussed later), the operator's overall stress level will also be updated at least once every 0.25 minutes.

The evaluation of the frustration stress component is somewhat more complicated. In principle, this stress is modeled as being proportional to the time an operator spends in finding the root cause of the accident sequence (SGTR in this study). Recall that there are two logic trees used to represent fault diagnosis, each having three diagnosis levels (shown in Figure 4.7). An operator may need to wait (cycle) for a period of time at each level before a conclusion is reached. This cycling is caused by the operator's failure to find the necessary corresponding evidence (A_2) for that level. It is assumed that an operator's frustration stress will accumulate in proportion to the time spent at each tree level. Whenever an intermediate conclusion (i.e., those conclusions other than the root cause, SGTR) is reached, the accumulated stress will be somewhat relieved. The frustration stress is reset to zero when the root cause is obtained. Note that the total frustration stress is the sum of the stress induced from the operator's inability to immediately process the two logic trees.

Figure 4.9 provides a schematic representation of the frustration stress model. This model can be represented as follows:

$$S_f(t) - S_f(t-\Delta t) = \begin{cases} F_1*\Delta t & \text{diagnosis proceeding} \\ -F_2 & \text{partial diagnosis} \\ -S_f(t^-) & \text{complete diagnosis} \end{cases} \tag{4.3}$$

where $S_f(t)$ is the frustration stress at time t, F_1 is the frustration stress factor, F_2 is the frustration stress relief when an intermediate conclusion is reached in the fault diagnosis process, and $S_f(t^-)$ is the frustration stress just prior to diagnosis of SGTR.

The effects of group interactions (communication) on individual stress are also considered in a simple manner in this study. This stress component is called the irritation stress. Whenever a message is emitted by the sender, a negative tone representing the sender's total stress is attached to the message. The receiver's irritation stress component caused by a received message is assumed to be proportional to the sender's tone:

$$\Delta S_i = (I_1)*(\text{sender's tone} - \text{receiver's tolerated tone}) \tag{4.4}$$

where ΔS_i is the increase in irritation stress, and I_1, the irritation stress factor, represents the receiver's sensitivity to the sender's tone. The receiver's "tolerated tone" is the level of irritating tone a receiver can stand without being irritated. When the value of the term in the parentheses is negative, the irritation caused by this message is set to zero. Thus, no positive effects from the sender's tone are treated in this simple model.

Table 4.10 summarizes the stress model parameters described above, and provides base case nominal values and the potential dynamic range of each variable. These nominal values are set low enough that they do not affect predicted individual or group behavior. (This is consistent with observations from the SGTR exercise videotapes, since no significant stress–related behaviors were observed.) The effects of variations in these parameters are tested in Chapter 5.

As mentioned in Section 2.4.3.2, it is assumed that an operator's accumulated stress will affect his behavior through its effects on the following individual characteristics:

- time factor
- filter threshold
- message sendout threshold
- message to concern threshold
- memory decay time

The time factor is introduced in Eq. (4.1); it is used to modify the nominal amount of time needed to accomplish a given task. Situations where increases in stress lead to increases in task execution time are treated by modifying the time factor.

The filter threshold, discussed in Section 4.4.2.1, only allows information with a certain level of importance to be observed by the operator during general monitoring. Increases in stress can lead to a narrowing of the operator's field of attention (he will focus increasingly on items judged to be of greatest importance). This phenomenon is treated by increasing the filter threshold with stress.

The message sendout threshold, to be discussed in Section 4.5.2, plays a similar role for message transmission. As an operator's stress level increases, he may become increasingly reluctant to send a message to his crew members. This is treated by increasing the message sendout threshold with stress. (This model does not treat a possible alternate reaction, in which the operator may chatter increasingly with accumulating stress.)

The message to concern threshold, discussed in Section 4.4.2.2, is used to determine if a concern will be generated as the result of an incoming message. If a concern is not generated, the message is essentially ignored by the receiver. Increases in stress leading to increasing unwillingness of the receiver to pay attention to the message are modeled by increasing the message to concern threshold.

The memory decay time, discussed in the following section, is used to model the rate at which information is lost from short–term memory. Increases in stress can reduce the memory decay time.

As in the case of the stress accumulation treatment, a highly simplified model is used to demonstrate how stress effects can be dealt with in the crew model. In this model, the parameters listed above are assumed to be proportional to the difference between an operator's stress level and his "stress expression threshold." This latter threshold represents the operator's resistance to the effects of stress. No positive effects are considered, i.e., an operator's efficiency will not be increased even when the threshold is higher than his current level of stress. An assumed linear relationship is used to update those parameter values when the stress changes:

$$\Delta P_i = C_i * \Delta S \tag{4.5}$$

where ΔP_i represents the change in the parameter value and C_i represents the appropriate stress effect coefficient for that parameter. Nominal values for the C_i are provided in Table 4.10.

It can be seen that the simple stress model described provides a good deal of flexibility for the analyst to treat individual variations in stress accumulation and response to stress. A substantial amount of work is required to rigorously, or even semi–rigorously quantify the model parameters. However, even without defensible estimates for the model parameters, interesting insights can be gained by performing sensitivity studies. This is further pursued in Chapter 5.

4.4.4.4 Capacity and Decay of Short–Term Memory

Section 2.4.2.2 points out that two characteristics of short–term memory that must be considered in the analysis are its limited capacity and the decay of its contents. This affects items stored in the concern list, action list, and scheduled actions set. Memory decay is treated using a simple model.

For each operator, a routine is activated every 0.25 minutes to check all items stored in the above–mentioned lists. The routine first calculates the "modified decay time" for each item as follows:

$$\text{modified decay time} = (\text{nominal decay time}) * \left[\frac{\text{item priority}}{\text{normalization priority}}\right] \tag{4.6}$$

where the "nominal decay time" is assigned an initial value of 1.5 minutes, and the "normalization priority" is assigned a value of 0.4. The term in the parentheses models the assumption that the more important an item, the longer it will be remembered. The mean decay time for each item in short term memory is then compared with the difference between the current time and the item's file time (mentioned in Section 4.4.2.2). The file time is the time that an item is filed in short term memory. If the difference is greater than the modified decay time, the item will be removed from the list, i.e., it will be forgotten by the operator.

Note that this step function representation of the forgetting mechanism is not expected to be very accurate. These mechanisms are likely to be better represented by a more gradually decaying process (where the likelihood of forgetting increases with time and with decreased item priority). However, the step function model does provide a simple way to simulate memory decay.

For those items that are not eliminated by the step function decay model, the routine next tests to see if items are lost because the limited short–term memory capacity of the operator is exceeded. The concept of a "magic number" (taking on a nominal value of 7 ± 2) discussed in Ref. 33 and mentioned in Section 2.4.2.2, is adopted for simulating this limited capacity. The magic number is the maximum number of items that a person can recall from his short–term memory. Thus, if the total number of items in the concern and action lists is less than the magic number (scheduled actions are included in the action list), all items are kept. Otherwise, items with lower priorities are removed one by one until the number of items left in short term memory equals the magic number.

The above discussion shows how variations in individual characteristics that affect short term memory decay can be modeled. The nominal decay times, assigned priorities to items, and the magic number can all be varied to reflect differences between different operators.

As a particular example, each plant parameter, concern, or action is assigned a priority by the operator. Operators may assign different values to the same item due to differences in their areas of responsibility, training, education, etc. Priority assignments made in this work rely heavily upon information gathered from interviews with the Charles River Plant operators and from observation of the operators' actions during the videotaped SGTR exercises.

It should be noted that the model allows these priorities to vary dynamically during the simulated accident sequence. For example, the priority of a particular plant parameter will be increased by 0.2 if the system to which it belongs to is being actively monitored. The function of the "concern merge" process can also change the priority of a concern and that of the selected action. As discussed in Section 4.4.2.3, whenever a new concern is merged into an existing concern, the priority of the existing concern is increased by 0.1 (until a maximum value of 1.0 is reached).

4.5 Implementation of Crew Model

The focus of the previous section is on the implementation of the model for an indivdual operator. This section discusses a number of important issues arising when modeling an operator's interaction with the plant and with other operators.

4.5.1 Interactions Between Operators and Plant

The plant model used in this study is described in Section 4.3; the equations employed are presented in Appendix D. This model computes the current values of plant parameters (the parameters are updated every 0.17 minutes), generates alarms when appropriate, and can respond to a number of operator actions. Those parameters appearing on the control board displays are stored in a set called the PARAMETER.SET. The statuses of alarms are stored in the ALARM.SET (Table 4.11 lists the alarms modeled and their respective setpoints), and the statuses of key systems are stored in the SYSTEM.STATUS.SET.

The control room crew members are modeled as interacting with the plant in two ways. First, they monitor information obtained from the control board displays (as defined by the contents of the three sets mentioned above). This model's implementation of three monitoring processes (general, specific, and alarm monitoring) is described in Section 4.4.2.1. Second, they can manipulate control switches, thereby affecting plant behavior. This second interaction is implemented by allowing the operator modules to modify (via specific ACTION process routines) the boundary conditions of the plant model.

Table 4.12 lists the operator actions for controlling the plant that are allowed in this analysis. It can be seen that the number of possible actions is relatively small; this list is appropriate for the early phases of an SGTR accident, but needs to be extended in order to cover the entire scenario.

4.5.2 Interactions Between Individual Operators

One of the basic premises of this study is that crew interactions can be modeled as the result of communications between operators and individual processing of messages received by communication. As pointed out in Section 2.5,, communication can involve task–related or non–task related messages (swearing is an example of the latter), and be transmitted verbally or non–verbally. In this implementation of the crew model, task–related verbal messages are modeled explicitly. (Such an approach is allowed by the limited number of distinct messages of this class observed in the early phases of the SGTR exercises.) Non–task related messages are treated by associating a "message tone" with task–related messages; non–verbal communication is assumed to implicitly included in the treatment of verbal messages.

4.5.2.1 Task–Related Communication

Task–related messages can be associated with other specific actions. For example, a message exchange between the SRO and another crew member usually follows the completion of monitoring or control manipulation process (the crew member informs the SRO of the results of the completed process, and the SRO acknowledges this message). In such cases, the message exchange is included in the process routine for the associated action. There are other cases where the sending of task–related messages is treated separately from other processes. For example, the SRO may command a subordinate to obtain a piece of information from the control board displays after coming to an intermediate conclusion in his fault diagnosis process. In these cases, a separate ACTION process routine is generated and scheduled by the sending operator module. Note that the receiving module does not generate an analogous action process to receive the message; all incoming messages activate the receiver's action/concern manager (Section 4.4.3.1). This manager puts the message in the "phenomena noticed" recorder; the message is then processed through normal channels.

Section 2.5.1 identifies possible failures in the communication of task–related information. Two modes of failure treated in this implementation of the crew model are: a) the sender does not send out his intended message, and b) the receiver does not pay attention to (rejects) the message. Message garbling is not treated; this failure mode is not observed in the Charles River SGTR exercise videotapes, and, moreover, is very difficult to model.

In order to treat the first failure mode, a simple model is used to quantify the willingness of a sender to send out a message. This willingness is assumed to be a function of the priority of the message, as perceived by the sender, and of the relative confidence between the sender and receiver.

$$\begin{aligned}\text{sender's willingness} = {} & \text{message priority(sender)} \\ & + (W_1 - \text{sender's confidence in receiver}) \\ & + [(\text{receiver's confidence in sender}) * (\text{sender's self–confidence}) - W_2]\end{aligned} \tag{4.8}$$

where W_1 and W_2 are both normalization coefficients assigned a nominal value of 0.5. The message priority (as perceived by the sender) usually is affected by the priority of the preceding actions and may depend on the type of the message. For example, a command is assigned a higher priority than a suggestion. The second line models the increase in the sender's willingness when the sender's confidence in the receiver's technical ability is low. The third line models situations where a sender is more willing to send out a message if he believes that the message will not be rejected, i.e., when his perception of the receiver's confidence in his (the sender's) technical ability is high.

The sender's willingness level calculated in Eq. (4.8) is compared with the sender's "message sendout threshold" to decide if the sender will actually send the intended message. Whenever the sender's willingness is greater than or equal to the threshold, the message will then be sent out. Since, as pointed out in Section 4.4.4.3, the message sendout threshold is assumed to increase with increasing stress, it can be seen that the parameter "sender's willingness" models the effects of inherent message importance and of crew structure; the message sendout threshold models the effect of the sender's emotional state (as represented by his stress level). It can also be seen that the sender's net willingness to send a message can change over time.

The possibility that a received message is rejected by the receiver (and therefore does not become a concern) is treated in the similar way. First, the receiver's willingness to handle a message is evaluated as follows:

$$\text{receiver's willingness} = \text{message priority(receiver)} + (\text{receiver's confidence in sender} - W_3) \tag{4.9}$$

where W_3 is a normalization parameter with a nominal value of 0.5. Here, the priority of the message is assigned by the receiver and may differ from that assigned by the sender. The second line models situations in which a receiver is more willing to pay attention to a message when his confidence in the sender's technical ability is higher. Similar to the emission of messages, whether or not a message is handled is determined by comparing the receiver's willingness calculated in Eq. (4.9) and by his current "message to concern threshold." This threshold can also vary with stress.

In addition to outright communication failures, the crew model also deals with situations where communications are delayed. In particular, the sender may decide to delay message transmission if he perceives that the intended receiver is currently occupied. In this model, a receiver is defined to be occupied when he is involved in a message exchange, is monitoring an alarm, or is checking the radiation monitor (which is away from the control panels). The state of the receiver is indicated by the receiver's attribute OCCUPATION.SELF. Whenever the receiver is occupied, the sender will hold the message until the receiver is free. These waiting situations are implemented by letting the sender check the receiver's state of occupation every 0.05 minutes. A message will eventually be sent when the receiver is free or when the accumulated checking time is more than 0.5 minutes (that is, over 10 cycles of checking).

4.5.2.2 Non–Task Related Communication

Non–task related communication can affect crew performance during an accident scenario since changes in the emotional state of the operators and in the relationships between operators can affect task–related communication and the processing of information. Clearly, the construction of general models to generate non–task related communication and to respond to this communication can be extremely complex. This study employs a highly simplified model that allows a limited treatment of these issues.

This model does not explicitly generate non–task related messages. Rather, it assumes that these messages can be treated by associating an emotional tone with each task–related message. The tone of the message is assumed to affect the receiver's stress level. Any resulting changes in the receiver's stress level are then treated using the stress model described in Section 4.4.4.3.

The message tone is assumed to be a function of the sender's stress level at the time the message is sent:

$$\text{tone} = T_2 * (\text{sender's stress}) \tag{4.10}$$

where T_2, the "stress to tone factor," quantifies the fraction of the sender's stress level the sender will express by his tone of communication. This factor is assumed to have a nominal value of 1.0. Note that this model is appropriate for treating messages with negative tones; positive messages are not treated in this study.

When the receiver receives a message with a negative tone, his irritation stress (I_s) is assumed to increase, as discussed in Section 4.4.4.3. Since Eq. (4.10) shows that the stress level of the receiver affects the tone of his messages, it can be seen that this model can treat progressively deteriorating interactions among the crew members. Furthermore, as discussed above, stress can affect the willingness of a sender to send a message and of the receiver to handle a message. (Note that the model assumes that the tone of a message is always noticed by the receiver, even when the message is rejected.) Thus, the model can also treat one path by which a total breakdown of communication is reached.

4.6 Benchmarking and Testing Runs

The crew model, whose implementation details are provided in the previous sections, represents a fairly complex hypothesis for the behavior of a Charles River Plant crew during the early phases of a steam generator tube rupture accident. Not all of the model parameters can be quantified on the basis of direct observation. Even if these parameters could be quantified, it is not obvious that, plausible though the model may be, the model's predictions will necessarily match actual crew behaviors. In order to: a) empirically determine reasonable values for a number of the model parameters, and b) determine if the model is, upon comparison with actual data, reasonable, a number of benchmarking runs are performed.

To accomplish the first objective, a number of preliminary benchmarking runs are made using parameters characterizing 3 of the 10 Charles River Plant crews. By comparing the results from these runs are compared with the videotaped performances of these crews, the parameters of interest are adjusted until a good fit is obtained. A good fit means that

- the model accurately simulates actions of operators and interactions between operators during a SGTR sequence, and
- the simulated crew responses vary with the composition of the crew members in ways that parallel the differences observed in the actual behavior of crew members.

To accomplish the second objective, a fourth crew is simulated in a blind test. The parameters used in this simulation are assigned using the "tuned" rules developed in the benchmarking runs. The results of the tuned benchmarking runs are also of interest, and are discussed in this section as well.

It should be noted that the 4 crews selected (Crews #2, #4, #7, and #10) are chosen to include a wide variety of crew compositions. For example, the technical abilities of the 4 SROs are low, medium, high–medium, and high, respectively.

4.6.1 Benchmarking Runs

The benchmarking runs, performed using parameters characterizing Crews #2, #4, and #7, are used to develop estimates of two model parameters: the "time factor" and the "control activity cycle time." Both of these are discussed in Section 4.4.4.2. The former is used to modify the nominal amount of time spent in any given task [see Eq. (4.1)]. The latter applies specifically to the amount of time spent by each operator in fault diagnosis activities.

To perform the benchmarking runs, nearly all input parameters described in the previous sections are set to their nominal values. In addition to the time factor and control activity cycle time mentioned above, the exceptions are:

- operator technical ability,
- operator self–confidence, and
- an operator's relative confidence in his fellow crew members.

These parameters are assigned values on the basis of interview results, as described in Section 4.4.4.1 (see Table 4.8).

Although not adjusted during these benchmark runs, it should be noted that a number of the nominal values/behavior rules used in these simulations are based on data obtained by observation. For example, a number of the task durations (listed in Table 4.9) are averages of observed times. Perhaps more significantly, the rules used to predict differences in individual operator responses to key cues (see Table 4.7) are empirically developed based on observations. Of course, because of the small number of observations, there is significant uncertainty in the general applicability of these rules. Nevertheless, they are useful for explaining the variability observed in the videotaped SGTR exercises.

Using the benchmarking runs, it is determined that time factors of 1.0 and control activity cycle times of 0.1 minutes are appropriate for all of the operators except one. In the case of the SRO in Crew #2 (who has a relatively low technical ability rating as assigned by experts, and who is assigned low relative confidence ratings by his subordinates), the time factor assigned is 1.1 and the control activity cycle time assigned is 0.5 minutes.

The benchmarking runs are not used to estimate values for model parameters governing stress buildup/response and short term memory capacity/decay. This is because none of the videotaped crew behaviors could be clearly linked to mechanisms related to these issues. The effects of variations in the parameters governing these issues are treated in sensitivity studies presented in Chapter 5.

4.6.2 Comparisons of Simulated and Observed Crew Behavior

The simulated crew behaviors for the four chosen crews are summarized in Table 4.13. Also summarized are the observed crew behaviors from the videotaped exercises. Each crew–specific simulation starts from either the activation of the balance of plant (BOP) radiation alarm or the pressurizer level deviation alarm (depending on the actual sequence of events faced by the crew in the SGTR training exercise), and ends when the SRO commands the crew to initiate primary side cooldown and depressurization. The total time for each SGTR training exercise is 20 – 25 minutes.

In general, when considering the qualitative predictions of the crew model simulation (i.e., predictions of key event occurrence/non–occurrence and of the temporal ordering of these events), the simulation predictions match the actual crew performances quite well. A few discrepancies are found in the porition of the scenario prior to reactor trip, when the operators are following memorized procedures. When considering the quantitative predictions (i.e., predictions of the actual timing of specific events), some additional discrepancies are found, especially after the occurrence of reactor trip.

Figures 4.10 through 4.13 present the crew model's predictions for each of the four crews analyzed (Crews #2, #4, #7, and #10, where the Crew #10 simulation represents the blind test for the model). Each figure provides a time track for each crew member and a time track for the plant. Along a time track, each box includes the message (if any) sent out by an operator (lower part), and the corresponding cue that triggers the message transmission (upper part). The dashed line at the left edge of each box represents the starting time of the message (the right–hand edge does not represent the ending time of the message).

Note that an action related to a message generally is executed before the message is sent out. For example, an RO sends a message regarding the current pressurizer status after completing a related monitoring action. Note also that the time line shown in the figures is not to scale.

A quick appraisal of the crew model's accuracy can be made by looking at the shaded boxes in Figures 4.10 through 4.13. Each shaded box represents a discrepancy between the simulated and observed operator behavior. These discrepancies involve either different responses to cues or significant differences in response timing (more than one minute between the simulated and observed actions). It can be seen that the number of shaded boxes is relatively small. Thus, the crew model appears to reasonably represent crew responses at the Charles River Plant during the early phases of an SGTR training exercise.

The discrepancies shown in Figures 4.10 through 4.13 are discussed below.

4.6.2.1 Performance of Crew #2 (Figure 4.10)

The only discrepancy occurs when the crew members are responding to the balance of plant (BOP) radiation alarm. In the simulator exercise observed, the RO went to check the radiation monitor (proactively) right after the alarm and reported that the steam generator blowdown radiation alarm was on to the SRO. This behavior is quite unusual, since the radiation monitor panel is not in the RO's area of responsibility. It is judged that the RO's behavior is related to his low confidence in the SRO. Another possible effect of this low confidence is the RO's suggestion to trip the reactor. Recall that, as shown in Table 4.7, the postulated criteria for the RO to make this suggestion are: a) the RO has low confidence in the SRO, and b) he has technical ability rating of medium or higher.

Except for this discrepancy, the crew model successfully simulates a number of interesting behaviors observed during Crew #2's response. These include interruption of ongoing actions,

In the simulation, the model treats a situation where an operator's ongoing action is interrupted, and the effect of this interruption on subsequent events. Here, the ARO does not finish his response to the BOP radiation alarm until 1:15 (min:sec), although he starts this action right after the alarm first comes on (at 0:00). The reason for this delay is that his alarm response action is interrupted by other actions that are related to both the SRO's command at 0:19 and the need to respond to the pressurizer level deviation alarm at 0:51. Another interruption can be observed on the SRO's time track. Although the pressurizer level deviation alarm comes on at 0:51, the SRO starts responding to this alarm at 1:37. In general, interruptions to the SRO's ongoing actions are largely caused by his frequent message exchanges with his subordinates.

Figure 4.10 shows another interesting sequence of events/behaviors starting at 1:47. Here, the SRO concludes from his control activity that the pressurizer level is still decreasing and that there is leakage on the primary side. The normal response to these conclusions are orders to start up a second centrifugal charging pump and to reduce reactor power. However, he does not issue these orders. The RO, noting that the expected command has not been received and not having high confidence in the SRO, suggests to the SRO at 2:50 that reactor power should be reduced. At 2:55, the SRO (who has high confidence in his RO) accepts this suggestion and recovers the missed action.

A similar situation arises at 3:18, where the SRO once again does not take the normal course of action. At this time, he has concluded that an SGTR is underway, but does not command his subordinates to trip the reactor. The RO makes a suggestion to the SRO at 5:05 that the reactor should be tripped. When this suggestion is not acted upon, the RO repeats his suggestion at 5:25. The SRO eventually responds to the suggestion, and orders a reactor trip at 5:58.

This last scenario illustrates how the crew model allows one form of "group decision making" in a situation where there the SRO is the only official decision maker. It is assumed that for each plant parameter–based decision, the SRO has a setpoint that is related but not necessarily identical to the official setpoint. In the case of reactor trip, for example, the Abnormal Operating Procedures recommend that the reactor be tripped when the pressurizer level approaches 14% (see Section 3.2.3.1). However, some SROs may trip the reactor sooner; there may be others who might wait longer before tripping reactor later. In the model, the SRO always makes his decision based on the value of the plant parameter relative to his internal setpoint. However, suggestions by his RO can change his setpoint (if he has high confidence in his RO). Thus, in certain situations, the model allows more than one person to participate in decision making.

As a final note on the simulation of Crew #2 (and of all crews), it should be recognized that the physical model presented in Appendix D is slightly modified in order to model the observed plant (training simulator) behavior realistically. For example, the nominal reactor trip setpoint based on pressurizer level is 14%, as mentioned above. However, use of this value in the model of Appendix D leads to inaccurate representations of subsequent event timing. In this study, the nominal trip setpoint value is changed to 20%. In other words, when the Appendix D model predicts a pressurizer level of 20%, the operators respond as if the level were actually 14%.

4.6.2.2 Performance of Crew #4 (Figure 4.11)

Figure 4.11 shows that there is only one discrepancy between the simulated and observed crew behaviors (before reactor trip). In the videotaped exercise, the SRO commanded power reduction at 2:00 instead of at 0:48 as predicted by the crew model simulation. The corresponding cue, "primary side leakage," is judged to be available to the SRO at 0:48, hence the reason for the time delay is difficult to assess.

It is interesting to observe that the videotapes indicate that the ARO was monitoring the pressurizer status continuously, but he never proactively reported any related information to the SRO. As shown in Table 4.7, the postulated cause for this general behavior pattern is the ARO's low self–confidence. (The same behavior pattern is also observed for the AROs in Crews #7 and #10.) The impact of the ARO's failure to send a proactive message may not be critical in a straightforward SGTR sequence (where no additional hardware failures are included). However, it may affect the crew's efficiency when a critical component fails, as discussed in the sensitivity studies in Chapter 5.

4.6.2.3 Performance of Crew #7 (Figure 4.12)

Two discrepancies are identified when comparing the simulated and the observed crew behavior. The first one is related to the action of starting the second centrifugal charging pump, which is a typical response to the cue "pressurizer level still decreasing." In the actual exercise, the SRO for Crew #7 did not send this command (to start the pump); the RO suggested at 2:39 that the pump be started. The SRO responded to this suggestion by commanding an increase in charging flow rate and the isolation of letdown flow; this is performs the same function as the startup of a second centrifugal charging pump, but is less effective. It is judged that the SRO's responses are related to his personal style in responding to the cue, which is not included in this implementation of the crew model. Note that, although it is not shown in Figure 4.12, the RO in the simulation is predicted to brew a suggestion regarding pump startup. This suggestion is cancelled by the command of the SRO, who commands pump startup at 1:27.

The second discrepancy invovles the timing of the SRO's conclusion about the root cause of the accident (SGTR). Because of the SRO's good technical ability, the simulation assumes that he will not jump to conclusions at the second level of the secondary side control activity tree (see Section 4.4.2.5 and Figure 4.7). Per training, he is expected to command the ARO to check for a mismatch in steam generator levels, and will only conclude that an SGTR may be underway after the ARO informs him that there is a clear difference in steam generator levels. However, judging from the videotape of Crew #7's behavior, the SRO apparently jumped to the conclusion that an SGTR was underway without commanding the ARO to check for a mismatch in levels. Therefore, the time at which he concluded that an SGTR accident is underway is much earlier than the predicted time (1:25 versus 2:30). Again, it is believed that this discrepancy is related to the SRO's personal style in handling problems.

4.6.2.4 Performance of Crew #10 (Figure 4.13)

The simulation results for Crews #2, #4, and #7 are developed using model parameters tuned to obtain good agreement with the videotaped performances of these crews. The simulation of Crew #10 is used as a blind test of the simulation model. The purpose of this blind test is to check the robustness of the crew model in simulating different crew compositions. Only the input data for operator technical ability, self–confidence, and confidence in others are varied to match the actual characteristics of this crew; the remaining parameters are set using the same values used in the benchmarking runs.

Figure 4.13 shows that there are only two discrepancies between the blind test results and the observed crew behavior. These two discrepancies are interrelated. In the videotaped exercise, the SRO did not send out a command to reduce power and tripped the reactor rather early (at 2:47, as opposed to the simulation prediction of 3:56). It is judged that the pressurizer level at the time the crew tripped the reactor was about 22%, which is 8% higher than the value suggested in the Abnormal Operating Procedures. It appears that the SRO thought the available evidence was clear enough to conclude the accident was an SGTR and manual reactor trip was eventually inevitable. Thus, he skipped the power reduction command, which would be meaningless when reactor trip is expected to occur in less than a minute, and immediately initiated manual reactor trip.

4.7 Summary

This chapter's deterministic implementation of the crew model framework described in Chapter 2 employs an discrete event simulation approach. Each individual operator is characterized by a set of event and process routines and a group of sets/lists containing information needed by the event and process routines. The event routines are used to treat events occuring at discrete points in time; the process routines are used to treat strings of related events (e.g., a series of actions).

In contrast with a literal interpretation of the Monitoring → Situation Assessment → Planning → Execution sequential conceptual model provided in Figure 2.1, the discrete event (and process) simulation approach has two significant advantages: it allows a simple, intuitive treatment of parallel processes, and it allows for dynamic scheduling of these processes. The ability to treat parallel processes enables the construction of a model where the operator recognizes that a number of issues (concerns) must be dealt with, where each issue/concern can be associated with a set of activities (i.e., a script). Dynamic scheduling allows the operator model to reprioritize the different concerns when new information is received from the plant, other operators, or from internal control activity.

The translation of the concepts in Chapter 2 into a simulation model is straightforward in many areas. The concern list and the action list, for example, are represented by the sets CONCERN.LIST and ACTION.LIST; this direct translation is facilitated by the English–like style of the SIMSCRIPT II.5 programming language, as well as by the object–oriented modeling approach employed.

In other areas, some additional modeling is required. For example:

- parameters characterizing individual operators (e.g., technical ability, self–confidence, confidence in crew members) are quantified using data from interviews;
- models for the influence of these parameters on operator behavior are operationalized through the use of thresholds (e.g., for sending messages) and rules (e.g., for selecting response scripts of different operators to the same cue);
- scripts are developed to represent observed operator responses to cues;
- the control activity of an individual operator is represented by a pair of simple logic trees; and
- the conceptual models for stress buildup/effect and for memory decay are operationalized using simple, deterministic models.

Because data and theory are lacking for a number of these implementation models, efforts are made to ensure that the implementation models are simple. Due to the modular nature of the crew model, these simple models can be replace with more accurate ones when the latter become available.

Benchmarking runs are performed for 3 of the 10 Charles River Plant crews to empirically determine reasonable values for model parameters governing the time required by an operator to perform a number of tasks (including cognitive tasks). These parameters are then used in a blind test simulation for a fourth crew.

The results of the four simulations (the benchmarking runs and the blind test) indicate that the implemented crew model represents the behavior of the Charles River Plant crews (during the early phases of an SGTR accident) quite well. Most of the events predicted, and the order of these events, correspond with observations of actual crew performances (as recorded by videotapes of SGTR training exercises). The model also produces satisfactory results in predicting the time a crew spends in accomplished the required tasks until the beginning of the primary side cooldown and depressurization (at which point, some 20–25 minutes after the initial tube rupture, the videotaped training exercises were terminated).

It should be cautioned that there is not a great deal of variability among the different crew performances, due to the extensive training of the Charles River Plant crews on SGTR and due to the relative simplicity of the SGTR exercises videotaped (the crews did not need to deal with any equipment failures other than the original tube rupture). Therefore, it is not extremely surprising that the crew model performs relatively well. However, it should also be pointed out that the crew model does explain some of the variability among the different crew performances; examination of Figures 4.10 through 4.13 and the discussion in Section 4.6.2 show that there are differences between the different crews are greater than the differences between the simulation predictions and actual performances (as represented by the shaded boxes in each of the figures).

Table 4.1 - Comparisons of Linear Regression Model and PRISM Predictions

Physical Variables		Number of Data Points Used in Linear Regression	$\left(\frac{X_{PRISM} - X_{Regression}}{X_{PRISM}}\right) \times 100$
Charging Flow		11	0.11
Steam Generator Pressure		20	0.80
Main Feedwater Flow (before Reactor trip)	Faulted S/G	16	1.70
	Intact S/G	16	0.58
Steam Flow (before Reactor trip)	Faulted S/G	16	0.27
	Intact S/G	16	0.06
Pressurizer Level	before Rx trip	13*	7.47
	after Rx trip	20	13.3
Primary Pressure		24	4.52
Safety Injection Flow		13	6.69
Hot Leg Temperature		25	0.66
Reactor Power		11	4.76
Steam Generator Level of	Faulted S/G	19	9.72
	Intact S/G	19*	6.37

* PRISM output has been modified to reflect the Charles River Plant.

Table 4.2 - Key Attributes of Operator Entity (Page 1 of 4)

Identification	
NAME	Can be SRO, RO, or ARO
Self and Group Ratings	
TECHNICAL.ABILITY	Can be High, Medium-High, Medium, Medium-Low, Low
CONFIDENCE.IN.SRO	Can be High, Medium, Low. Affects selection of response to cues, message exchanges.
CONFIDENCE.IN.RO	Can be High, Medium, Low. Affects selection of response to cues, message exchanges.
CONFIDENCE.IN.ARO	Can be High, Medium, Low. Affects selection of response to cues, message exchanges.
SELF.CONFIDENCE	Can be High, Medium, Low

Table 4.2 - Key Attributes of Operator Entity (Page 2 of 4)

Attributes Affecting Information Transmission	
FILTER.THRESHOLD	Values in [0,1]. Nominal value = 0.5. Affects information gathering during general monitoring. Can be affected by stress level.
MESSAGE.SENDOUT.THRESHOLD	Values in [0,1]. Nominal value = 0.5. Affects willingness to send messages. Can be affected by stress level.
MESSAGE.TO.CONCERN.THRESHOLD	Values in [0,1]. Nominal value = 0.5. Affects willingness to handle (generate concerns for) messages. Can be affected by stress level.
Attributes Affecting Information Processing	
TIME.FACTOR	Values > 0. Nominal value = 1.0. Affects time required to perform tasks. Can be affected by stress level.
CA1.CYCLE.TIME	Values > 0. Nominal value = 0.1 minutes. Time required to perform one level of fault diagnosis. Can reflect technical ability.
CA2.CYCLE.TIME	Values > 0. Nominal value = 0.1 minutes. Time required to perform one level of fault diagnosis. Can reflect technical ability.
NORMALIZING.PRIORITY	Values > 0. Nominal value = 0.4. Affects decay time of items stored in short term memory.
INTERRUPT.FACTOR	Nominal value = 0.0. Difference between a new concern and an ongoing action needed to interrupt the ongoing action.
INTERRUPT.TIME.CRITERIA	Values > 0. Nominal value = 0.0. Determines if the ongoing action will be completed soon enough that it should not be interrupted.

Table 4.2 - Key Attributes of Operator Entity (Page 3 of 4)

Attributes Affecting Stress Buildup	
BURDEN.FACTOR	Values > 0. Nominal value = 0.001. Rate at which burden (workload) stress increases with items in short term memory.
FRUSTRATION.TO.STRESS.FACTOR	Values > 0. Nominal value = 0.001. Rate at which frustration stress increases with time-to-diagnosis.
FRUSTRATION.RELIEVE.FACTOR	Values ≥ 0. Nominal value = 0.5. Amount of frustration stress relief when intermediate diagnoses are made.
IRRITATION.TO.STRESS.FACTOR	Values > 0. Nominal value = 0.001. Rate at which irritation stress increases with negatively toned messages.
TOLERATED.TONE	Values ≥ 0. Nominal value = 3.0. Most negative message tone tolerated before irritation stress builds up.
STRESS.EXPRESSION.THRESHOLD	Values ≥ 0. Nominal value = 3.0. Used when determining degree to which stress-sensitive parameters increase with stress.
STRESS.TO.TONE.FACTOR	Values > 0. Nominal value = 0.1. Rate at which tone changes (becomes more negative) as stress increases.
INITIAL.STRESS	Values ≥ 0. Nominal value = 3.0.

Table 4.2 - Key Attributes of Operator Entity (Page 4 of 4)

Internal Setpoints	
PZR.LEVEL.TRIP.POINT	Nominal value = 14%
CHARGE.FLOW.TRIP.POINT	
FRACTION.OF.TRIP.RECONSIDER	

Note: This table does not include a number of attributes used to determine the current state of the operator. These parameters (e.g., a pointer to the current state of the fault diagnosis process) are internal to the program and not directly accessible by the user.

Table 4.3 - Key Sets Owned by Operator Entity

Name	Notes
ABANDONED.SET	
ACTION.DONE.SET	
ACTION.LIST	Contains actions (ordered by priority) scheduled for execution. In short term memory.
CONCERN.LIST	Contains operator's concerns (ordered by priority) scheduled for consideration. In short term memory.
EXPECTED.MESSAGE.SET	Contains messages expected by owning operator. In short term memory.
MESSAGE.SET	Artificial recorder.
PHENOMENA.NOTICED.SET	Contains new values of plant parameters and new messages that may result in concerns. Artificial recorder.
PLANT.HISTORY.SET	In static knowledge base.
PLANT.PROPERTY.SET	Contains plant plant status perceived by operator. In static knowledge base.
PRIORITY.VALUE.SET	In static knowledge base.
PROCEDURE.STEP.SET	Contains particular Emergency Operating Procedure steps to be followed by the operators. In static knowledge base.
SCRIPT.SET	Contains particular scripts (e.g., Abnormal Operating Procedure steps) to be followed by the operators. In static knowledge base.
SYSTEM.ATTENTION.SET	In short term memory.

Table 4.4 - Attributes of Key Model Entities

Attribute / Entity[1]	AVAILA-BILITY	EXPECTED .STATUS	FILE.TIME	NAME	PRIORITY	RELATED .SYSTEM	RESPON-SIBILITY	SENDER or DOER	STATUS	VALUE	WORK. TIME
ACTION			✓	✓	✓			✓			✓
ALARM				✓		✓			✓		
CONCERN			✓	✓	✓	✓				✓	
EXPECTED. MESSAGE				✓		✓					
MESSGAE			✓		✓	✓		✓	✓	✓	
PARAMETER				✓		✓			✓	✓	
PLANT. HISTORY	✓			✓		✓					
PLANT. PROPERTY		✓		✓	✓				✓	✓	
PRIORITY. VALUE				✓						✓	
PROCEDURE .STEP				✓	✓		✓				✓
SCRIPT				✓	✓	✓					
SYSTEM. ATTENTION			✓	✓							
SYSTEM. STATUS	✓			✓					✓		

[1] All of these entities are data structures and can belong to sets.

Table 4.5 - Summary of Concern Merge Functions

New concern (to be merged)	Existing concern in the concern list	New generated (or updated) concern	Applicable to
X	X	X *	All
PZR level decreasing	PZR level decreasing	PZR level still decreasing	All
PZR pressure decreasing	PZR pressure decreasing	PZR level still decreasing	All
Charging flow increasing	Charging flow increasing	PZR level still decreasing	All
S/G blowdown valve isolated	S/G blowdown radiation high	S/G blowdown radiation high	All
SGTR	N/A	SGTR declaration	SRO
SGTR	N/A	Trip consideration	SRO
Start second charging pump? (suggestion from RO)	PZR level still decreasing (will generate action "start second charging pump")	PZR level still decreasing	SRO
Reduce power ? (suggestion from RO)	Primary side leakage (will generate action of "reduce power")	Primary side leakage	SRO
Trip reactor ? (suggestion from RO)	Trip consideration (will generate action of "trip reactor")	Trip consideration	SRO
PZR level approaches trip	Trip consideration	Trip consideration	SRO
SGTR declaration	SGTR	SGTR	RO/ARO
SGTR	PZR level approaches trip point	PZR level approaches trip point	RO

* general merging: same concerns may be generated and merged

Table 4.6 - Observed Variations in Operator Behavior During SGTR Exercises

Cue	Operator	Option 1 (number of operators choosing this options/number of situations applicable)	Option 2 (number of operators choosing this options/number of situations applicable)
Radiation high alarm	SRO	Went to check radiation monitor himself (5/10)	Commanded ARO to check monitor (5*/10)
PZR level decreasing	SRO	Commanded RO to start up second charging pump (5/10)	No action (5/10)
PZR level decreasing and no SRO command	RO	Suggested SRO to start up second charging pump (1/5)	No suggestion (4/5)
PZR level still decreasing in an uncontrolled manner	SRO	Commanded RO to reduce power (7/10)	No action (3/10)
PZR level still decreasing and no SRO command	RO	Suggested SRO to reduce power (2/3)	No suggestion (1/3)
S/G blowdown radiation alarm	SRO	Called chemistry department to check S/G water quality (6/10)	Called chemistry department to check S/G water quality and commanded ARO to check for S/G mismatch (4/10)
PZR level deviation alarm	ARO	Monitored PZR status but did not proactively report to SRO (6/10)	Monitored PZR status and reported to SRO (4/10)
Secondary radiation high alarm	ARO	Monitored S/G status but did not proactively report to SRO (6/10)	Monitored S/G status and reported to SRO (4/10)

* an RO (in 1 of the 5 crews) went to check the radiation monitor without SRO's command.

Table 4.7 - Criteria for Selecting Responses to Cues/Concerns

Cue/Concern	Operator	Criterion	Operator's response when criterion is fullfilled / Operator's response when criterion is NOT fullfilled	# of observed crews fit / # applicable
BOP radiation alarm on	SRO	SRO technical ability ≥ Medium	Go to check radiation monitor himself	8/10
			Command ARO to check radiation monitor	
S/G problem	SRO	SRO technical ability = Medium	Call chemistry department to check S/G water quality	8/10
			Call chem. dept., command ARO to check S/G mismatch	
PZR level still decreasing	SRO	SRO technical ability ≥ Medium	Command RO to start second charging pump	8/10
			No action	
PZR level still decreasing, no command from SRO	RO	RO technical ability > Medium	Schedule a suggestion to start up second charging pump	5/5
			No action	
Primary side leakage	SRO	SRO technical ability > Low	Command RO to reduce reactor power	8/10
			No action	
Primary side leakage, no command from SRO	RO	RO technical ability ≥ Medium	Schedule a suggestion to reduce power	2/3
			No action	
SGTR or PZR level ~ 14 %	RO	RO technical ability ≥ Medium, confidence in SRO = low	Schedule a suggestion to trip reactor	1/1
			No action	
Radiation and PZR alarms	ARO	ARO self confidence = High	Check S/G and PZR status, proactively report to SRO	10/10
			Check S/G and PZR status, no report to SRO	

Table 4.8 - Characteristics of Operators in Simulated Crews

Crew	Operator	Technical Ability	Confidence in SRO	Confidence in RO	Confidence in ARO
#2	SRO	Low	Low	High	High
	RO	High-Medium	Low	Medium	Medium
	ARO	Medium	Low	Medium	High
#4	SRO	Medium	High	Medium	Low
	RO	High-Medium	Medium	Medium	Low
	ARO	Low	High	High	Low
#7	SRO	High-Medium	Medium	High	Low
	RO	High	Low	High	Low
	ARO	Medium-Low	High	High	Low
#10	SRO	High	Medium	Low	Low
	RO	Medium-Low	High	Medium	Low
	ARO	Medium	High	High	Low

Table 4.9 - Nominal Work Times for Operator Tasks (Page 1 of 2)

Task Type	Operator	Task Name	Nominal work time (minutes)
General	All	Message exchange	0.05/piece
	All	Alarm monitoring	0.15/alarm
	RO/ARO	General monitoring	0.15/parameter
	RO/ARO	Specific monitoring	0.10/parameter
	SRO/RO	Cycle time for control activity	0.10/level
Scripts	SRO	Check radiation monitor	0.20
		Call chemistry dep. to check SG	0.15
		Considering trip the reactor	0.20
		E-3 procedure entry (E-0 step 26)	0.20
		Deciding isolation of faulted SG	0.10
	RO	Check SG status	0.15
		Check PZR status	0.15
		Start second charging pump	0.20
		Reduce reactor power	0.20
		Consider reactor trip suggestion	0.20
		Execute manual reactor trip	0.20
	ARO	Check SG (after radiation alarm)	0.20
		Check PZR (after level alarm)	0.10
		Check radiation monitor	0.25
		Check SG blowdown iso. valves	0.15
		Check SG mismatch	0.30
		Proactively check PZR status	0.20
		Proactively check SG status	0.30
		Execute manual reactor trip	0.20
		SG vessel rupture check (E-0, 25)	0.25
		Isolation of the faulted SG (E-3, 2)	2.0
Procedure Steps	RO	E-0 step 1	0.20
		E-0 step 4	0.15
		E-0 step 8	0.20
		E-0 step 13	0.10
		E-0 step 17	0.15
		E-0 step 20	0.30
		E-0 step 21	0.10
		E-0 step 24	0.15
		E-0 steps 27-31	1.50
		E-3 step 1	0.15
		E-3 step 4	0.15
		E-3 step 13	0.2

Table 4.9 - Nominal Work Times for Operator Tasks (Page 2 of 2)

Task Type	Operator	Task Name	Nominal work time (minutes)
Procedure Steps	ARO	E-0 step 2	0.25
		E-0 step 3	0.15
		E-0 step 5	0.15
		E-0 step 6	0.15
		E-0 step 7	0.15
		E-0 step 9	0.15
		E-0 step 10	0.10
		E-0 step 11	0.15
		E-0 step 12	0.15
		E-0 step 14	0.15
		E-0 step 15	0.20
		E-0 step 16	0.15
		E-0 step 18	0.15
		E-0 step 19	0.25
		E-0 step 22	0.20
		E-0 step 23	0.15
		E-3 step 2	1.50
		E-3 step 5	0.15
		E-3 step 6	0.15
		E-3 step 7	0.20
		E-3 step 8	0.30
		E-3 step 9	0.15
		E-3 step 10	0.20
		E-3 step 11	0.15
		E-3 step 12	0.15
		E-3 step 14	0.15

TABLE 4.10 - Summary of Stress Level Parameters

Parameter	Stress Change Coefficient	Nominal Value	Range
INITIAL STRESS	-	3.0	static
BURDEN FACTOR	-	0.001	static
FRUSTRATION TO STRESS FACTOR	-	0.001	static
FRUSTRATION RELIEF FACTOR	-	0.5	static
IRRITATION TO STRESS FACTOR	-	0.001	static
TOLERATED TONE	-	3.0	static
STRESS EXPRESSION THRESHOLD	-	3.0	static
TIME FACTOR	0.2	1.0	100 to 140 %
FILTER THRESHOLD	0.05	0.5	100 to 120 %
MESSAGE SENDOUT THRESHOLD	0.05	0.5	100 to 120 %
MESSAGE TO CONCERN THRESHOLD	0.05	0.5	100 to 120 %
MEMORY DECAY TIME	-0.1	1.5 min.	100 to 80 %
STRESS TO TONE FACTOR	-	1.0	static

Table 4.11 - Alarms and Their Setpoints

Alarm	Correspondent physical variables and setpoints
Automatic reactor trip	Pressurizer pressure ≤ 13.44.MPa
Safety injection	Pressurizer pressure ≤ 12.89 MPa
Steam generator level high	B Steam generator level or A,C Steam generator level ≥ 55% NR (narrow range)
Steam generator level high-high	B Steam generator level or A,C-Steam generator level ≥ 84% NR
Pressurizer level deviation	Pressurizer level ≤ 53.84% or ≥ 63.84% (normal operating value = 58.84% at full power)
Secondary radiation high	External input (can be set at any time)

Table 4.12 - Boundary Conditions Affected By Operator

Physical Variable	Boundary Conditions	Equations (all time in minutes)
	Before Rx trip (without power reduction)	Rx-power = Rx-power
Rx-power	Before Rx trip (with power reduction)	Rx-power = Rx-power * (1- 0.001* (current time - time power reduction begins))
	After reactor trip	Rx-power = Power before reactor trip * 0.0756 * (current time - reactor trip time) ** (-0.2)
Charge-flow	One pump running	Charge-flow = 0.641 * current time
	Two pump running (2nd CCP started)	Charge-flow = 0.962 * current time
PZR- pressure	Before reactor trip	PZR-pressure = 4.434 + 0.00337 * Rx-power - 0.34 * Charge-flow - 0.529 * Number-of-tube-rupture
	After reactor trip	PZR-pressure = 22.612 - 0.046 * Rx-power - 0.609 * Charge-flow - 1.29 * Steam-dump-open-elapsed-time - 2.306 * Number-of-tube-rupture - 4.414 * PZR-PORV-open-elapsed-time - 0.598 * PZR-spray-open-elapsed-time
Hot-leg-T		Hot-leg-T = 274.7 + 0.0081 * Rx-power + 1.336 * PZR-pressure + 1.047 * PZR-PORV-open-elapsed-time + 0.544 * PZR-spray-open-elapsed-time + 1.047 * Steam-dump-open-elapsed-time
SG-pressure		SG-pressure = 7.563 - 0.0002 * Rx-power - 0.326 * Steam-dump-open-elapsed-time

Physical Variable	Boundary Conditions	Equations (all time in minutes)
B-SG-level	Before reactor trip	B-SG-level = 122.96 - 0.0187 * Rx-power - 0.345 * PZR-pressure - 0.531 * SG-pressure + 0.085 * Number-of-tube-rupture
	After reactor trip	B-SG-level = 432.8 - 4.31 * Rx-power - 3.339 * PZR-pressure - 1.752 * Number-of-tube-rupture
AC-SG-level	Before reactor trip	AC-SG-level = 119.32 - 0.0169 * Rx-power - 0.234 * PZR-pressure - 0.329 * Number-of-tube-rupture
	After reactor trip	AC-SG-level = 238.49 - 3.041 * Rx-power + 0.74 * PZR-pressure - 1.892 * Number-of-tube-rupture
B-SG-fw	Before reactor trip (main feedwater)	B-SG-fw = 1430 - 12.197 * B-SG-level - 0.102 * Rx-power
	After reactor trip (emergency feedwater)	B-SG-fw = 12.0
AC-SG-fw	Before reactor trip (main feedwater)	AC-SG-fw = 1514 - 13.066 * AC-SG-level - 0.113 * Rx-power
	After reactor trip (emergency feedwater)	AC-SG-fw = 12.0
B-SG-steam-flow	Before reactor trip	B-SG-steam-flow = AC-SG-steam-flow + 5.35
	After reactor trip	B-SG-steam-flow = 12.0
AC-SG-steam-flow	Before reactor trip	AC-SG-steam-flow = 459.3 - 0.182 * AC-SG-level + 0.017 * Rx-power - 0.074 * AC-SG-fw + 0.413 * (PZR-pressure - SG-pressure)
	After reactor trip	AC-SG-steam-flow = 12.0

Physical Variable	Boundary Conditions	Equations (all time in minutes)
PZR-level	Before reactor trip	PZR-level = -255.67 - 0.01346 * Rx-power + 22.897 * PZR-pressure - 0.004 * Hot-leg-T + 3.669 * Number-of-tube-rupture
	After reactor trip	PZR-level = 141.75 - 0.277 * Rx-power + 15.496 * PZR-PORV-open-elapsed-time + 0.979 * PZR-spray-open-elapsed-time + 6.475 * Number-of-tube-rupture + 3.501 * PZR-pressure - 0.545 * Hot-leg-T
SI-flow	Before reactor trip	SI-flow = 0.0
	After reactor trip	SI-flow = 66.82 + 0.114 * RX-power + 0.14 * PZR-level - 5.737 * PZR-pressure + 1.126 * Number-of-tube-rupture

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Table 4.13 - Comparison of Simulated and Observed Crew Behavior

Plant or Crew Behavior	Crew #2		Crew #4		Crew #7		Crew #10	
	sim.	obs.	sim.	obs.	sim.	obs.	sim.	obs.
BOP radiation alarm	0:00	0:00	2:33	2:45	0:00	0:00	0:00	0:00
Pressurizer level deviation alarm	0:51	0:35	0:00	0:00	0:00	0:00	0:00	0:00
SRO commands ARO to check radiation monitor	0:19	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SRO checks radiation monitor himself	N/A	N/A	2:48	2:50	0:24	0:23	0:24	0:10
ARO proactively reports pressurizer and steam generator status	Yes	Yes	No	No	No	No	No	No
SRO: start second charging pump	N/A	N/A	0:45	1:20	1:27	N/A	1:27	1:20
RO suggests starting second charging pump	N/A	N/A	N/A	N/A	N/A	2:39	N/A	N/A
SRO: reduce power	N/A	N/A	0:48	2:00	1:36	1:23	1:36	N/A
RO suggests power reduction	2:50	2:45	N/A	N/A	N/A	N/A	N/A	N/A
SRO concludes SGTR	3:18	2:55	3:24	3:00	2:30	1:25	2:42	2:07
RO suggests reactor trip	5:05, 5:25	4:46, 5:15	N/A	N/A	N/A	N/A	N/A	N/A
SRO: trip reactor	5:58	5:30	3:51	4:10	3:56	3:20	3:56	2:47
SRO: go to E-3	13:47	16:25	11:31	13:25	11:36	11:20	11:36	13:20
Faulted steam generator isolated	18:01	19:40	15:43	15:00	15:49	14:00	15:48	19:00
Faulted steam generator level at isolation (% NR)	98	96	97	90	96	90	94	92
SRO: start cooldown and depressurization	21:10	22:37	18:49	17:45	18:54	17:00	18:54	23:00

1. sim: simulated behavior
2. obs: observed behavior
3. All times are in minute: second

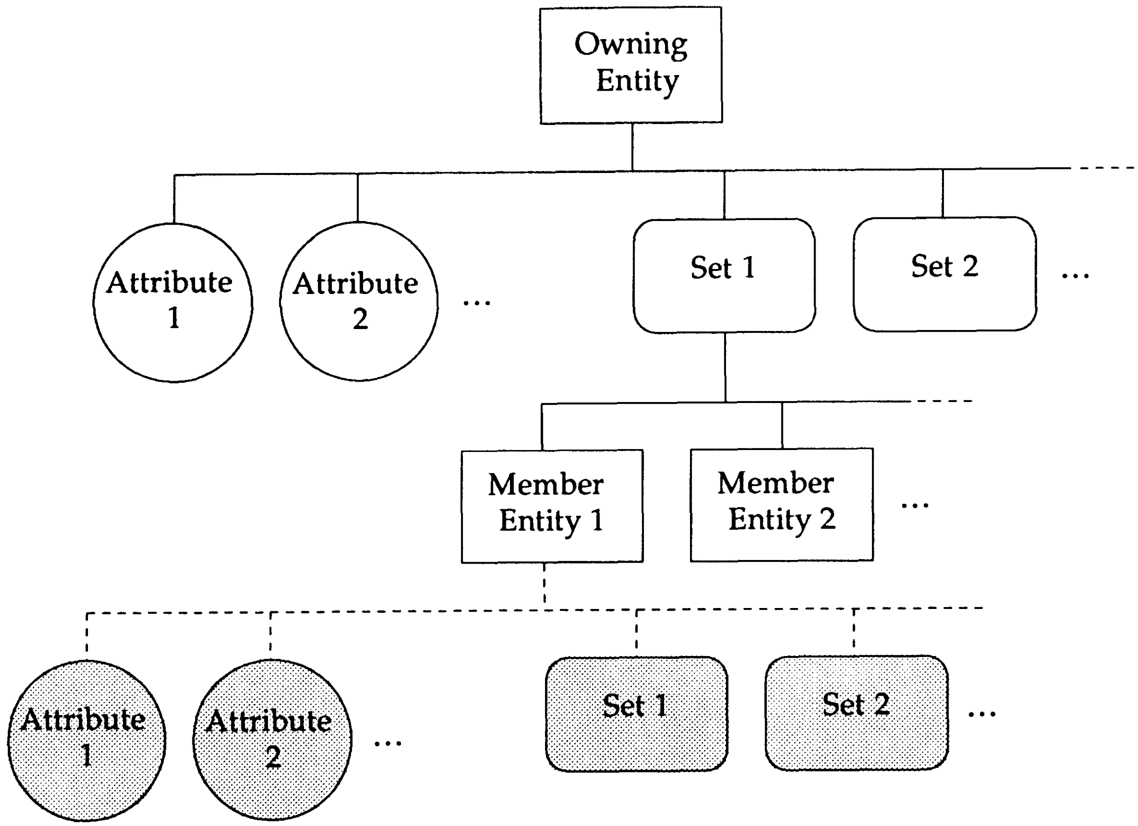

Figure 4.1 - Schematic of SIMSCRIPT II.5 Data Structure

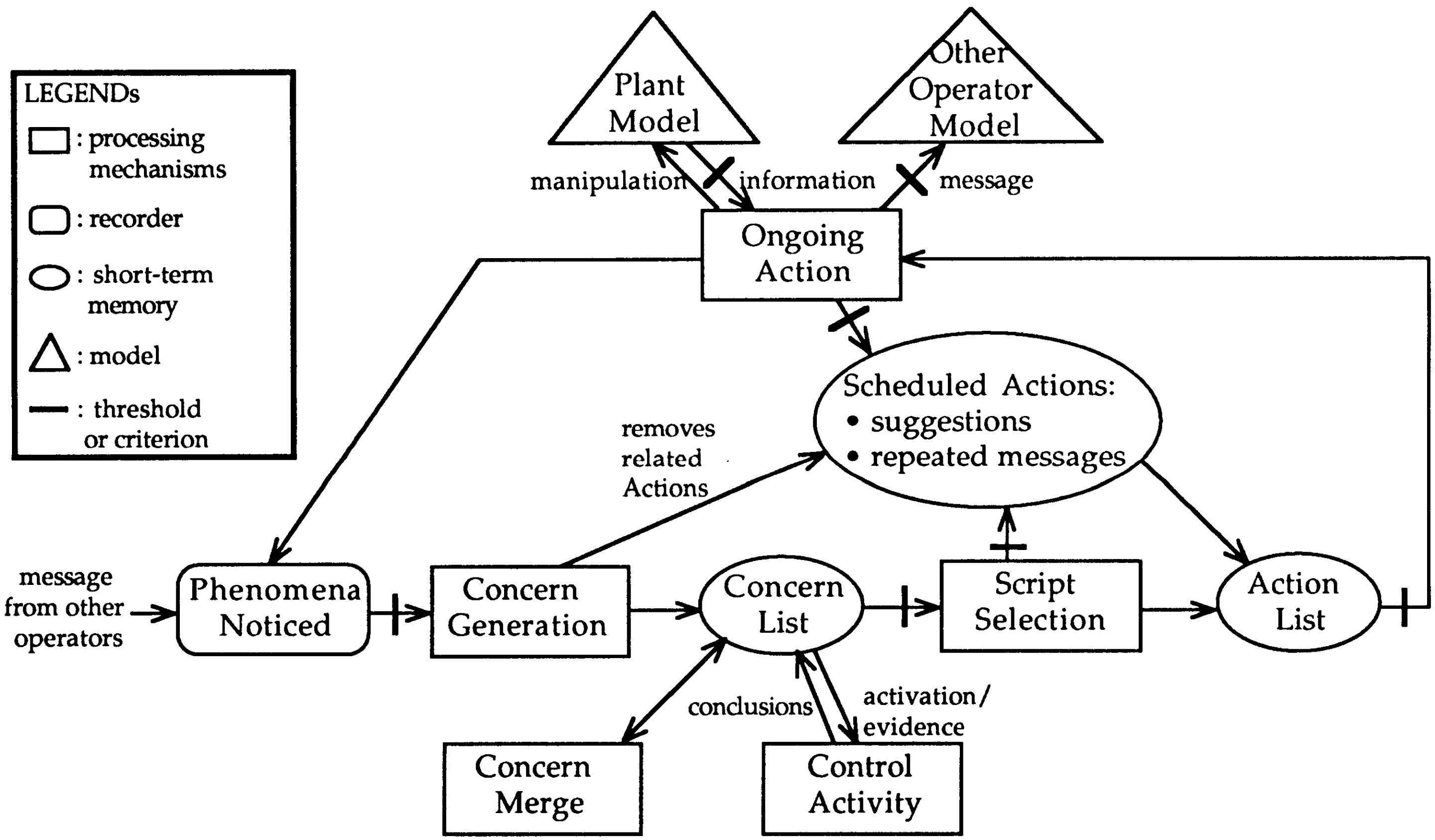

Figure 4.2 - Simplified Flow Chart For Individual Operator Model As Implemented

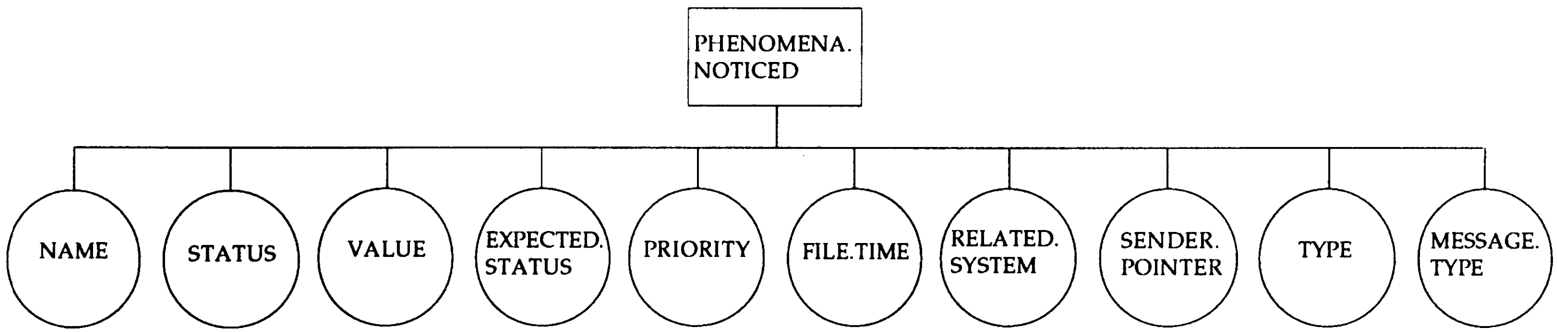

Figure 4.3 - PHENOMENA.NOTICED Data Structure

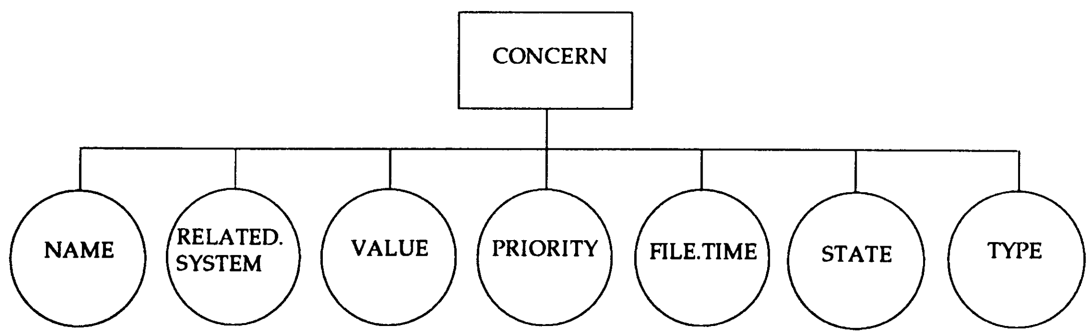

Figure 4.4 - CONCERN Data Structure

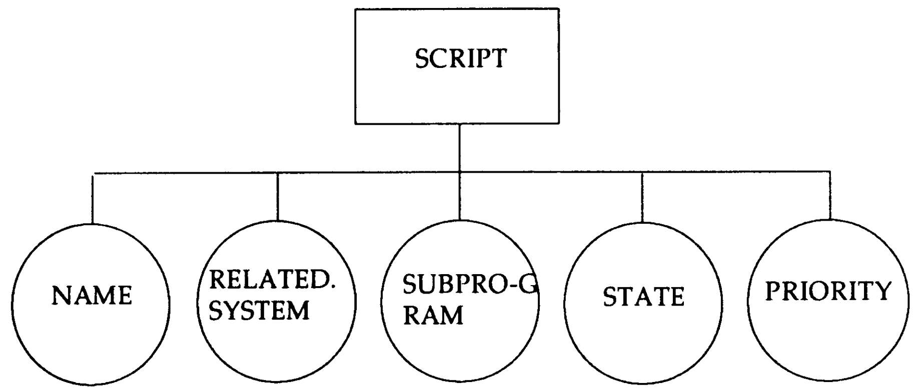

Figure 4.5 - SCRIPT Data Structure

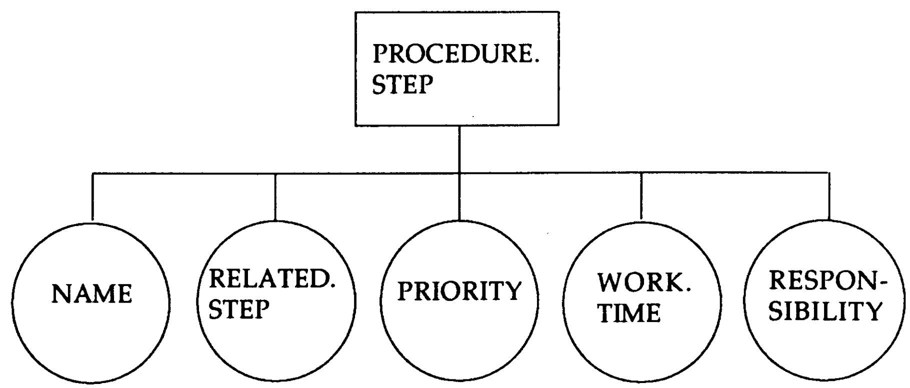

Figure 4.6 - PROCEDURE.STEP Data Structure

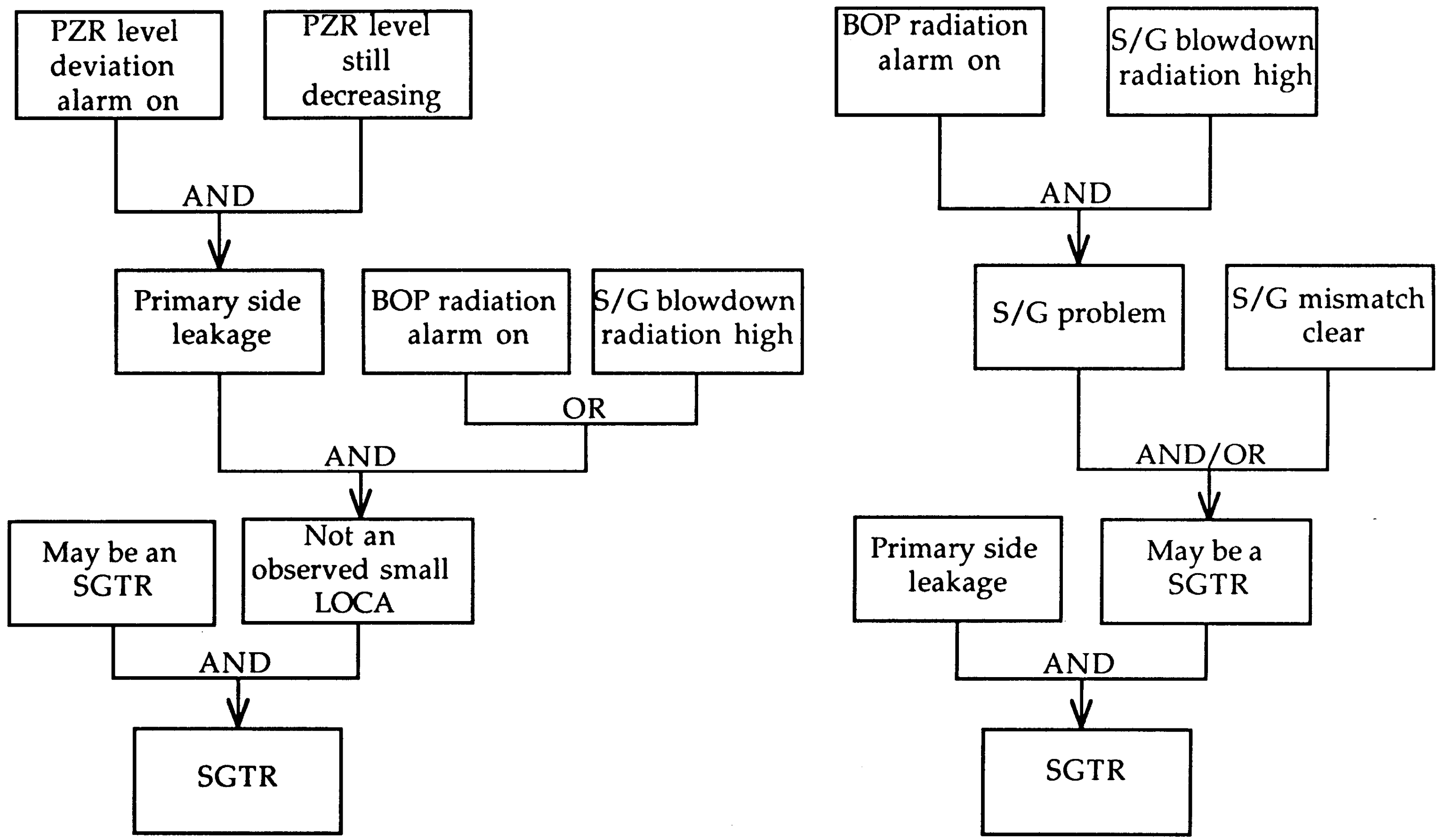

Figure 4.7 - Production Rule" Trees Used in Fault Diagnosis

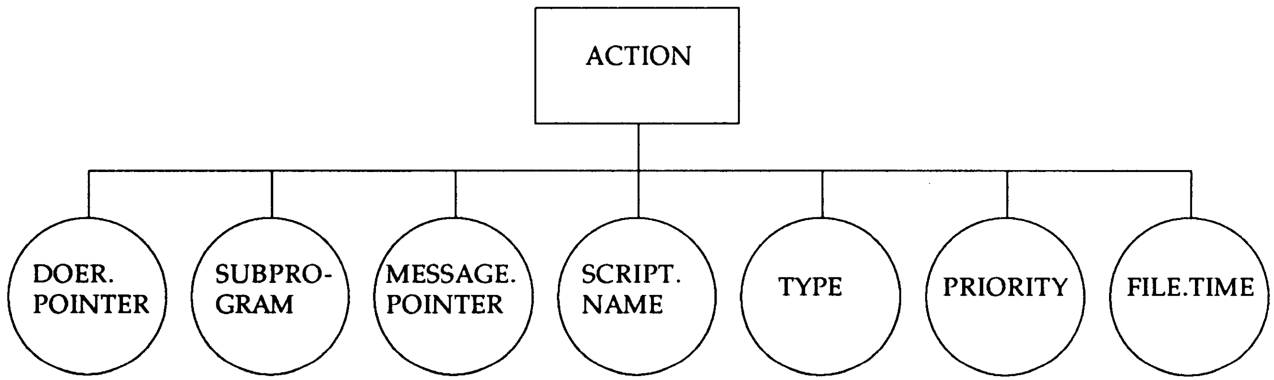

Figure 4.8 - ACTION Process Routine Data Structure

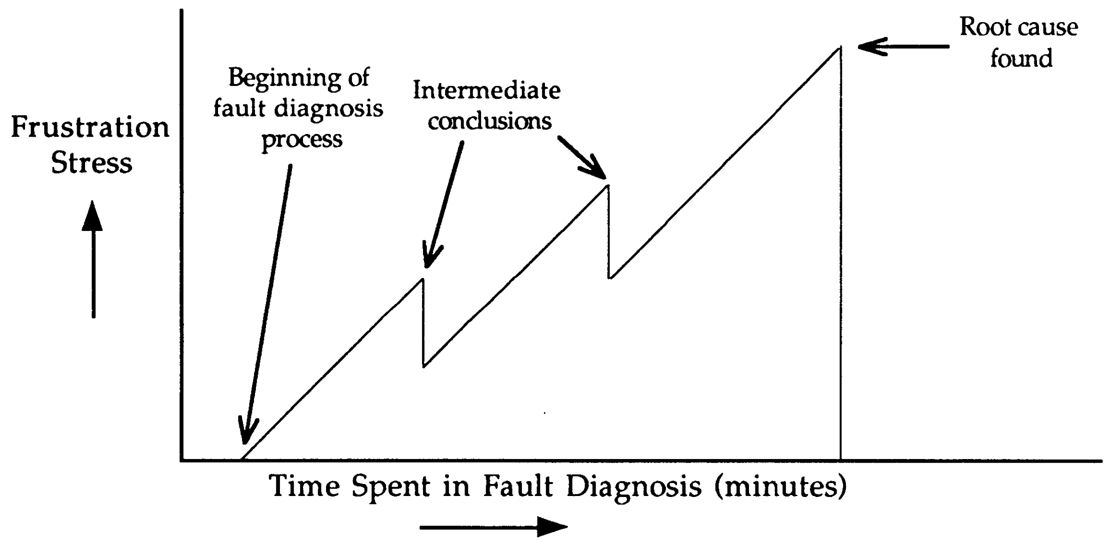

Figure 4.9 - Simple Model for "Frustration" Stress Buildup

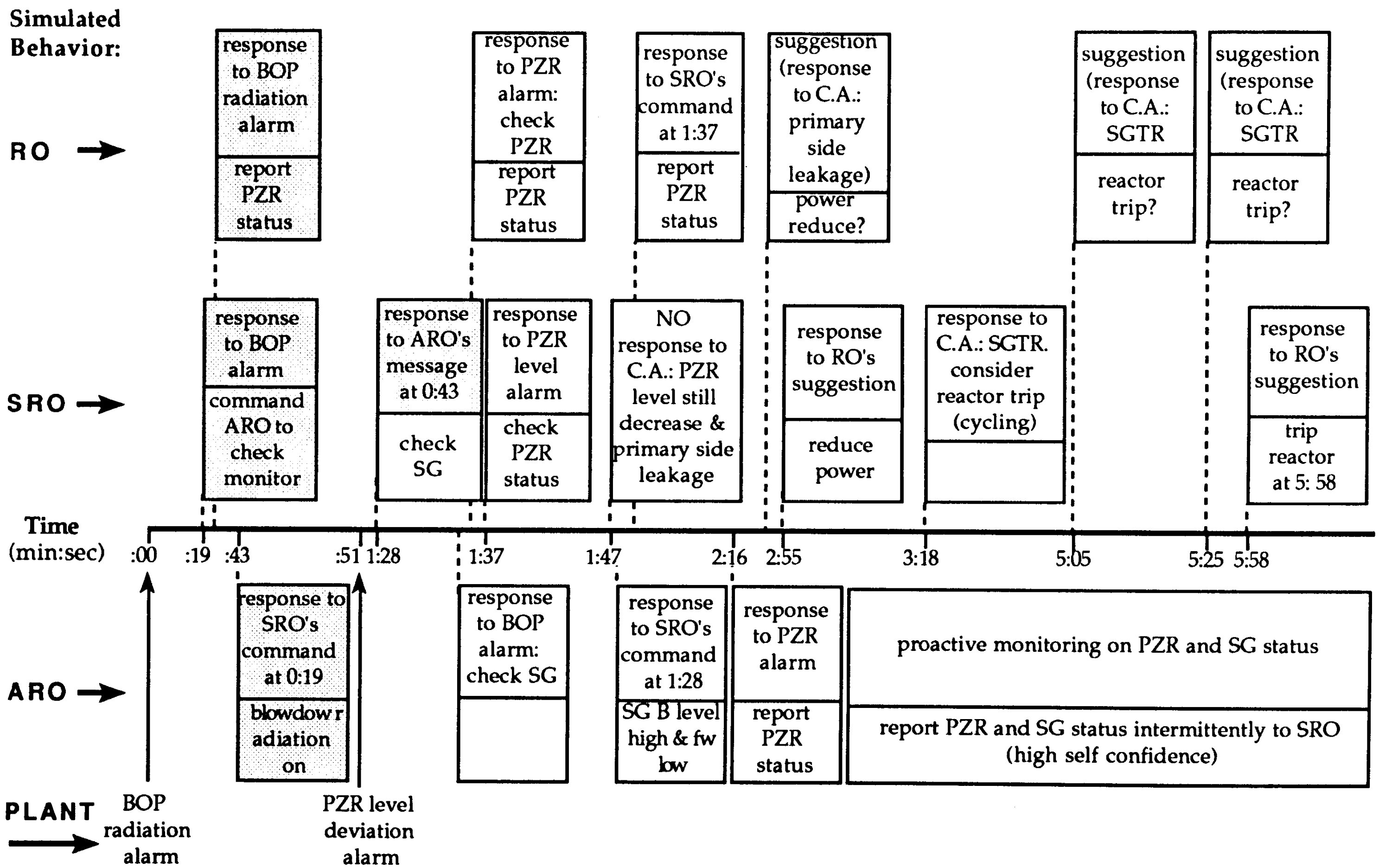

Figure 4.10 - Comparison of Simulated and Observed Crew Behaviors (Crew #2)

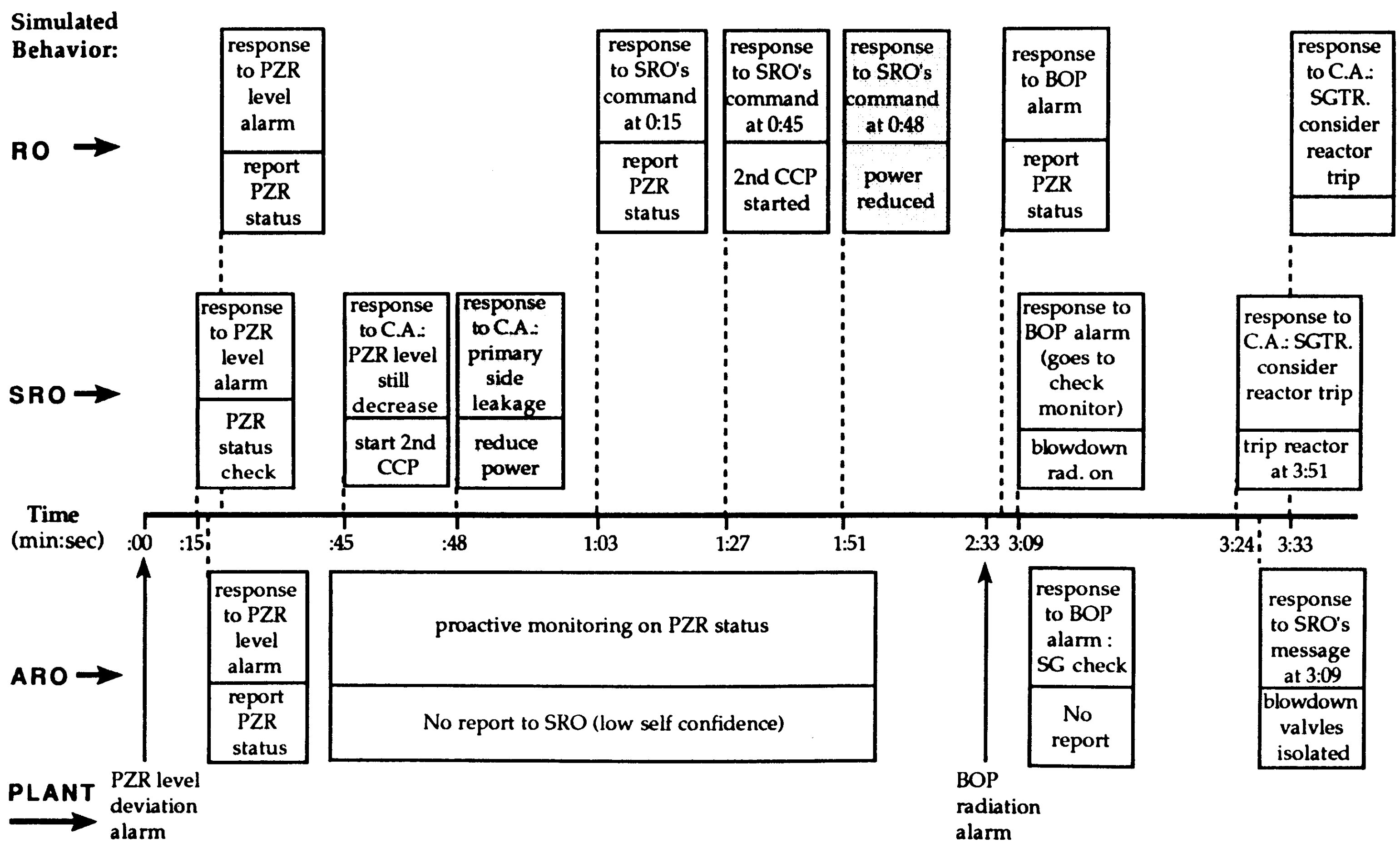

Figure 4.11 - Comparison of Simulated and Observed Crew Behaviors (Crew #4)

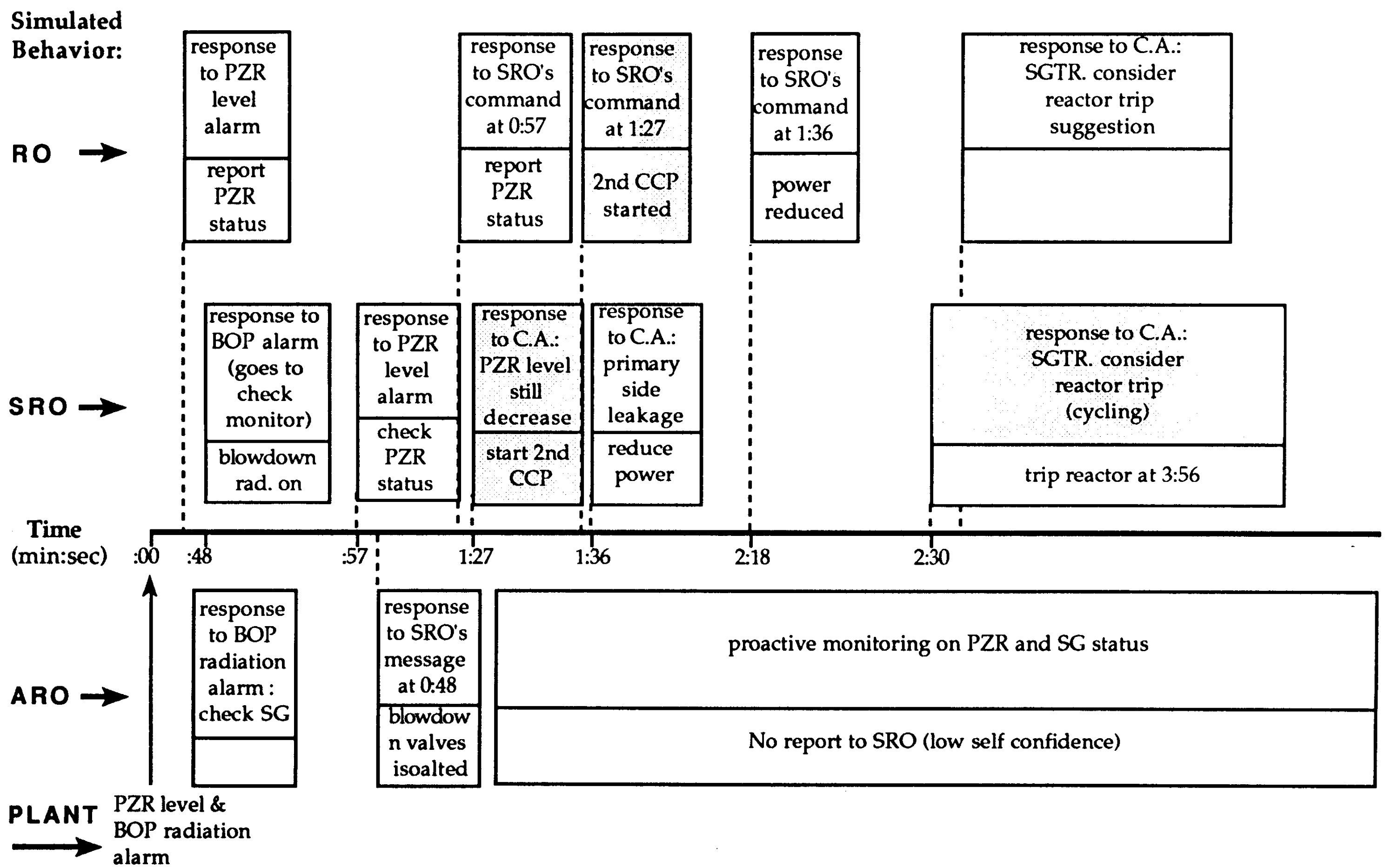

Figure 4.12 - Comparison of Simulated and Observed Crew Behaviors (Crew #7)

5. SENSITIVITY ANALYSES

5.1 Introduction

The benchmark and blind test runs reported in Section 4.6 are used to assess the implemented crew model's ability to simulate the behavior of the Charles River Plant crews observed during steam generator tube rupture (SGTR) training exercises. This chapter describes a number of sensitivity studies performed to: a) test the robustness of the model predictions as the characteristics of the operating crew are modified (not necessarily reflecting any actual crews), and b) to understand the implications of the some of the models used (e.g., for stress buildup and its effects) and determine the sensitivity of the results to changes in these models.

In the benchmark and blind test runs, the input parameters for each crew and individual operator are assigned values consistent with field data (described in Chapter 3). The remaining input data are assigned nominal values, as described in Section 4.6. In the sensitivity studies, many of these input parameters are varied.

To study the impact of crew composition on performance, the technical abilities of the crew members are varied, as described in Section 5.2. Section 5.3 continues this sensitivity analysis in the context of a more challenging SGTR scenario, in which a key indicator for SGTR (the balance of plant radiation alarm) is lost. Sections 5.4–5.7 present sensitivyt analyses testing the effect of varying parameters characterizing short–term memory, stress buildup and its effects, and crew interactions.

The principal parameters used to evaluate crew performance are the level of the faulted steam generator when it is isolated and the time of isolation. (The level is the most important parmeter, since an overly high value indicates a potential challenge to the relief valves of the faulted steam generator, and a possible release of radioactive material into the environment.) Other criteria used to evaluate crew performance are the efficiency of root cause analysis (whether and when SGTR is diagnosed), the time at which the reactor is tripped, and the time at which primary system cooldown and depressurization is initiated.

5.2 Individual Technical Ability

Analysis of the data from the field study suggests that there is a strong relationship between the technical ability of an operator and his choice of possible responses to a specific cue. This result is built into the simulation model (see Table 4.7). As a result, the performances of crews whose members have similar technical abilities are predicted to be similar (see Figures 4.12 and 4.13), whereas crews with very different technical abilities are predicted to have very different performances (e.g., see Figures 4.10 and 4.13). The test runs described in this section explore in greater depth the degree to which crew performance changes with individual technical ability.

Note that in these runs, it is assumed that two other individual characteristics, self–confidence and control activity cycle time, vary with individual technical ability. (The control activity cycle time is a measure of how quickly the operator will draw a conclusion from available information.) It is assumed that the operator's self–confidence is assumed to be proportional with his technical ability; if an operator has high technical ability, he is assigned a high self–confidence rating as well[20]. It is also assumed that the control activity

[20]Section 5.6 describes the results of an analysis in which the SRO is assumed to have low technical ability but high self–confidence.

cycle time is inversely proportional with his technical ability. All other input data are assigned their nominal values.

5.2.1 Extreme Crew Compositions

In reviewing the characteristics of individuals in the Charles River Plant control room crews, it appears that crew members are generally selected such that the ability of all crews, averaged over the crew members, is comparable from crew to crew. For example, an SRO with relatively low technical ability is usually compensated for by assigning an RO or ARO with high technical ability to that crew. Interviews with the training supervisors at the Charles River Plant confirm that the instructors consider this general principle in their crew assignment policy.

In this section, a number of runs are done for crews with highly unlikely compositions. In these test runs, the technical abilities of the crew members are assumed to be uniformly high or uniformly low (with self-confidence and control activity cycle time assignments as discussed earlier). These hypothetical crews are designated "HHH" and "LLL," where the first letter corresponds to the technical ability of the SRO, the second to the technical abilility of the RO, and the third to the technical ability of the ARO. The control activity cycle time for the SRO (RO) with low technical ability is further varied to represent the difficulty this operator may have in diagnosing the root cause of an accident The largest value (20 minutes) represents hypothetical operators who lack the knowledge needed for fault diagnosis.

Some key results from these runs are shown in Table 5.1; the crew attributes are provided in the first two columns. Table 5.1 presents the times (in minutes) at which key tasks are accomplished. The results of these runs can be summarized as follows:

- For a straightforward SGTR (an SGTR without additional hardware failures), the emergency operating procedures (EOPs) guide the crew to accomplishing the required mitigative actions. This guidance is sufficient even for crews whose members all have low technical ability. For example, the first tested LLL crew (Line 2 in Table 5.1) is only 1.7 minutes slower in bringing the plant to the desired state when compare with the HHH crew (Line 1 in the same table).
- The longer a crew takes to find the root cause of the accident, the longer they take to bring the plant to the desired state (see Columns 6 and 9 in Table 5.1).
- It is interesting to see that although the LLL crews take longer to isolate the faulted steam generator, the level of the faulted steam generator at isolation is <u>lower</u> than that for the HHH crew simulations. This is because the HHH crews take the mitigative action prescribed in the Abnormal Operating Procedures of starting up a second centrifugal charging pump. This action increases the primary side pressure and hence the leakage rate to the faulted steam generator[21].

5.2.2 Intermediate Crew Compositions

These test runs compare the performance of various hypothetical crews formed in accordance with the *de facto* crew assignment policy discussed above. Each test crew is composed such that the average of the crew members' technical abilities is about medium.

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[21]The startup of the second charging pump is solely motivated by the drop in pressurizer level and is not based on a diagnosis of SGTR.

Note that a "low technical ability SRO" is one who has a low technical ability relative to other SROs, and not in comparison with the RO or ARO in his crew. An HMM crew (a high technical ability SRO teamed with a medium technical ability RO and a medium technical ability ARO) is used for purposes of comparison. Again, the self-confidence (SC) of an operator is assigned proportional to his technical ability. Other individual and group characteristics are set to their nominal values.

The predicted performances of these hypothetical crews are shown in Table 5.2. This set of test runs shows that:

- In a crew whose SRO has a high technical ability, the crew performance is not strongly related to the technical abilities of the subordinates. Note that this conclusion may not be valid for more complex scenarios, as discussed in Section 5.3.
- The performance of a medium or low technical ability SRO can only be compensated by assigning a RO with a high technical ability. It is assumed that, due to the official distribution of role and status, it is highly unlikely that an ARO will make suggestions, regardless of his technical ability (this assumption is confirmed by interviews with training supervisors in the field study). As a result, the ARO cannot make enough of a difference in the overall crew performance to compensate for a weak SRO.
- Crew performance is nominal or better when either the SRO or the RO has a high technical ability (see Lines 5–8 and 12 in Table 5.2).

5.3 Additional Hardware Failure

As mentioned in Chapter 4, the crew model is benchmarked on training exercises involving a straightforward SGTR scenario, i.e., a scenario in which no hardware failures occur other than the tube rupture itself. The failure of additional critical components or the lack of clear indications may be expected to complicate the fault diagnosis process and thus delay both the crew's diagnosis and its execution of mitigative actions. The failure of the secondary (or balance of plant, BOP) radiation alarm is chosen to explore this possibility.

The BOP alarm is activated by an increase in the secondary radiation levels and indicates that there is a leakage of primary coolant to the secondary side. Because the most likely path is through the steam generator, the secondary radiation alarm is a major indication of steam generator tube rupture. Another indication of an SGTR sequence is a mismatch between the level and feedwater flow rate of the faulted steam generator and those of the intact steam generators. However, this indication may take some time to develop[22].

Due to the leakage through the ruptured tube, the pressurizer level decreases. When an operating crew observes this level decrease, but does not note a BOP radiation alarm,

[22]The primary coolant leaking into the faulted steam generator increases the steam generator level. Attempting to compensate for this rise in level, the automatic regulator for steam generator level decreases the feedwater flow rate to this steam generator. Thus, the level and feedwater flow rate for the faulted steam generator no longer match those for the other (intact) steam generators. These mismatches are not immediately observable but are noted through the level and flow rate trends; hence some time is needed before they can be clearly detected.

they will likely conclude that the root cause is a small loss of coolant accident (SLOCA).

In this set of runs, it is assumed that the steam generator level and feedwater flow rate mismatches are not clear enough for the crew to detect a tube rupture early in the accident. As a result, the SRO/RO will always conclude initially that a SLOCA is underway. The crew will then trip the reactor when the pressurizer level approaches the setpoint (14%) recommended by the Abnormal Operating Procedures (AOPs). Following reactor trip, the SRO will begin the first applicable Emergency Operating Procedure (EOP), E–0 "Post Reactor Trip or Safety Injection."

In following E–0, the first point at which the crew can branch out of the procedure arises at Steps 25 and 26. Step 25 of E–0 checks for a possible steam generator vessel rupture[23] and asks "Is there any steam generator with uncontrollably decreasing level and pressure?" At this point the SRO asks the ARO to determine if this is the case. In this SGTR scenario, the nominal ARO response is, after checking, to report that there is no steam generator with decreasing level or pressure. Step 26 checks for SGTR by asking the SRO to check the status of the BOP radiation alarm (which is off in this sensitivity run). The crew will likely continue to follow E–0 until six steps later, when the procedure explicitly asks the SRO "Is there any steam generator with increasing level?" If the answer to this question is "yes," then the crew will transfer to the E–3 (SGTR) procedure.

Note that the crew may transfer to the E–3 procedure earlier if the ARO's response to Step 25 is more informative than the nominal response. At this time (approximately 12 minutes into the sequence), the steam generator level and feedwater flow rate mismatches should be clear. A proactive ARO may indicate that the level in one of the steam generators (the faulted one) is abnormally high. Alternatively, the RO, who is double–checking the ARO's actions (he has access to the steam generator status on his control panels), may also observe the abnormally high level and send the same message to the SRO[24].

With a proactive message from either subordinate, the SRO may still continue to believe that the problem is an SLOCA rather than an SGTR. It is assumed that only an SRO with a technical ability level of medium or higher will change his diagnosis; the actions of an SRO with low technical ability are assumed to be strongly affected by confirmation bias (discussed in Chapter 1). If the SRO changes his original diagnosis and concludes that an SGTR is underway, the SRO is assumed to transfer from E–0 (Step 26) to procedure E–3, despite the lack of the radiation alarm.

Four hypothetical crews are simulated in this series of runs. Table 5.3 shows the results, with the technical ability (and self–confidence) of each crew member listed in the last three rows. For three of the four crews, either the RO or ARO sends a proactive message regarding the level of the faulted steam generator. Among these three crews, one SRO does not change his original SLOCA diagnosis and transfer to the SGTR procedure. This leads to a delay in transferring to E–3, and a delay in the isolation of the faulted

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[23]The rupture of a steam generator vessel creates a leak from the secondary loop into the containment building. Thus, the feedwater level and (secondary side) pressure of the ruptured steam generator decrease.

[24]In this sensitivity run, the criterion assumed for an ARO to send out a proactive message regarding steam generator level in response to the inquiry Step 25 is that the ARO has a technical ability level of medium or higher; the criterion for the RO is that his technical ability is higher than medium. The criterion for the RO is stricter because the steam generator is not in his normal area of responsibility.

steam generator. These simulations runs show:

- The SRO's technical ability no longer is the dominant factor for crew performance in this more challenging scenario. Because the SRO does not have direct access to the steam generator status, he can only make the correct judgment if his subordinates provide information proactively. Thus, the technical abilities of the ARO and RO, as well as the effectiveness of communication, play more important roles in this scenario.

- When the crews misses the first opportunity to branch to the SGTR procedure (Step 26 in E–0), they delay isolating the faulted steam generator by at least 2.7 minutes. This time delay causes an additional level increase of the faulted SG level of 12 to 18 percent (from 97 to 115 or from 103 to 115 percent). This increases the likelihood of steam generator relief valve opening and of radiation release to the environement (if other delays occur).

5.4 <u>Capacity of Short–Term Memory</u>

As discussed in Section 4.4.4.4, the base case analysis uses a "magic number" to model the capacity of short–term memory; Ref. 33 suggests that this number is approximately 7 (plus or minus 2). In these test runs, the "magic number" is changed for all operators in the crew to observe how changes in short–term memory capacity affect individual and crew behavior. It is found that increasing the magic number produces no effect while decreasing it degrades individual performance and thus crew performance.

When the memory capacity is limited to 3 items, the SRO/RO will have difficulty drawing conclusions in the fault diagnosis process (control activity)[25]. Essentially, the concerns that provide the evidence required for fault diagnosis are crowded out of the concern list by more immediate concerns that arise during the scenario. [Recall that, as described in Section 4.4.2.5, the operator needs to find corresponding evidence (A_2) to combine with an initial proposition (A_1) in drawing a conclusion (B), and that this corresponding evidence is drawn from the concern list.] Thus, the operator loses the "big picture" required to diagnose the root cause. In this case, the crew performance is similar to that of crews in which the operators lack the knowledge (production rules) for fault diagnosis.

5.5 <u>Stress</u>

To explore the implications of the model for stress developed in Section 4.4.4.3, the coefficients representing each operator's sensitivity to the various sources of stress modeled are varied (independently) in this set of runs. The three sources of stress are workload pileup (leading to burden stress S_b), frustration from unsuccessful fault diagnosis processes (leading to frustration stress S_f), and irritation from negatively toned received messages (leading to irritation stress S_i). Eqs. (4.2)–(4.4) identify four corresponding parameters: B_1, F_1, F_2, and I_1 (the burden factor, frustration factor, frustration stress relief, and irritation factors, respectively).

The accumulation of stress is assumed to affect an operator's behavior through its effects on the following individual characteristics:

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[25]Section 4.4.2.5 points out that fault diagnosis control activity need only be modeled for the SRO and RO, due to the division of responsibilities among crew members at the Charles River Plant.

- time spent in executing tasks,
- possibility that an operator may not observe a plant parameter,
- possibility that an operator may not send a message,
- possibility that an operator may not handle a message, and
- time to decay of information in memory.

The first four characteristics increase with increases in overall stress level; the memory decay time decreases with increased stress.

5.5.1 Sensitivity to Workload

Burden stress (S_b) represents the stress arising from an operator's workload. As given in Eq. (4.2), it is assumed that

$$S_b(t) = B_1 * (\text{no. items in short–term memory}) \tag{4.2}$$

where $S_b(t)$ is the burden stress at time t and the coefficient B_1 is called the burden factor. B_1 varies with each individual and is assumed to be constant throughout the simulated sequence. Its maximum value is 0.3[26].

Table 5.4 summarizes the performance of a crew as the burden factors of the operators are varied. In this table, the dash ("–") indicates that the burden factor for that operator is assigned a value of 0.001, the nominal value that represents a negligible sensitivity to workload. The first test run (Line 1 in the table) provides the nominal crew response for comparison. The conclusions from these test runs can be summarized as follows:

- Changes in the SRO's and RO's burden factors affect the crew performance only slightly. This effect is limited to slowing down the crew's response, i.e., increasing the time at which key tasks are accomplished.

- Changes in the ARO's burden factor produce obvious effects on crew performance. The crew reaches the last task (cooldown and depressurization) approximately three minutes later than in the nominal case. Because more than three–fourths of the tasks (procedure steps) are executed by the ARO after reactor trip, the ARO's increased time factor cause significant delays. His time factor increases by 40 percent when his stress reaches its maximum value (5.0).

- Although stress affects some thresholds as well as the memory decay time, performance degradation related to these effects were not observed.

5.5.2 Sensitivity to Frustration Stress

As shown in Eq. (4.3) and Figure 4.9, the increase in frustration stress when a problem is undiagnosed is modeled as being proportional to the time an operator spent in

[26]In this study, the maximum value on the stress scale is 5.0 (high) and the initial stress is set to 3.0 (medium). The maximum stress increase from the workload is therefore 2.0. This increase obtains when the memory is filled to capacity. Using a "magic number" of 7, the maximum burden factor is $2.0/7 \approx 0.3$.

diagnosing the problem:

$$S_f(t) - S_f(t-\Delta t) = \begin{cases} F_1 * \Delta t & \text{diagnosis proceeding} \\ -F_2 & \text{partial diagnosis} \\ -S_f(t^-) & \text{complete diagnosis} \end{cases} \quad (4.3)$$

where $S_f(t)$ is the frustration stress at time t, F_1 is the frustration stress factor, F_2 is the frustration stress relief when an intermediate conclusion is reached in the fault diagnosis process, and $S_f(t^-)$ is the frustration stress just prior to diagnosis of SGTR. Note that the accumulation of frustration stress is part of a positive feedback loop. The longer an operator takes to find the root cause, the higher his frustration stress, which causes his time factor to increase. The increased time factor then slows the operator fault diagnosis process further.

Since the model assumes that only the SRO and RO perform fault diagnosis, the ARO is not sensitive to this stress component. Table 5.5 shows the results of test runs where the frustration factor (F_1) is varied. Again, the dash "–" represents the nominal value of 0.001. The results show almost no effect of the buildup of frustration stress on crew performance.

The sensitivity to frustration stress is negligible because the CA cycle time, the time an operator spends at each level of a control activity, is short (0.1 minutes for both the SRO and RO). The average time that an operator took to find the root cause (SGTR) is only about two minutes. As a result, the diagnosis time depends more on the presence of the evidence than on the time an operator takes to make a conclusion given the evidence. Significantly longer control activity cycle times, or significantly more complicated control activity reasoning chains, will affect the diagnosis time and could make the effects of this stress component more observable.

5.5.3 Sensitivity to Irritation Stress

The effect of a message on a receiver's irritation level depends on the negativity of the tone expressed by the sender, the receiver's tolerated tone and his irritation factor*:

$$\Delta S_i = (I_1) * (\text{sender's tone} - \text{receiver's tolerated tone}) \quad (4.4)$$

where ΔS_i is the increase in irritation stress, and I_1, the irritation stress factor, represents the receiver's sensitivity to the sender's tone. The receiver's "tolerated tone" is the level of irritating tone a receiver can stand without being irritated. The sender's tone is given by Eq. (4.10):

$$\text{sender's tone} = T_2 * (\text{sender's stress}) \quad (4.10)$$

where T_2 is the "stress to tone factor."

The stress to tone factor (T_2) is assigned a value of 1.0 throughout this set of runs. The tolerated tone is assigned a value of 3.0, which is the initial value of an operator's stress. Note that the accumulation of irritation stress is incremental, i.e., every time a message is received, this stress component will increase. Also note that a message cannot reduce this stress component; the model does not consider a "calming" effect so that there is no release of this stress component.

One feature of this model is that the operator's irritation stress can be felt in the tone of the messages he sends. As a result, when two operators are sensitive to irritation, both operators' irritation stress will increase after each exchange (command and response/report); their irritation stress can reach the saturated value (5.0) in a relatively short time. Table 5.6 shows the effects of irritation stress buildup on crew behavior. In this table, the last three columns show either the time at which each operator's stress reaches its saturation value (maximum) or the stress value at the end of the simulation. These test runs show:

- In a crew with only one operator sensitive to negatively toned messages, the effects on crew performance are minor.
- When more than one operator is sensitive to negatively toned messages, these operators' stress levels will build up quickly (see Lines 2 through 7 in Table 5.6).
- In the extreme case (Line 4), all three operators' stress levels reach saturation (5.0) in 5 minutes. This causes a significant delay in isolating the faulted steam generator and a significant increase in the faulted steam generator level at the time of isolation.

5.5.4 Sensitivity to All Stress Sources

In this final set of runs related to stress, different combinations of burden, frustration, and irritation factors are simulated. Table 5.7 summarizes the performances of the hypothetical crews under these conditions. Comparing Line 2 of Table 5.7 and Line 2 of Table 5.6, it can be seen that the effects of combined burden and irritation stress are dramatic. The increase in the burden stress component accelerates the buildup of stress for all operators and therefore increases the time delay in isolating the faulted steam generator. Note that after reactor trip, most of the crew communications occur between the SRO and ARO (the ARO is responsible for most of the Emergency Operating Procedure steps); hence, their stress builds up more quickly than that of the RO.

The operators' frustration stress is significant only early in the sequence since it is relieved when the root cause is found; by comparison, the burden stress is present throughout the scenario. When more than one operator is sensitive to irritation, the stress felt by other operators can increase quickly due to increases in their burden stress.

5.6 Self–Confidence

Throughout the earlier tests, an operator's self–confidence is assumed to be proportional to his technical ability. This set of runs explores the performance of a crew with an SRO who has a low technical ability but is highly confident. The results are shown in Table 5.8, where in all runs, each crew have the same technical ability combination (LHH).

In the first run (Line 1 of Table 5.8), the self–confidence of the crew members is assumed to be positively correlated with technical ability, i.e., the SCs are LHH. The relative confidence level among operators is assigned the nominal value of 0.5 (medium). In the second run (Line 2), the self–confidence ratings are kept the same, but each operator's relative confidence in his fellow crew members is adjusted to reflect technical ability. Thus, the SRO's confidence in his crew members is greater than the nominal value while their confidence in him is below nominal. The third run (Line 3) is similar to the second, except that the SRO is assumed to have a high self–confidence and only nominal confidence in his crew.

Another difference between the second and third runs, not shown in Table 5.8, is the reactor trip setpoint (based on pressurizer level) of the RO. In the third run, the trip setpoint is raised, increasing the likelihood that the RO will suggest a reactor trip before this is commanded by the SRO.

Table 5.8 shows that the simulation model does not predict any significant differences in performance as the SRO's self-confidence is varied. This is because an operator's self-confidence is modeled as having only two effects. First, a highly confident subordinate (RO/ARO) will be more outspoken and will produce proactive messages. Second, a highly confident SRO will reject the RO's suggestion of reactor trip[27]. In Line 2, the SRO adopts the RO's suggestion, whereas in Line 3, he does not. However, the effect of this difference is minor due to the closeness of the SRO's and RO's trip set points (14% and 16%, respectively). Note that the trip setpoint value of 14% is strongly recommended by the Abnormal Operating Procedures and a large deviation is therefore unlikely. The pressurizer level also changes quickly (approximately 7.5%/minute) in this portion of the scenario, so that by the time the RO decides to make the suggestion to the SRO, the SRO's (internal) setpoint is either reached or has already been reached. As a result, the timing of the crew responses is, for this scenario, not affected by whether the SRO adopts the RO's suggestion or not.

5.7 Relative Confidence Level

In this analysis, the relative confidence level between an SRO and an RO is varied to determine for which values communication between the two breaks down.

As mentioned in Section 4.5.2.1 and shown in Eq. (4.8), it is assumed that the sender's willingness to send a message increases with the sender's assessed priority of the message, increases as his confidence in the receiver decreases, and increases if the receiver's confidence in him increases (in the sender's perception). This perceived confidence is the product of the sender's self-confidence and the receiver's confidence in the sender. When an operator's willingness to send out a message is less than the "message send-out threshold," he will not send out the message. The value of this threshold is proportional to an operator's stress; his willingness to communicate decreases as his stress increases. Note that this model works for some personality types; others may actually talk more.

The implication of this model is that communication will break down when the relative confidence between operators is imbalanced, i.e., when the sender's confidence in the receiver is high and the sender senses that the receiver's confidence in him is low. This is shown using the crew model simulation, as can be seen from the results in Lines 1–3 and Lines 5–7 of Table 5.9. Because it increases the message send-out threshold, the buildup of the sender's stress can further degrade these situations (compare Lines 3 and 4 or Lines 7 and 8 in Table 5.9).

The predicted consequence of communication breakdown is that all crew members stop executing tasks. The SRO stops sending commands because no information is provided from the subordinates, and the subordinates have no tasks to be executed since no command is issued. Of course, this is a highly hypothetical situation that was not observed in the videotaped simulation exercises.

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[27]In the actual implementation of the model, the RO's suggestion that the reactor be tripped is not directly accepted or rejected. Instead, in response to the suggestion, the SRO can change his own setpoint. This setpoint is then used to determine if the reactor should be tripped.

5.8 Summary

The sensitivity analyses described in this chapter provide a number of interesting results regarding crew composition. They show that, for the boundary conditions considered (these prescribe the responsibilities of the different crew members and the distribution of role and status among the crew members, as well as the accident scenario), a strong SRO can compensate for weak subordinates and a strong RO can compensate for a weak SRO. However, given the current crew structure, a good ARO does not have much of an impact on overall crew performance. When the boundary conditions are changed, these conclusions can change. For example, when the BOP radiation alarm is failed, the technical ability of the ARO becomes a key factor in determining the crew's degree of success.

The sensitivity analyses also show that, given the boundary conditions of the analysis, some of the hypothesized effects built into the crew model do not have a significant impact on the scenario outcome, whereas others are much more important. In the former category, large increases in short–term memory capacity (from the "magic number" of 7) do not lead to significant differences, nor do large increases in the "frustration factor" (modeling increases in stress due to inability to diagnose a problem), nor do changes in operator self–confidence. In the latter category, the factors governing up the buildup of stress due to workload and irritation from negatively toned communications can significantly degrade crew performance, as can changes in the relative confidence between operators.

Regarding the effect of stress, increases in an operator's stress level affects his efficiency in executing a task, his willingness to send out messages, his willingness to handle received messages, and the reduces his ability to observe available information from the control board displays. The sensitivity runs indicate that the first two items are most significant. In the most extreme cases, the crew isolates the faulted steam generator 4 to 5 minutes later than in the nominal case. As a consequence, the level of the faulted steam generator is some 17% higher than in the nominal case. Note that since this result is for an average crew, the situation could be worse for a below average crew.

Regarding the issue of relative confidence, communication within a crew can break down before the end of a scenario when operators lack confidence in each other. This breakdown can be accelerated by the accumulation of stress, since, as mentioned above, stress affects the willingness of a sender to send a message and a receiver to handle a message.

These sensitivity studies are not exhaustive. They do indicate the robustness of the crew model, since the model does not break down when input parameter combinations significantly different from those employed in the benchmarking runs are used. They also provide important insights into the behavior of a number of submodels employed by the crew model simulation. Finally, they provide a number of results which are plausible, providing at least a partial indication of the plausibility of the underlying model.

Table 5.1 - Effect of Varying Individual Technical Abilities (Extreme Crew Compositions)

Run	Crew TA and SC	CA cycle time min.	Start up 2nd CCP min.	Reduce power min.	SGTR conclusion min.	Trip Rx min.	Go to E3 min.	S/G isolation (%NR) min/%	Cool-down & depress. min.
1	HHH	0.1	1.5	1.5	1.8/1.9	4.0	11.6	15.8/95	19.0
2	LLL	0.5	NP††	NP	2.8/2.8	5.7	13.3	17.5/92	20.7
3	LLL	2.0	NP	NP	6.8/6.5	7.1	14.8	19.0/92	22.1
4	LLL	20.0†	NP	NP	N/A	7.7 auto	15.1	19.3/93	22.5

† Representing the absence of production rules in operator's fault diagnosis
†† Never performed

Table 5.2 - Effect of Varying Individual Technical Abilities (Intermediate Crew Compositions)

Run	Crew TA and SC	Start up 2nd CCP min. *indicates RO's suggestion	Reduce power min. *same as left	SGTR conclusion min.	Trip Rx min.	Go to E3 min.	S/G isolation (%NR) min/%	Cool-down & depress. min.
5	HMM	1.5	1.6	2.6/1.6	3.9	11.6	15.8 (94)	19.0
6	HLL	1.5	1.6	2.5/2.6	3.9	11.6	15.8 (94)	19.0
7	LHH	2.3/2.0*	2.8/2.6*	2.1/2.2	4.0	11.7	15.9 (93)	19.1
8	LHM	2.3/2.0*	2.9/2.7*	2.1/2.2	3.8	11.4	15.6 (92)	18.8
9	LMH	NP	3.0/2.7*	2.1/1.4	5.8	13.5	17.7 (100)	20.8
10	MLH	NP	1.6	1.7/1.8	5.5	13.1	17.3 (102)	20.5
11	MMM	NP	1.5	1.6/1.6	5.0	12.7	16.9 (101)	20.1
12	MHL	2.3/2.2*	1.5	1.6/–	3.8	11.4	15.6 (95)	18.8

Table 5.3 - Effect of Additional Hardware Failure
(Loss of BOP Radiation Alarm)

	Case1	Case2	Case 3	Case 4
RO/ARO proactively sends message "B SG level abnormally high"	RO	none	ARO	ARO
SRO changes his belief of SLOCA to SGTR and goes to procedure E3	yes	no	no	yes
B SG isolated at (minutes)	15.6	19.4	19.5	16.7
B SG level when isolated (% NR)	97%	115%	115%	103%
Cooldown and depressurization started at (minutes)	18.8	22.6	22.6	19.8
SRO's Technical Ability	Medium	Medium	Low	Medium
RO's Technical Ability	High	Medium	Medium	Medium
ARO's Technical Ability	Low	Low	Medium	Medium

Table 5.4 - Effect of Varying Burden Stress Parameters

Crew Burden Factor: SRO/RO /ARO	Start up 2nd CCP *indicates RO's suggestion min.	Reduce power *indicates RO's suggestion min.	SGTR conclusion for SRO /RO min.	Trip reactor min.	Go to E3 min.	S/G isolation (%NR) min./%	Cool-down & depress. min.
-, -, -	2.6/2.5*	1.5	1.6	3.9	11.5	15.7/96	18.9
.01, - , -	2.6/2.5*	1.5	1.6	3.9	11.6	15.8/96	18.9
.05, - , -	2.6/2.5*	1.5	1.6	3.9	11.6	15.9/96	19.0
.1 , - , -	2.7/2.5*	1.5	1.6	3.9	11.7	15.9/96	19.1
.3 , - , -	2.8/2.6*	1.7	1.8	3.9	11.9	16.3/97	19.5
- , .05, -	2.6/2.5*	1.6	1.6	3.9	11.6	15.9/96	19.0
- , .1 , -	2.7/2.5*	1.6	1.6	3.9	11.8	16.0/97	19.2
- , .3 , -	2.7/2.6*	1.6	1.6	3.9	12.2	16.5/98	19.7
- , - , .05	2.6/2.5*	1.5	1.6	3.9	11.7	16.1/98	19.3
- , - , .1	2.6/2.5*	1.5	1.6	3.9	12.0	16.5/100	19.8
- , - , .3	2.6/2.5*	1.5	1.6	3.9	12.5	17.6/104	21.2
all .05	2.7/2.5*	1.5	1.6	3.8	11.9	16.3/98	19.5
all .1	2.7/2.6*	1.6	1.7	3.9	12.4	17.0/100	20.3
all .3	2.9/2.8*	1.8	1.9	3.9	13.5	18.8/107	22.5

Table 5.5 - Effect of Varying Frustration Stress Parameters

Crew Frus-tration Factor: SRO/RO /ARO	Start up 2nd CCP *indicates RO's sug-gestion min.	Reduce power *indicates RO's sug-gestion min.	SGTR conclu-sion for SRO /RO min.	Trip reactor * RO's sug-gestion min.	Go to E3 min.	S/G iso-lation (%NR) min./%	Cool-down & depress. min.
-,-,-	2.6/2.5*	1.5	1.6	3.9	11.5	15.7/96	18.9
.1,-,-	2.6/2.5*	1.5	1.6	3.9	11.5	15.7/96	18.9
.3 ,-,-	2.6/2.5*	1.5	1.6	3.9	11.5	15.7/96	18.9
1.0,-,-	2.6/2.5*	1.5	1.6	3.9	11.6	15.8/96	18.9
2.0,-,-	2.7/2.5*	1.6	1.7	3.9	11.5	15.7/96	18.9
-,.3,-	2.6/2.5*	1.6	1.6	3.9	11.6	15.8/95	18.9
-,1.0,-	2.7/2.5*	1.6	1.6	3.9	11.6	15.8/95	18.9
-,2.0,-	2.7/2.6*	1.6	1.6	3.8	11.5	15.7/95	18.8
.1,.1,-	2.6/2.5*	1.5	1.6	3.9	11.5	15.8/96	18.9
.3,.3,-	2.6/2.5*	1.5	1.6	3.9	11.6	15.8/95	18.9
1,1,-	2.6/2.5*	1.6	1.7	3.9	11.6	15.8/95	18.9
2,2,-	2.7/2.6*	1.7	1.8	3.8	11.4	15.6/94	18.8

Table 5.6 - Effect of Varying Irritation Stress Parameters

Crew Irri-tation Factor: SRO/RO/ARO	Trip reactor min.	Go to E3 min.	S/G iso-lation (%NR) min./%	Cool-down & depress. min.	SRO Stress saturated at (min.) or value at End*	RO Stress saturated at (min.) or value at End*	ARO Stress saturated at (min.) or value at End*
-,-,-	3.9	11.5	15.7/96	18.9	3.0*	3.0*	3.0*
.1,.1,.1	3.9	11.6	15.8/97	19.1	3.5*	3.5*	3.5*
.3,.3,.3	3.9	12.9	18.8/109	23.2	9.0 min.	9.0 min.	9.0 min.
1,1,1	3.99	14.5	20.2/114	24.6	5.0 min.	5.0 min.	5.0 min.
.3,.3,-	3.9	11.7	16.0/97	19.3	4.4*	4.2*	3.0*
.3,-,.3	3.9	12.3	18.1/107	22.4	11 min.	3.0*	11 0 min.
1,1,-	3.99	12.8	17.3/103	20.9	5.7 min.	5.7 min.	3.1*
1,-,1	3.9	13.4	19.2/110	23.4	6.1 min.	3.0*	6.1 min.
1,-,-	3.9	11.6	15.8/97	19.0	3.36*	3.0*	3.0*
-,1,-	3.9	11.6	15.8/97	18.9	3.0*	3.1*	3.0*
-,-,1	3.9	11.6	15.8/97	19.1	3.0*	3.0*	3.15*

Table 5.7 - Effect of Varying Parameters for All Stress Components

Burden Factor: SRO/RO /ARO	Frus-tration Factor: SRO/RO /ARO	Irri-tation Factor: SRO/RO /ARO	Trip Rx min	Go to E3 min.	S/G iso-lation (%NR) min./%	Cool-down & depress. min.	SRO/RO/ ARO's stress saturated at(min.) or value at End*
-,-,-	-,-,-	-,-,-	3.9	11.5	15.7/96	18.9	3.0*/3.0* /3.0*
all .01	-,-,-	all .1	3.9	12.1	16.9/101	20.9	20/3.8*/20
all .01	.1,.1,-	all .1	3.9	12.1	17.1/102	21.2	19/4.0*/19
all .03	.1,.1,-	all .1	3.8	12.9	18.7/109	23.1	11/4.9*/12
all .1	.1,.1,-	all .1	3.9	14.5	20.2/113	24.6	6.0/8.3/10.6

Table 5.8 - Effect of Varying SRO Self-Confidence

Crew TA: LHH SC:	Start up 2nd CCP *indicates RO's sug-gestion min.	Reduce power *indicates RO's sug-gestion min.	SGTR conclu-sion for SRO /RO min.	Trip reactor *indicates RO's sug-gestion min.	Go to E3 min.	S/G iso-lation (%NR) min./%	Cool-down & depress. min.
LHH	2.3/2.0*	2.8/2.6*	2.1/2.2	4.0	11.7	15.9 (93)	19.1
LHH	2.3/2.0*	2.8/2.6*	2.1/2.2	4.0/3.5*	11.7	15.9 (93)	19.1
HHH	2.3/2.0*	2.8/2.6*	2.1/2.2	4.0/3.5*	11.7	15.9 (93)	19.1

Table 5.9 - Effect of Varying Relative Confidence Levels

Self-Confidence of SRO/RO	**SRO's Confidence in RO**	**RO's Confidence in SRO**	**Sensitivity to stress level†**	**Breakdown in Message Exchange (min.)**
0.95/1.05	0.5	0.5	Low	No
0.95/1.05	0.35	0.65	Low	No
0.95/1.05	0.3	0.7	Low	Yes (6.0)
0.95/1.05	0.35	0.65	High	yes (10.0)
0.95/1.05	0.65	0.35	High	No
0.95/1.05	0.7	0.3	Low	No
0.95/1.05	0.75	0.25	Low	Yes (0.7)
0.95/1.05	0.7	0.3	High	Yes (20.0)

† Low sensitivity: Burden, Frustration, and Irritation factors for operators are assigned the nominal value 0.001

High sensitivity: Burden Factor for SRO/RO/ARO: 0.01
Frustration Factor for SRO/RO/ARO: 0.1
Irritation Factor for SRO/RO/ARO: 0.1

6. CONCLUDING REMARKS

6.1 Introduction

Current human reliability analysis models have weaknesses in modeling cause–effect relationships underlying operator actions during an accident scenario. These relationships can be the source of multiple, dependent failures and could therefore have a critical impact on plant risk. A number of cognitive models for individual operators are currently being developed to address these weaknesses. These models, which treat the reasoning underlying an operator's intention formation, appear to be quite promising. However, they have only a limited ability to model interactions between operators and the effects of these interactions on crew performance.

This report describes a systems–oriented framework for modeling the behavior of a control room operating crew during an accident, and applies this framework in a simulation of a steam generator tube rupture (SGTR) scenario. The remainder of this chapter outlines the key characteristics of the approach, discusses the SGTR application of the approach (including a number of sensitivity analyses in which individual and group characteristics are varied), and indicates where additional work is needed before the model can be practically applied in a human reliability analysis.

6.2 Crew Model Characteristics

The operating crew model treats the crew explicitly as a group of interacting individuals. Each operator receives information from the plant and the other operators. The received information (note that some incoming information may not be received by the operator) is processed using knowledge retrieved from short–term (dynamic) and long–term (static) memory; both scripted, automatic responses and responses developed from control activities (fault diagnosis in this case) are treated. The operator's responses can include actions that affect the plant (via control switch manipulation) or other operators (via the sending of messages). Thus, group behavior is modeled as the implicit result of the individual processing of operators and the communication between operators.

Similar to earlier artificial intelligence inspired models for human cognition, this model treats an operator as a reasoning machine. As in the other models, weaknesses of an actual operator in this role can be treated by appropriate modifications of the facts stored in the simulated operator's memory (knowledge base) and production rules used to manipulate and draw conclusions from available information. In addition, this model explicitly includes other sources of imperfection. Thresholds are incorporated to block the flow of information, delay times for processing information are acknowledged, and limitations in short–term memory capacity are treated. Furthermore, the effect on these parameters/issues due to crew structure (e.g., the relative confidence an operator has in a fellow crew member) and non–task related behavior associated with stress buildup are treated to a limited extent.

The modeling framework is applied to an SGTR scenario using a deterministic, systems–oriented viewpoint. Model entities are characterized by their input, processing functions, and output. (This approach not only systematizes model construction, it also leads to an organized approach for data collection.) The discrete event/process simulation language (SIMSCRIPT II.5) is used to encode the model; efforts are made to ensure that, whenever practical, the model is modular and that there is a one–to–one correspondence between real and model (program) entities. This approach simplifies the treatment of individual variability among crew members. It also simplifies model expansion to include additional personnel outside of the control room crew (e.g., local equipment operators, experts in the technical support center), aids the model construction process, and improves model maintainability.

It should be pointed out that not all of the sub–models/entities used in the crew model have a strong theoretical basis. For example, it is not clear if the "concern list" and "action list," the two primary structures used in the simulation to organize task–related information in an operator's short–term memory, have actual psychological counterparts. In these cases, simple, plausible models are employed. Heavy reliance is placed on observations drawn from videotapes of operating crews at a non–U.S. pressurized water reactor (the "Charles River Plant") during SGTR training exercises to ensure that these simple models lead to an integrated crew model that reasonably emulates observed behaviors. Moreover, the modularity of the crew model simplifies the replacement of these simple models when improved ones become available.

6.3 SGTR Application Results

The operating crew simulation model is applied in two analyses of SGTR accidents. In the first set of runs, the performances of four crews at the Charles River Plant are simulated. Three of these runs are benchmarking calculations designed to identify reasonable values for two uncertain model parameters (the "control activity cycle time" and the "time factor"). The fourth run is performed as a blind test of the model, using the tuned parameter values obtained from the benchmarking runs. Most of the input data are constant across all four runs; the primary differences involve the parameters characterizing the individual operators (their technical ability, self–confidence, and confidence in each of their fellow crew members). In the second set of runs, a number of sensitivity analyses are performed. These are designed to investigate the robustness of the crew model simulation, as well as to determine the sensitivity of the model to changes in specific parameters.

6.3.1 Benchmark and Blind Test Runs

The results of the benchmark and blind test runs show that the crew model simulation reasonably predicts the behavior of a four operating crews simulated. Figures 4.10 through 4.13 show that the simulation usually correctly predicts the occurrence, ordering, and timing of key events. There are some discrepancies, as indicated by the shaded boxes in these figures. These are, however, relatively few.

From a detailed modeling standpoint, these runs demonstrate the ability of the crew model to explore interesting issues not directly addressed by cognitive models for single entities (either individuals or groups of individuals). One potentially important issue is associated with the time required by a crew to perform a critical set of actions. Time is a central parameter in some human reliability analysis models; however, at least for the SGTR training exercises observed, it appears that the time to key events is not well correlated with expert assessments of crew "technical ability" or "teamwork quality" (e.g., see Table 3.13).

Because the crew model simulation predicts the intentions of all crew members, as well as their actions, this potential paradox can be investigated. In particular, a review of the output generated from the benchmark and blind test runs indicates that, quite often, an operator is delayed in performing intended actions because of interruptions not under the operator's control. These interruptions usually are due to messages from other operators. Note that because the SRO is the focus of communication, this situation is more important for the SRO than for the other operators. Thus, the model provides a rationale for the lack of correlation between operator ability and the delay time in responding to cues; it also provides a tool that might be useful in better assessing "teamwork quality."

Another interesting issue treated by the crew model is the role/importance of proactive communication in crew performance. The simulation runs show that the RO's and ARO's suggestions and proactive messages often provide supportive information in helping the decision maker (the SRO) respond to a specific cue. Proactive messages are found to be especially critical when an additional hardware failure (failure of the balance of plant radiation alarm) is postulated. Since the SRO relies upon his subordinates to supply information, there may significant time delays in his selecting an appropriate response to a change in plant status. These time delays can be affected by the relationship between the SRO and his subordinates (as discussed below). In principle, the effect of group structure on these time delays can be modeled implicitly (e.g., by using performance shaping factors) by models which treat an operating crew as a single entity. However, the crew model provides a more mechanistic representation involving parameters that can be at least partially quantified from observed data.

6.3.2 Sensitivity Runs

The results of the sensitivity runs show that the operating crew model simulation generates plausible results when various parameters (e.g., those characterizing stress buildup) are varied significantly. For example, as the sensitivity of crew members to negatively toned messages is increased, the model predicts a more rapid buildup of stress, which affects both the tone of subsequent messages and reduces the willingness of a sender (receiver) to send (receive) a message. (Note that the original willingness of a sender, for example, depends on the interpersonal relationship between the sender and the receiver.) At some point, the communication process becomes significantly impaired or even breaks down completely. Communication breakdown has been found to be a key factor in a number of civil aviation accidents, where the structure of the cockpit crew is similar to that of a nuclear power plant control room crew.

The sensitivity studies also develop plausible results associated with the effect of crew composition on performance. It is found that although two crews may have a comparable overall technical ability (summing the abilities of all crew members), different distributions of ability over the crew members can yield substantially different crew performance. For example, the performance of a crew with a low technical ability SRO, a medium technical ability RO, and a high technical ability ARO is predicted to be less efficient than that of a crew with high technical ability SRO, medium technical ability RO, and a low technical ability ARO. The usefulness of the crew model lies not only in the production of these somewhat intuitive results, but also in the creation of a more formal rationale for these results which can then be used to help improve crew performances.

Of course, the results obtained in the sensitivity studies are not definitive, given the limited theoretical basis for some of the models and the limited benchmarking data available. Nevertheless, the results indicate what types of lessons can be derived with this modeling approach.

Despite the limitations of the current implementation of the crew model, it is believed that this simulation can be used to improve the training of individual operators and of a crew. For example, in a sensitivity study in which the balance of plant (secondary) radiation alarm is lost, the crew model predicts that the SRO can, without the aid of proactive messages from his subordinates, commit a mistake in diagnosing the root cause. The consequence of this mistake is predicted to lead to a time delay in isolating the faulted steam generator and hence a higher water level in that steam generator. Therefore, by encouraging the subordinates to provide suggestions and proactively report during training, the crew performance may be improved. Of course, messages will interrupt a receiver's activities, as discussed earlier. Thus, in principle, the crew model might be

useful in developing an optimal set of rules governing message transmission.
an be applied on a PRA.

6.4 Future Work

The objective of human reliability analysis in probabilistic risk assessment is to accurately characterize the likelihood of human error in a set of specific situations. The current implementation of the operating crew model developed in this study has two limitations that prevent its immediate, direct application in such an analysis. First, the simulation model is deterministic. Second, and more importantly, the simulation model relies heavily upon observations of actual crew behaviors during SGTR simulation exercises. Since these exercises did not involve any failures in addition to the inititating tube rupture, and were handled in a relatively straightforward manner by all of the operating crews, the model does not yet treat operator behaviors under confusing conditions. To address these concerns, the crew model requires a number of refinements.

First, the model for the individual operator needs improvement. Stochastic variability (e.g., in selecting scripts in response to cues) needs to be quantified, as does state of knowledge uncertainty in deterministic parameters. The task–related processing portion of the model should be expanded to treat errors in intention formation, planning and execution not currently dealt with. The scripts developed for SGTR response need to be generalized to allow treatment of a wider variety of scenarios. A more generalized control activity model is also needed to handle a wider variety of situations. Together with the generalized scripts, this will allow treatment of more complex scenarios.

The emphasis of the current model for individuals is on task–related behavior. Non–task related behavior is treated in a very limited manner, using a simple mode for stress buildup and impact on monitoring, communication, time to perform tasks, and memory decay. Since non–task related behavior can have a significant impact on task–related behavior, a more general model for non–task related behavior may be need to be developed and integrated into the current crew model.

Improved models for the treatment of the crew as a group of operators could also be useful. In the area of communication, the current crew model treats both the content and tone of messages to simulate the verbal/nonverbal and informational/emotional communications. In general, this approach is believed to be useful in treating verbal and informational message exchanges. However, the concept of tone may not treat non–verbal or emotional communication adequately; such communication has been shown to contribute to the occurrence of a number of civil aviation accidents. Furthermore, message–garbling is not treated. In the area of crew structure, it should be pointed out that the crew model treats the relationships between operators (which affect the sending and receiving of messages) in a static manner. The analyst defines the relative confidence between an operator and his fellow crew members prior to the start of a run. The model does not allow these relationships to change over the course of an accident. Depending on the likelihood of significant structural changes (e.g., when a subordinate loses confidence in a superior), a model to predict dynamic changes in crew structure may be needed.

A third area requiring additional work involves the plant model. To limit the amount of work associated with the development of a general thermal–hydraulic model, the current plant model developed for this study only applies to the early portion of a steam generator tube rupture scenario. For application in a risk assessment study, a very fast and accurate thermal–hydraulic simulation must be integrated into the crew model.

In addition to crew model refinements, it is extremely important that additional work be done on the collection of data. The modeling approach followed in this study requires the use of data on individual characteristics (technical ability and self–confidence), group characteristics (division of responsibilities and relationships between operators), and actual crew performances. The data used in this study are limited both in terms of sample size (10 crews at a single plant performing training exercises for a single SGTR scenario) and representativeness (the scenario was a relatively simple one, as SGTR scenarios go). Comparable information is needed for a larger number of crews performing under more challenging circumstances. Work also needs to be done to improve the data collection process itself; the questionnaire provided in Appendix B may be a useful first in this direction.

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APPENDIX A. QUESTIONS AND ADDITIONAL DATA FROM CHARLES RIVER PLANT FIELD TRIP

This appendix summarizes the data collected during a one-month visit to a 2-unit, non-U.S. PWR. The data consists of results from interviews with control room operators, from interviews with former shift supervisors, and from reviews of videotapes of crews responding to steam generator tube rupture training exercises. Only the information relevant to the scope of this study are provided here.

It should be noted that some of the raw data gathered during the trip has been judged to be sensitive by the utility. Steps have been taken to allow the use of this information in this study. The ten operating crews, whose self-ratings are listed in this appendix, are randomly ordered. Crew performance times (e.g., the time required to identify the sequence as a SGTR) are presented in a rescaled, relative form. In this manner, confidentiality is preserved, yet lessons can still be drawn from the data.

The questions asked in interviews with the control room operators are provided in Table A.1. Table A.2. describes the questions asked in interviews with the five former shift engineers (3 of them were training supervisors). Part of the results from questions asked to operators are summarized in Tables A.3 and A.4. Table A.3 describes the crew members' rating on the crew's technical ability and its teamwork quality, which are the results to Questions 1e and 1h. The "confidence levels" between operators, which were results of Questions 4b and 4c, are provided in Table A.5. Table A.6 summarizes the parameters that operators thought were the most important during normal plant and SGTR operation (i.e., answers to Questions 1i and 3d). The experts' ratings of individual operator technical ability and crew's teamwork quality are provided as Table A.6.

Based on observations of the videotapes and simulator exercises, the timing of key actions in the SGTR exercises are summarized in Table A.7. All times presented have been rescaled in the relative form. Table A.8 describes the variation of the observed operator behavior in responding to some specific cues during the SGTR exercises.

There are some other interesting results from questions asked in interviews with the control room operators. For example, the average score of answers to Question 3c (answered by 30 operators), about the importance of teamwork in the SGTR sequence, was 94, where the question states, "Take 100 as 'extremely important'". Regarding the necessity of reporting to the SRO during a SGTR sequence (Question 3e), the ROs and AROs (on average) felt that 95% of actions and information should be reported. These results show the operators' awareness of the importance of teamwork or coordination in a crew response as well as the effects of training in requiring the subordinate to report all information to the SRO during an accident scenario.

Table A.1 Questions Asked in Interviews with Control Room Operator

1. Normal Operation
   1a. Are you satisfied with the working hours (shifts)? Take 100 as fully satisfied and 60 as barely acceptable.
   1b. Which shift do you like the most? the least?
   1c. Are you satisfied with the salary, the fringe benefit, and the promotion system? Use the standard in 1a.
   1d. How long have you been worked together with your team members?
   1e. Rate your crew in the aspect of technical ability, take the average of 10 crews as 60.
   1f. Do you think other groups of employees (e.g., maintenance) are respectful to the operators? Do you think yourself being respected? Use the standard in 1a to give ratings.
   1g. Which of the following field do you think you would like to learn more? (1)Reactor physics (2)Thermal hydraulic (3)Operating skills
   1h. Rate your crew in the aspect of teamwork quality, take the average of 10 crews as 60.
   1i. Name 3-5 parameters that you think are most important in your responsibility area.

2. Training
   2a. How close do you think the simulator responses are to that of the real reactor? Take 100 as "exactly the same" and 60 as "reflecting only a bold picture".
   2b. In general, do you think the simulator training is effective? Take 100 as "very effective" and 60 as "somewhat effective".

3. Emergency Operation: SGTR
   3a. For SGTR sequence, do you think the simulator training is effective?
   3b. Briefly describe what you will do in a SGTR sequence.
   3c. How important do you think the teamwork is in a SGTR sequence? Take 100 as "extremely important".
   3d. Name 3-5 parameters you would like to lost the least in a SGTR sequence.
   3e. Do all actions and information have to be reported to the SRO? If not, rate the percentage the should be.

4. Confidence Level
   4a. Have there been any different opinions existed between you and your crew members? If yes, how were these resolved?
   4b. In your past experience, what is the percentage that you were right regarding to the technical problems?
   4c. In your past experience, what is the percentage that you crew member was right regarding to the technical problems?

5. Operational Policies and Procedures
   5a. How do you think about the currently used AOPs and EOPs? What are their advantages and disadvantages?

Table A.2 Questions Asked in Interviews with Former Shift Supervisors

1. Crew Evaluation
   1a. Rate all SROs, Ros, and AROs in the aspect of their technical ability.
   1b. Is there any crew that the actual leader is not the SRO?
   1c. Please comment on the leadership of each SRO.
   1d. Rate all crews in the aspect of teamwork quality.

2. Training
   2a. How close do you think the simulator responses are to that of the real reactor? Take 100 as "exactly the same" and 60 as "reflecting only a bold picture".
   2b. In general, do you think the simulator training is effective? Take 100 as "very effective" and 60 as "somewhat effective".

3. Operational Policies and Procedures
   3a. How do you think about the currently used AOPs and EOPs? What are their advantages and disadvantages?

Table A.3 Crew Members' Ratings on Crew's Technical Ability and Teamwork Quality

Items	Rater	CREWS										Average (μ) and Standard Deviation (σ)
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	
Crew Technical Ablity	SRO	90	80	65	85	90	58	70	80	80	85	$\mu = 78.4$ $\sigma = 10.7$
	RO	80	80	70	75	80	61	75	80	75	85	$\mu = 76.1$ $\sigma = 6.70$
	ARO	60	65	50	80	80	70	75	80	60	80	$\mu = 70.0$ $\sigma = 10.8$
Crew Teamwork Quality	SRO	80	92	60	80	90	58	70	85	85	85	$\mu = 78.5$ $\sigma = 11.9$
	RO	80	80	60	70	85	80	80	80	60	85	$\mu = 76.0$ $\sigma = 9.40$
	ARO	60	65	50	85	90	70	85	90	80	70	$\mu = 75.0$ $\sigma = 13.1$

Table A.4 Operators' Confidence Levels in Crew Members

Items	Rater	CREWS #1	#2	#3	#4	#5	#6	#7	#8	#9	#10
SRO's Confidence Level	RO --> SRO*	85	90	80	80	85	90	80	90	80	90
	ARO --> SRO	80	90	80	80	80	90	80	90	80	90
	SRO --> RO**	80	95	70	60	90	60	80	70	70	90
	SRO --> ARO	85	95	60	60	90	75	80	80	75	90
RO's Confidence Level	SRO --> RO	85	80	50	80	85	50	90	60	80	80
	ARO --> RO	75	90	90	80	85	70	80	60	90	90
	RO --> SRO	95	80	90	80	85	85	70	60	90	90
	RO --> ARO	92	90	100	80	85	60	65	60	90	80
ARO's Confidence Level	SRO --> ARO	92	90	80	80	90	85	80	85	75	70
	RO --> ARO	90	90	80	80	90	85	80	85	75	80
	ARO --> SRO	70	88	80	90	90	85	100	80	75	90
	ARO --> RO	80	90	80	90	90	85	90	75	75	80

* the confidence level that SRO think RO has in SRO

** SRO's level of confidence in RO

Table A.5 Important Parameters Chosen by Control Room Operators

Normal Operation

Parameter	SRO	RO	ARO	Total
RCS T-avg	5	7	6	18
Thermal Power	9	7	2	18
Primary Pressure	5	5	7	17
Power Output (MWe)	9	4	3	16
Steam Generator Level	3	2	6	11
Pressurizer Level	1	2	4	7
Steam Generator Pressure	0	0	3	3
Control Rod Position	1	1	1	3
Main Feedwater status	1	0	1	2
Turbine Vibration	2	0	0	2
Radiation	0	1	0	1

SGTR Sequence

Parameter	SRO	RO	ARO	Total
RCS T-avg	8	9	8	25
Primary Pressure	7	8	7	22
Steam Generator Level	3	1	9	13
Steam Generator Pressure	5	3	4	12
Pressurizer Level	1	6	2	9
Emergency Feedwater Flow	3	1	1	5
Pressurizer Heater & Spray	1	0	0	1

Table A.6 Expert Rating of Individual Operator Technical Ability and Crew Teamwork Quality

Items	Operator	CREWS #1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Average (μ) and Standard Deviation (σ)
Individual Technical Ability	SRO	66.6	67.2	73.8	76.4	79.6	84.3	84.8	88.4	89.3	96.4	$\mu = 80.7$ $\sigma = 9.80$
	RO	68.0	78.0	77.3	83.3	84.0	65.3	98.0	80.9	81.3	71.3	$\mu = 78.7$ $\sigma = 9.30$
	ARO	90.0	82.4	98.0	70.7	74.7	79.3	78.7	83.7	92.0	82.0	$\mu = 83.1$ $\sigma = 8.20$
Crew Teamwork Quality		67.3	65.9	71.7	71.7	80.5	70.0	96.7	87.1	87.8	90.6	$\mu = 78.9$ $\sigma = 11.0$

Note: Experts consists of 5 former shift engineers (3 of them were training supervisors). The score shown is the average of all five experts.

Table A.7 Key Time of Crew Actions in SGTR Simulation Exercises

Items	CREWS										Average (μ) and Standard Deviation (σ)
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	
Time to diagnose SGTR (Judged from dialog among operators)	0.74	1.0	0.31	0.48	0.46	0.42	0.28	0.42	0.34	0.31	$\mu = 0.48$ $\sigma = 0.23$
Time to initiate SGTR procedure (E-3)	0.68	1.0	0.52	0.78	0.87	0.83	0.56	0.82	0.77	0.78	$\mu = 0.76$ $\sigma = 0.14$
Time to isolate the faulted S/G	0.68	1.0	0.59	0.75	0.84	0.88	0.46	0.96	0.82	1.0	$\mu = 0.80$ $\sigma = 0.18$
Time to initiate primary side cooldown and depressurization	0.74	1.0	0.59	0.71	0.88	0.86	0.64	0.89	0.79	0.98	$\mu = 0.81$ $\sigma = 0.14$

Note: All times have been normalized, the longest time taken by crews in each category is assigned as 1.0.

Table A.8 - Observed Variations in Operator Behavior During SGTR Exercises

Cue	Operator	Option 1 (number of operators choosing this options/number of situations applicable)	Option 2 (number of operators choosing this options/number of situations applicable)
Radiation high alarm	SRO	Went to check radiation monitor himself (5/10)	Commanded ARO to check monitor (5*/10)
PZR level decreasing	SRO	Commanded RO to start up second charging pump (5/10)	No action (5/10)
PZR level decreasing and no SRO command	RO	Suggested SRO to start up second charging pump (1/5)	No suggestion (4/5)
PZR level still decreasing in an uncontrolled manner	SRO	Commanded RO to reduce power (7/10)	No action (3/10)
PZR level still decreasing and no SRO command	RO	Suggested SRO to reduce power (2/3)	No suggestion (1/3)
S/G blowdown radiation alarm	SRO	Called chemistry department to check S/G water quality (6/10)	Called chemistry department to check S/G water quality and commanded ARO to check for S/G mismatch (4/10)
PZR level deviation alarm	ARO	Monitored PZR status but did not proactively report to SRO (6/10)	Monitored PZR status and reported to SRO (4/10)
Secondary radiation high alarm	ARO	Monitored S/G status but did not proactively report to SRO (6/10)	Monitored S/G status and reported to SRO (4/10)

* an RO (in 1 of the 5 crews) went to check the radiation monitor without SRO's command.

APPENDIX B. IMPROVED QUESTIONNAIRE FOR CONTROL ROOM CREW INTERVIEWS

This appendix provides a questionnaire developed for evaluating the relative confidence level between operators in a NPP control room operating crew. The questionnaire is a modified (and condensed) version of that developed by Ref. B-1. The original one have been tested on employees in a information technology firm, a navy civilian agency, and a social service agency. The total sample size is about 500. The test results show that [B-1] strong correlations exist between the answers to the questions related to issues of "Informal (IF)" and "Trustworthiness (T)," and between that of "Open and Two-way" and "Informative (IF)." The result also show that the "Effectiveness (E)" is strongly related to the trustworthiness and informative.

This questionnaire can be divided into two parts: Part 1 is the self-rating of the respondent, Part 2 to Part N are the respondent's ratings on his crew members. "N" represents the number of operators in a crew. The contents of a typical questionnaire is provided as Table B.1. Note that since Part 3 to Part N are similar to Part 2, they are not provided in this table. In each part, the questions related to respondent's or other crew member's work situation are contained in Section A. The questions in Part B are either related to issue of "Open and Two-way" or "Informal," while the issues of "Informative" and "Teamwork" are included in Section C. The last section, the Section D, covers the issues of "Effectiveness."

Since every operator in a crew will rate himself as well as his crew members, the results from all operators in the same crew can be used first for consistency check and then for evaluating the "relative confidence level' between operators (see Chapter 4 for definition). It is expected that the this questionnaire will improve the approach used in current data collection (described in Chapter 4), and be more systematically draw the relationship structure between operators in a control room operating crew.

Reference

B-1) R. Klauss and B. M. Bass, "Interpersonal Communication in Organizations," Academic Press, New York, 1982.

Table B.1 Questionnaire for Relative Confidence Evaluation

1A: YOUR BACKGROUND AND WORK SITUATION

Please select the most appropriate response and write its letter in the blank.

____ 1. Sex A. Male B. Female

____ 2. How long have you been working as a control room operator?
A. < 6 mo. B. 6 mo. to 1 yr C. 1-2 yrs D. 2-4 yrs E. > 4 yrs

____ 3. How long have you been part of your control room crew?
A. < 6 mo. B. 6 mo. to 1 yr C. 1-2 yrs D. 2-4 yrs E. > 4 yrs

PART 1B: SELF-RATING
SUBJECT: COMMUNICATION STYLE

In the blank space next to each statement write the number which best describes how frequently you behave or act that way. The numbers represent the following descriptive terms:

7 = Always
6 = Usually
5 = Often
4 = Fairly often
3 = Sometimes
2 = Once in a while
1 = Never
0 = Cannot say, don't know

OT 1. I ask for others' views on problems and issues.

IF 2. I am very informal and relaxed when I communicate.

OT 3. I give others feedback on their suggestions and comments.

IF 4. I am very natural in the way I relate to others.

OT 5. I am receptive to points of view which differ from mine.

Table B.1 Questionnaire for Relative Confidence Evaluation (continuation)

PART 1C: SELF-RATING
SUBJECT: INDIVIDUAL CHARACTERISTICS

In the blank space next to each statement write the number which best describes the extent to which you agree or disagree with the particular statement. The numbers represent the following:

7 = Very much agree
6 = Moderately agree
5 = Somewhat agree
4 = Neither agree or disagree
3 = Somewhat disagree
2 = Moderately disagree
1 = Very much disagree

IT 1. I am very well qualified for my job.

T 2. I consider myself to be very friendly.

IT 3. I am very well informed on issues that I am responsible for.

T 4. I tend to be very pleasant company.

IT 5. I am very skilled in my work.

Table B.1 Questionnaire for Relative Confidence Evaluation (continuation)

PART 1D: SELF-RATING
SUBJECT: EFFECTIVENESS & SATISFACTION

In the blank space next to each statement write the number which best describes your overall judgement about the statement.

_E_ 1. The overall work effectiveness of your crew can be classified as:

Use the scale below:
5 = Extremely Effective
4 = Very Effective
3 = Effective
2 = Only Somewhat Effective
1 = Not Effective

_E_ 2 Your crew is comfortable in solving problems when they arise.

Use the scale below:
7 = Very much agree
6 = Moderately agree
5 = Somewhat agree
4 = Neither agree or disagree
3 = Somewhat disagree
2 = Moderately disagree
1 = Very much disagree

_E_ 3. To make your crew the most effective crew you have ever known, to what degree are improvements needed?

Use the scale below:
5 = Very High Degree
4 = High Degree
3 = Moderate Degree
2 = Slight Degree
1 = Very Low Degree

Table B.1 Questionnaire for Relative Confidence Evaluation (continuation)

2A: RATING OF THE FOCAL PERSON BACKGROUND

Please select the most appropriate response and write its letter in the blank.

____ 1. How long have you been working together with the focal person in the same crew?
A. Under 6 mo   B. 6 mo to 1 yr.   C. 1-2 yr   D. 2-4 yr   E.> 4 yr

____ 2. How often do you interact with the focal person?
A. once per shift   B. once per hour   C. once per 10 minutes
D. once per 2 minutes   E. continuously

____ 3. How often do you interact with the focal person while off duty?
A. never   B. 1-2 times per day   C. 3-5 times per day
D. 6-10 times per day   E. more than 10 times per day

PART 2B: RATING OF THE FOCAL PERSON SUBJECT: COMMUNICATION STYLE

In the blank space next to each statement write the number which best describes how frequently you behave or act that way. The numbers represent the following descriptive terms:

7 = Always
6 = Usually
5 = Often
4 = Fairly often
3 = Sometimes
2 = Once in a while
1 = Never
0 = Cannot say, don't know

OT 1. He asks for others' view on problems and issues.

IF 2. He is very informal and relaxed when he communicates.

OT 3. He gives me feedback on my suggestions and comments.

IF 4. He is very natural in the way he relates to others.

OT 5. He is receptive to points of view which differ from his.

Table B.1 Questionnaire for Relative Confidence Evaluation (continuation)

PART 2C: RATING OF THE FOCAL PERSON
SUBJECT: INDIVIDUAL CHARACTERISTICS

In the blank space next to each statement write the number which best describes the extent to which you agree or disagree with the particular statement. The numbers represent the following:

7 = Very much agree
6 = Moderately agree
5 = Somewhat agree
4 = Neither agree or disagree
3 = Somewhat disagree
2 = Moderately disagree
1 = Very much disagree

_IT_ 1. I frequently use his technical knowledge to support my work.

_T_ 2. I consider him to be very friendly.

_IT_ 3. I consider him to be very well informed on issues that he is responsible for.

_T_ 4. I consider him to be a very pleasant company.

_IT_ 5. I consider him to be very skilled in his work.

PART 2D: RATING OF THE FOCAL PERSON
SUBJECT: EFFECTIVENESS & SATISFACTION

In the blank space next to each statement write the number which best describes your overall judgement about the statement.

_E_ 1. How effective do you work with the focal person?

_E_ 2. How effective is the focal person in meeting job-related needs?

Use the scale below for items 1-2:
5 = Extremely Effective
4 = Very Effective
3 = Effective
2 = Only Somewhat Effective
1 = Not Effective

Appendix C – Sample SIMSCRIPT II.5 Program

This appendix presents a simple program intended to illustrate both some of the useful features of SIMSCRIPT II.5 and how SIMSCRIPT II.5 can be used to model discrete events and processes. The system modeled consists of two pumps. It is assumed that the first pump has a failure time of 10000 hours and a repair time of 100 hours; the second pump has a failure time of 14000 hours and a repair time of 100 hours. It is also assumed that the system is struck by an earthquake which permanently fails both pumps at time t = 25000 hours. The model is deterministic; however, only slight modifications are needed to treat stochastic variability in event timing.

Figure C.1 shows a SIMSCRIPT II.5 program for this problem. The program consists of five major routines. The first two routines, the PREAMBLE and the MAIN routine, are common to most SIMSCRIPT II.5 programs. The remaining three routines (PUMP, EARTHQUAKE, and SYSTEM.STATUS.CHECK) are specific to the problem.

The PREAMBLE is used to define all important entities in the model. Here, one type of process (PUMP) and two types of events (EARTHQUAKE and SYSTEM.STATUS.CHECK) are defined. Note that the PUMP process has 4 associated parameters ("attributes"): name, status, time–to–failure, and time–to–repair. The PUMP process also can be a member of a set: the FAILED.SET (which is "owned" by the system).

The MAIN routine is used in this program to create two instances of the PUMP process, pump_1 and pump_2, and to initialize the parameter values for each pump. The routine also schedules the occurrence of the earthquake, and multiple checks of the system status (to provide output). Note that the first pump process is scheduled for execution at t = 0; the second pump process is scheduled for execution at t = 1000 hours. The SIMSCRIPT II.5 compiler implements the first scheduling by placing an event notice for pump_1 into the pending list with an execution time of 0 hours. Similarly, it places an event notice for pump 2 into the pending list with an execution time of 1000 hours. Figure C.2 shows the pending list prior to the "start simulation" statement; this latter statement, when encountered, instructs the program to begin the execution of the events in the pending list.

The PUMP process shows how two sequentially occurring events, pump failure and pump repair, can be modeled. Consider the first pump. At t = 0, the instance of the PUMP process called pump 1 begins execution. After the pump is removed from the FAILED.SET (see below) and its status is changed to "on," a "wait" statement is encountered. The wait statement suspends the pump_1 process until the specified amount of time (10000 hours in this case) passes. (The SIMSCRIPT II.5 compiler implements this suspension by inserting an event notice for process reawakening into the pending list; the execution time associated with this event notice is 10000 hours. The simulation clock is then advanced to the time of the next event notice – 1000 hours in this case. Figure C.3 shows the pending list after the new event notice has been inserted.) After the pump_1 process is reawakened, the status of the pump is changed and the process is suspended once more until the time–to–repair elapses (i.e., until repairs have been effected). Note the infinite loop structure built into the PUMP process; the process will continue in a failure–repair cycle until interrupted by an outside event/process.

The set FAILED.SET is used to keep track of the failed components in the system. Thus, when a specific PUMP process is initialized, the program ensures that the pump is not stored in the FAILED.SET. Later on, the pump will be stored ("filed") in or removed from the FAILED.SET, as determined by the unfolding scenario. In this particular example, the FAILED.SET is an extraneous data structure. However, it is included to show how SIMSCRIPT II.5 can be used to organize related entities in a data structure.

The EARTHQUAKE event shows how an event occurring at a discrete point in time can be modeled. It also shows how events (and processes) can be used to affect ongoing processes. In this case, the earthquake is used to interrupt both the pump_1 and pump_2 processes. (The SIMSCRIPT II.5 compiler implements interruptions by removing the event notices associated with the processes from the pending list.) As in the case of the internally scheduled pump hardware failures, each pump is filed in the FAILED.SET as part of the failure process.

The SYSTEM.STATUS.CHECK event is used to generate program output (see Figure C.4). Unlike the PUMP and EARTHQUAKE entities, it does not correspond to any physical entity in the modeled system. However, it can be treated in the same manner as these other entities.

This program shows a number of useful SIMSCRIPT II.5 characteristics. First, the user need not manipulate the pending list directly; commands are provided that make the scheduling of events relatively simple. (Note that the language has enough flexibility that the user can modify the pending list, if desired.) Second, the SIMSCRIPT II.5 syntax is very similar to English. This improves the readability and maintainability of the program. Third, the language allows the use of data structures that are more general than the simple arrays used by FORTRAN (e.g., see the attributes associated with a PUMP entity). Text, numbers, and arrays can be readily assigned with a given entity. Moreover, entities can be assigned to sets and can also be the owners of sets. All of these characteristics are exploited by the crew model described in the main body of this report.

Figure C.1 – Listing of Simple SIMPSCRIPT II.5 Program (Page 1 of 2)

```
PREAMBLE

  processes
    every PUMP
      has a name,
         a status,
         a time_to_failure, and
         a time_to_repair
      and may belong to the FAILED.SET

  event notices include EARTHQUAKE, SYSTEM.STATUS.CHECK

  the system owns the FAILED.SET

  define pump_1 and pump_2 as pointer variables
  define status and name as text variables
  define time_to_failure and time_to_repair as real variables

END ''PREAMBLE


MAIN

  create a PUMP called pump_1
  let name(pump_1) = "RHR-P1"
  let time_to_failure(pump_1) = 10000
  let time_to_repair(pump_1) = 100
  let status(pump_1) = "off"
  schedule the PUMP called pump_1 now

  create a PUMP called pump_2
  let name(pump_2) = "RHR-P2"
  let time_to_failure(pump_2) = 14000
  let time_to_repair(pump_2) = 100
  let status(pump_2) = "off"
  schedule the PUMP called pump_2 in 1000 hours

  schedule an EARTHQUAKE in 25000 hours

  for check.time = 5000 to 30000 by 5000
  do
    schedule a SYSTEM.STATUS.CHECK in check.time hours
  loop

  start simulation

END ''MAIN
```

Figure C.1 – Listing of Simple SIMPSCRIPT II.5 Program (Page 2 of 2)

```
PROCESS PUMP

  while 0 = 0
  do
    if pump is in the FAILED.SET
      remove pump from the FAILED.SET
    endif
    let status(pump) = "on"

    wait time_to_failure(pump) hours
    if pump is not in the FAILED.SET
      file pump in the FAILED.SET
    endif
    let status(pump) = "off"

    wait time_to_repair(pump) hours
  loop

END ''PUMP


EVENT EARTHQUAKE

  if pump_1 is not in the FAILED.SET,
    file pump_1 in the FAILED.SET
  endif
  interrupt the PUMP called pump_1
  let status(pump_1) = "off"

  if pump_2 is not in the FAILED.SET,
    file pump_2 in the FAILED.SET
  endif
  interrupt the PUMP called pump_2
  let status(pump_2) = "off"

END ''EARTHQUAKE


EVENT SYSTEM.STATUS.CHECK

  print 1 line with 24*time.v, status(pump_1), and status(pump_2) thus
Time = *******    Status(Pump 1) = ***    Status(Pump 2) = ***

  for every pump in the FAILED.SET
    print 1 line with name(pump) thus
            ****** is failed!

END ''SYSTEM.STATUS.CHECK
```

Figure C.4 – Output for Sample Program

```
Time =    5000    Status(Pump 1) = on     Status(Pump 2) = on
Time =   10000    Status(Pump 1) = off    Status(Pump 2) = on
                  RHR-P1 is failed!
Time =   15000    Status(Pump 1) = on     Status(Pump 2) = off
                  RHR-P2 is failed!
Time =   20000    Status(Pump 1) = on     Status(Pump 2) = on
Time =   25000    Status(Pump 1) = off    Status(Pump 2) = off
                  RHR-P1 is failed!
                  RHR-P2 is failed!
Time =   30000    Status(Pump 1) = off    Status(Pump 2) = off
                  RHR-P1 is failed!
                  RHR-P2 is failed!
```

Table D.1 Physical Variables Used in the Plant Model Equations

Notation	Meaning
Rx-power	Reactor power (MW thermal)
Charge-flow	Primary charging flow rate (kg/s)
PZR-pressure	Primary Pressure (Mpa)
Hot-leg-T	Primary hot leg temperature (degree c)
SG-pressure	Steam Generator pressure (Mpa)
B-SG-level	Faulted SG level (% narrow range)
AC-SG-level	Intact SG level (% narrow range)
B-SG-fw	Faulted SG feedwater flow rate (kg/s)
AC-SG-fw	Intact SG feedwater flow rate (kg/s)
B-SG-steam-flow	Faulted SG steam flow rate (kg/s)
AC-SG-steam-flow	Intact SG steam flow rate (kg/s)
PZR-level	Pressurizer level (%)
SI-flow	Safety injection flow rate (kg/s)
Number-of-tube-rupture	Number of ruptured tubes in the faulted SG
PZR-PORV-open-elapsed-time	How long have the PZR relief valve been manually opened
PZR-spray-open-elapsed-time	How long have the PZR spray valve been manually opened
Steam-dump-open-elapsed-time	How long have the steam dump valves been manually opened

APPENDIX D. THERMAL-HYDRAULIC MODEL

This appendix lists the equations incorporated in the plant model. This model, which is primarily based on the results from PRISM [D-1], is specialized toward the analysis of of steam generator tube rupture (SGTR) in a Westinghouse house 3-loop pressurized water reactor (PWR). The PRISM output data for the following two parameters are modified to reflect the scenario trends observed in the simulator of a non-U.S. plant, whose crews are chosen as the demonstration study. For PZR level before reactor trip, a value of 3%/min. * time elapsed since the beginning of the scenario was subtracted from each PRISM datum. A value of 9%/min. * time elapsed since reactor trip was added to each PRISM datum of SG level after reactor trip. The linear regression is used to correlate 17 plant parameters with each others, but not every parameters is dependent on the other 16 parameters (variables). A series of test on the correlations between any pair of variables have been done to decide which variables should be included in correlating a specific variable. Table A.1 lists all physical variables used in the plant model equations. These equations and their related "boundary conditions" are shown as Table A.2. These "boundary conditions" are usually related to operator's actions and/or to specific plant status (e.g., reactor has been tripped or not). Table D.3 lists those alarms simulated when a specific physical variable exceeded the correspondent set points.

D-1) S. P. Kao, "PRISM: An Integrated RCS and Steam Generator Simulation Model," Proceedings of the ANS International Topical Meeting in Mathematics, Computation, and Reactor Physics, Pittsburgh, PA, April 28-May 1, 1991.

Table D.2 Plant Model Equations and Their "Boundary Conditions"

Physical Variable	Boundary Conditions	Equations (all time in minutes)
	Before Rx trip (without power reduction)	Rx-power = Rx-power
Rx-power	Before Rx trip (with power reduction)	Rx-power = Rx-power * (1- 0.001* (current time - time power reduction begins))
	After reactor trip	Rx-power = Power before reactor trip * 0.0756 * (current time - reactor trip time) ** (-0.2)
Charge-flow	One pump running	Charge-flow = 0.641 * current time
	Two pump running (2nd CCP started)	Charge-flow = 0.962 * current time
PZR- pressure	Before reactor trip	PZR-pressure = 4.434 + 0.00337 * Rx-power - 0.34 * Charge-flow - 0.529 * Number-of-tube-rupture
	After reactor trip	PZR-pressure = 22.612 - 0.046 * Rx-power - 0.609 * Charge-flow - 1.29 * Steam-dump-open-elapsed-time - 2.306 * Number-of-tube-rupture - 4.414 * PZR-PORV-open-elapsed-time - 0.598 * PZR-spray-open-elapsed-time
Hot-leg-T		Hot-leg-T = 274.7 + 0.0081 * Rx-power + 1.336 * PZR-pressure + 1.047 * PZR-PORV-open-elapsed-time + 0.544 * PZR-spray-open-elapsed-time + 1.047 * Steam-dump-open-elapsed-time
SG-pressure		SG-pressure = 7.563 - 0.0002 * Rx-power - 0.326 * Steam-dump-open-elapsed-time

Table D.2 Plant Model Equations and Their "Boundary Conditions" (continuation)

Physical Variable	Boundary Conditions	Equations (all time in minutes)
B-SG-level	Before reactor trip	B-SG-level = 122.96 - 0.0187 * Rx-power - 0.345 * PZR-pressure - 0.531 * SG-pressure + 0.085 * Number-of-tube-rupture
	After reactor trip	B-SG-level = 432.8 - 4.31 * Rx-power - 3.339 * PZR-pressure - 1.752 * Number-of-tube-rupture
AC-SG-level	Before reactor trip	AC-SG-level = 119.32 - 0.0169 * Rx-power - 0.234 * PZR-pressure - 0.329 * Number-of-tube-rupture
	After reactor trip	AC-SG-level = 238.49 - 3.041 * Rx-power + 0.74 * PZR-pressure - 1.892 * Number-of-tube-rupture
B-SG-fw	Before reactor trip (main feedwater)	B-SG-fw = 1430 - 12.197 * B-SG-level - 0.102 * Rx-power
	After reactor trip (emergency feedwater)	B-SG-fw = 12.0
AC-SG-fw	Before reactor trip (main feedwater)	AC-SG-fw = 1514 - 13.066 * AC-SG-level - 0.113 * Rx-power
	After reactor trip (emergency feedwater)	AC-SG-fw = 12.0
B-SG-steam-flow	Before reactor trip	B-SG-steam-flow = AC-SG-steam-flow + 5.35
	After reactor trip	B-SG-steam-flow = 12.0
AC-SG-steam-flow	Before reactor trip	AC-SG-steam-flow = 459.3 - 0.182 * AC-SG-level + 0.017 * Rx-power - 0.074 * AC-SG-fw + 0.413 * (PZR-pressure - SG-pressure)
	After reactor trip	AC-SG-steam-flow = 12.0

Table D.2 Plant Model Equations and Their "Boundary Conditions" (continuation)

Physical Variable	Boundary Conditions	Equations (all time in minutes)
PZR-level	Before reactor trip	PZR-level = -255.67 - 0.01346 * Rx-power + 22.897 * PZR-pressure - 0.004 * Hot-leg-T + 3.669 * Number-of-tube-rupture
	After reactor trip	PZR-level = 141.75 - 0.277 * Rx-power + 15.496 * PZR-PORV-open-elapsed-time + 0.979 * PZR-spray-open-elapsed-time + 6.475 * Number-of-tube-rupture + 3.501 * PZR-pressure - 0.545 * Hot-leg-T
SI-flow	Before reactor trip	SI-flow = 0.0
	After reactor trip	SI-flow = 66.82 + 0.114 * RX-power + 0.14 * PZR-level - 5.737 * PZR-pressure + 1.126 * Number-of-tube-rupture

Table D.3 Alarms and Their Set points

Alarms	Correspondent physical variables and set points
Automatic reactor trip	PZR-pressure <= 13.44.Mpa
Safety injection	PZR-pressure <= 12.89 Mpa
SG level high	B-SG-level or AC-SG-level >= 55% NR (narrow range)
SG level high-high	B-SG-level or AC-SG-level >= 84% NR
PZR level deviation	PZR-level <= 53.84% or >= 63.84% (normal operating value: 58.84% at full power)
Secondary radiation high	External inputs (can be set at any time)