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A Mid-Layer Model for Human Reliability Analysis: Understanding the Cognitive Causes of Human Failure Events[1]

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Abstract: The Office of Nuclear Regulatory Research (RES) at the US Nuclear Regulatory Commission (USNRC) is sponsoring work in response to a Staff Requirements Memorandum (SRM) directing an effort to establish a single human reliability analysis (HRA) method for the agency or guidance for the use of multiple methods. As part of this effort an attempt to develop a comprehensive HRA qualitative approach is being pursued. This paper presents a draft of the method's middle layer, a part of the qualitative analysis phase that links failure mechanisms to performance shaping factors. Starting with a Crew Response Tree (CRT) that has identified human failure events, analysts identify potential failure mechanisms using the mid-layer model. The mid-layer model presented in this paper traces the identification of the failure mechanisms using the Information-Diagnosis/Decision-Action (IDA) model and cognitive models from the psychological literature. Each failure mechanism is grouped according to a phase of IDA. Under each phase of IDA, the cognitive models help identify the relevant performance shaping factors for the failure mechanism. The use of IDA and cognitive models can be traced through fault trees, which provide a detailed complement to the CRT.

Keywords: HRA, Failure Mechanism, Cognitive Model, IDA.

1. INTRODUCTION

In a Staff Requirements Memorandum (SRM) to the Advisory Committee on Reactor Safeguards (ACRS) [1], the US Nuclear Regulatory Commission (USNRC) directed the ACRS to "work with the staff and external stakeholders to evaluate the different human reliability models in an effort to propose a single model for the agency to use or guidance on which model(s) should be used in specific circumstances." As a first step toward meeting this directive, an effort has been undertaken to build on existing knowledge and methods in an attempt to develop a comprehensive qualitative analysis approach for human reliability analysis (HRA). Current HRA methods in use as well as psychological and cognitive theories were referenced in the development of the qualitative analysis approach. This approach is intended to be applicable for HRA within a full-power internal events probabilistic risk assessment (PRA) as well as for event evaluation associated with low-power shutdown (LPSD) operations.

The qualitative analysis to be proposed through this effort is a three-stage process. The first stage is the construction of crew response trees (CRTs). These CRTs resemble event trees and describe the evolution of the scenario and human failures (potential paths) through the procedures (e.g., emergency operating procedures [EOPs] or alarm response procedures [ARPs]). Instances of possible human failures are indentified within these CRTs, which are then explored further in supporting fault trees.

[1] The information presented in this paper does not currently represent an agreed-upon NRC staff position. The NRC has neither approved nor disapproved its technical content.

Therefore, a second stage within the qualitative analysis is the exploration of failure mechanisms (within a fault tree logic) underlying the possible human failures identified within the CRTs. A final step is the identification of relevant performance shaping factors (PSFs) driving the identified failure mechanisms.

The terms *failure mechanism* and *failure mode* are sometimes used interchangeably, leading to occasional confusion. In the present research project, the authors have adopted failure mode to refer to the specific instantiation of a failure (e.g., "failure to close valve"), whereas a failure mechanism prescribes a general explanation for the cause of the failure (e.g., "skip step in procedure"). The purpose of the research outlined in this paper is to introduce a consensus list of failure mechanisms, provide explicit links to cognitive models that account for those failure mechanisms, and further introduce how cognitive models map to specific PSFs. Note that the same failure mechanism may have multiple cognitive models to account for it, and each of these cognitive models may, in turn, map to a unique configuration of PSFs. The goal of the mid-layer model is to provide a clear mapping from failure mechanisms to PSFs via well-understood cognitive models.

This paper will discuss the development and identification of the failure mechanisms. The failure mechanisms represent the link connecting the PSFs to the possible human failures identified within the CRTs. Therefore, the failure mechanisms represent a middle layer to the qualitative analysis approach, with the CRTs representing a top layer and the PSFs representing the bottom or lower layer. The mid-layer linkage is an important component as it ensures the correct PSFs (and scenario context) are identified for quantifying the probability of the possible human failures.

The inclusion of such a mid-layer model within the qualitative analysis not only links the current method under development to other HRA methods that are currently in use (e.g., Cause-Based Decision Trees (CBDT) [2]), but also allows the method to be supported by human factors (HF) and psychological literature. This explicit grounding within the HF literature has not been a part of HRA methods in the past; however, the vast experience and knowledge available within the literature should be harvested in order to build more complete and comprehensive failure mechanisms as well as provide a cognitive framework linking operator psychological processes with behavior and performance. Another advantage to the inclusion of the mid-layer is to allow greater traceability of the application of the method.

2. OVERVIEW OF MID-LAYER MODEL APPROACH

2.1. IDA Cognitive Model

A set of failure mechanisms has been identified for use within the qualitative analysis. These failure mechanisms are linked to the possible human failures identified within the CRTs based on the IDA cognitive model [3]. The IDA cognitive model represents a three-stage model originally developed to model the response of nuclear power plant (NPP) operators within an emergency situation. The stages of the IDA cognitive model are:

1. *Information.* This stage focuses on the perception of the environment and presented cues to the operator. The information is presented externally to the operator. Cognitive processing of the information is limited to the task of perceiving the information, but limited processing of the information is done at this stage.
2. *Diagnosis/Decision.* This stage is internal to the operator. At this phase, the operator uses what information was perceived in the previous stage along with stored memories, knowledge, and experience to develop an understanding of and a mental model of the situation. Following this situational assessment, the operator engages in decision making strategies to plan the appropriate course of action. Operators may use external resources such as procedures to assist them in both parts of this stage.
3. *Action.* In this final stage, the operator puts the decided upon course of action into play.

The IDA model accords well with the information processing paradigm commonly used in cognitive psychology and HF. Information processing theory outlines how information from the environment is sensed and perceived (corresponding to the "I" phase of IDA), used for decision making (corresponding to the "D" phase of IDA), and translated into behavior (corresponding to the "A" phase of IDA).

Within each of these elements, a nested IDA structure may exist [4]. In other words, each phase of the IDA model may be decomposed into further IDA structures. For instance, I-in-I explains the information being perceived and recognized, D-in-I involves deciding what to do with the perceived information (e.g., discard it or keep it), and A-in-I is acting on the decision made. For the application described within this paper, only the nested structure for the primary I phase was used.

2.2. Failure Mechanisms

Although IDA was originally tailored to the behavior of NPP operators who are assumed to have expertise in the area and be largely directed by procedures, the larger list of failure mechanisms developed has applicability outside of this domain and can be applied in less constrained or procedure-directed situations. Tables 1-3 list those failure mechanisms identified within each of the IDA phases. These tables were derived from a review of failure mechanisms included in current HRA methods, a derivation of failure mechanisms from cognitive models in the psychological literature, and input from nuclear power plant operations expertise.

Included in these tables is a discussion relating the failure mechanisms to relevant literature within the fields of psychology and HF. In order to identify failure mechanisms within the psychological and HF literature, a search was conducted including examining the last ten years of articles published within the *Annual Review of Psychology*, the 50th anniversary edition of the *Human Factors* journal, and current text books in the cognitive psychology. Additional books and seminal articles related to topics found in this exploration were also included. Specific topic areas that were explored as being relevant to each of the IDA phases were:

- I Phase: sensation and perception models, situation awareness, information foraging theory, and working memory
- D Phase: situation awareness, sensemaking, naturalistic decision making (with particular emphasis on recognition primed decision making), cognitive biases, and working memory
- A Phase: slips, lapses, and working memory

Because memory limitations, and in particular working memory, can be so influential on the performance by a person, it was included in all phases of search. Although this list represents the greatest area of search, it is not meant to be all-inclusive or exhaustive. In conducting the literature review, if other areas of interest were discovered, they were also included as possible failure mechanisms. Note that due to space constraints, Tables 1-3 only provide examples of the cognitive models that support failure mechanisms. The complete list includes multiple evidence sources for most failure mechanisms, each source providing a different explanation for how the failure mechanism may manifest.

Table 1. Failure Mechanisms Identified for the I Phase of the IDA Cognitive Model

I-D-A Sub-loop	Failure Mechanism	Support in the Psychological and HF Literature
Information Error (I-in-I)	Cues not perceived	Broadbent's Filter Theory [5] explains sensory bottlenecks in which some cue or alarm may be missed by the operator due to sensory overload.
	Instrumentation failure	Failing instruments, either due to spurious affects or not being available or readable, are outside the cognition of the operator. These failures are due to the state and/or design of the plant.
	Information not available/missing	
Decision Error (D-in-I)	Intentionally not collecting	The operator may fail to attend to cues or alarms due to an improper focus of attention on some element to the exclusion of noticing other elements [5].
	Intentionally ignored alarms/cues	Cues may be ignored due to a confirmation bias [6] in which people tend to seek out information that confirms their current position and will ignore or disregard evidence to the contrary.
	Collect but dismiss	The Data/Frame theory [7] suggests that a person processes incoming information by comparing it to an initial frame of mind. The data may be integrated into the existing frame, the person may re-frame to account for the existing data, or the data may be dismissed as being irrelevant. If the initial frame is incorrect, important data may be dismissed as being irrelevant or unimportant.
	Collected wrong information	Collecting the wrong information may be due to confirmation bias in which the operator is seeking out information to confirm his or her current position [6]. Another possible explanation is incorrect information sampling by the operator due to, for example, an inadequate sampling strategy or internal model directing the sampling [8].
Action Error (A-in-I)	Reading error (procedures)	In one instance, the operator may misread or misperceive an instrument due to elements being arranged close together on a control panel [9]. This misperception can account for either misreading the correct indicator or reading the wrong indicator. A similar phenomenon may be witnessed when reading steps within a procedure.
	Reading error (indicator)	
	Locate the wrong indicator	
	Unintentionally ignored alarms or cues	Alarms and/or cues may be unintentionally ignored due to a narrowing of attention brought on up stress or a heavy workload such that the perception of relevant elements is reduced [8]

Table 2. Failure Mechanisms Identified for the D Phase of the IDA Cognitive Model

Failure Mechanism	Support in the Psychological and HF Literature
Assess the plant condition incorrectly	This collection of failures is primarily related to the situational awareness by the operator. If the situation is assessed incorrectly such as through data misinterpretation due to insufficient expertise or knowledge by the decision maker, the classification of the system and the problem solving process can be misleading or wrong [8].
Map the collected information to a different event	
Inability to develop diagnosis from the data	
Inappropriate goal selected	
Incorrect action ordering	
Skip procedure steps	The decision leading to an incorrect application of the procedures, either by skipping steps, postponing steps, or deviating in some way from the guidance, may be due to a misinterpretation of the situation by the operator such that the current procedural guidance is not judged to be applicable [10].
Deviate from procedure	
Postpone procedure steps	
Decide to wait for more information	Deciding upon the wrong action, whether seen through a delay of taking the action, incorrectly waiting for more information, or implementing the wrong action may be due to the incorrect mental simulation by the operator [11]. The mental simulation occurs while the decision maker is deciding upon the proper action to take in a situation and he or she mentally simulates the initiation and outcome of an action. This simulation may be incorrect for a number of reasons including an incorrect judgment of time available or time needed, an incorrect imagination of possible action outcomes, or not including a likely problem to occur within the simulation.
Decide to take an alternative action	
Decide to take an action later	

Table 3. Failure Mechanisms Identified for the A Phase of the IDA Cognitive Model

Failure Mechanism	Support in the Psychological and HF Literature
Select wrong component	The wrong action may be committed (e.g., selecting the wrong component or omitting a component) due to a strong but incorrect instinctive or habitual action. For instance, behavior that is correct in most situations but is on some occasions inappropriate or incorrect [12].
Omit one or more components	
Skip step in procedure	Skipping a step, whether an action step or a step within the procedural guidance, may be due to memory loading in which the amount of information that has to be carried in a person's head to complete the action exceeds the person's memory limits [13]. Therefore, steps are likely to be omitted.
Skip step in action	
Incorrectly repeat a step in the action	A step may be incorrectly repeated due to a distraction or interruption causing the action-taker to lose his or her place within the action progression [12].
Delay in execution of the action	A delay in action may be due to distraction or due to a momentary lapse in memory in which the action taker momentarily forgets the order of action steps or forgets what step within the action is next [12].
Failure to perform the action (omission)	The omission of an action may be due to a number of issues including fault memory or a distraction or an interruption.

The failure mechanisms were built into fault trees to be used in the qualitative analysis of the current HRA method under development. These fault trees can be linked back to the HFE as described in the CRTs (see separate article in this session on CRTs). A series of fault trees was developed, representing each of the IDA phases. Figures 1-3 show the relationship of the failure mechanisms within the I phase to processing by the operator. As seen in Figure 1, an error in information processing may occur due to either direct information, referring to rule-oriented processing, or indirect information, referring to knowledge-oriented processing. Figures 4 and 5 show the fault trees leading to the failure mechanisms for the D and A phases.

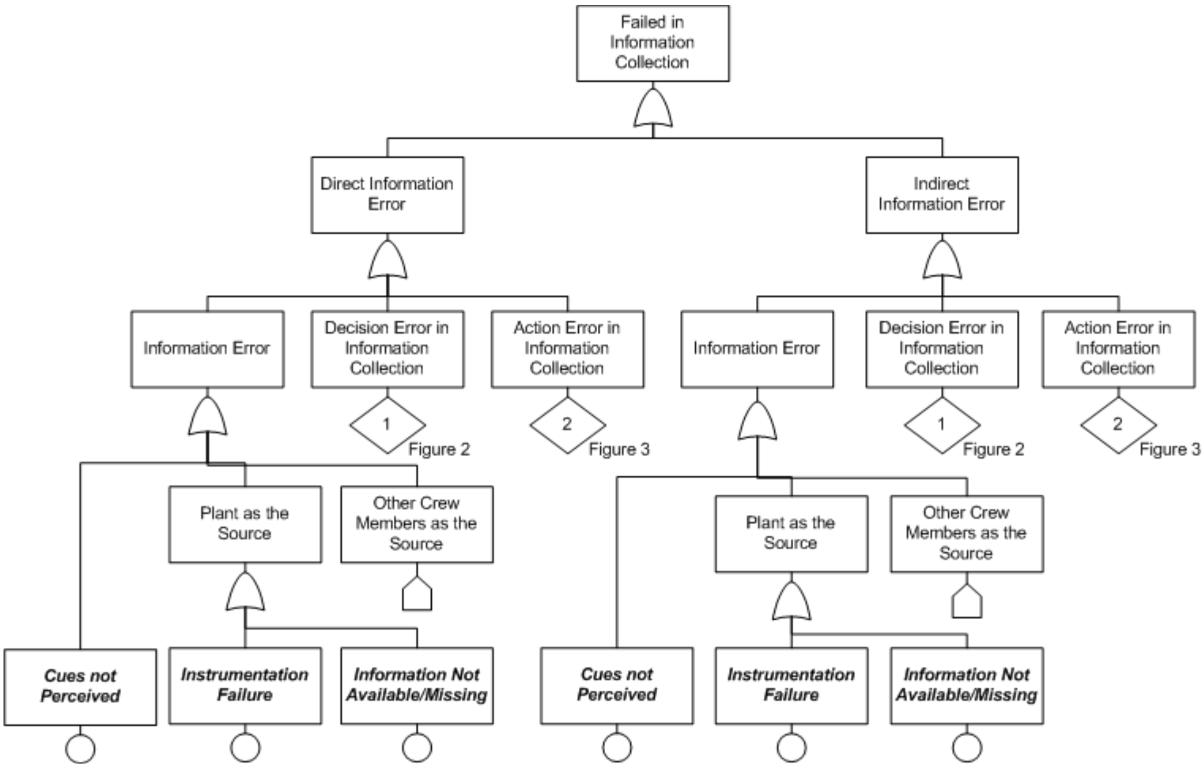

Figure 1. Fault Tree Identifying the Failure Mechanisms for the I Model Stage, Including the I-in-I Phase[2]

[2]The failure mechanisms are represented as the last (or bottom) elements within the fault trees and are identified in bold and italicized text.

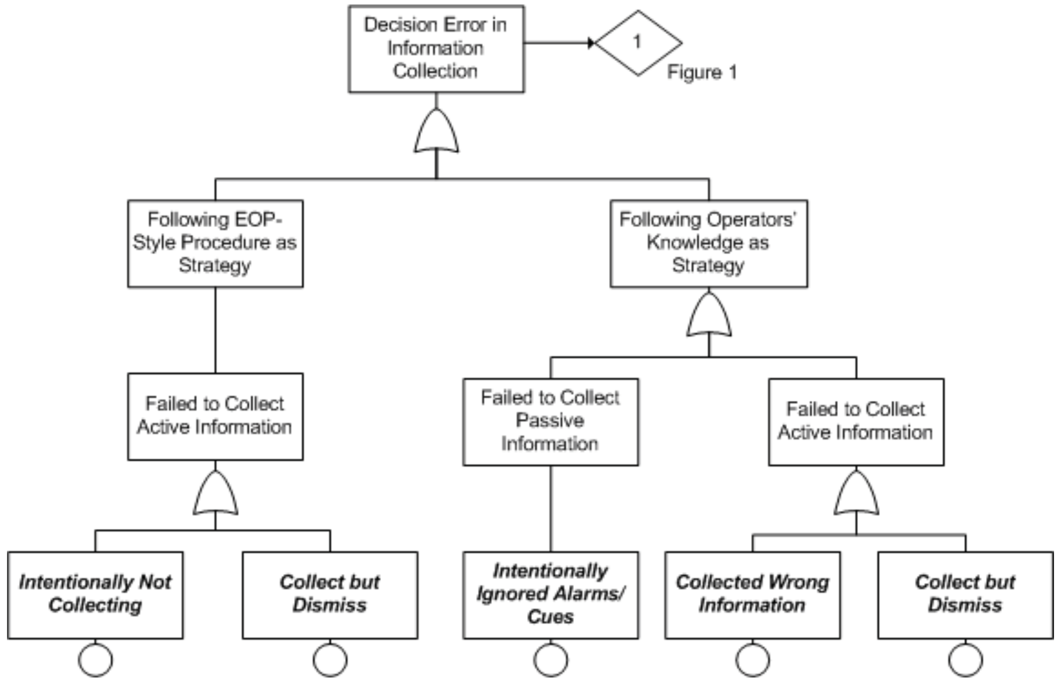

Figure 2. Fault Tree Identifying the Failure Mechanisms for the D-in-I Model Stage

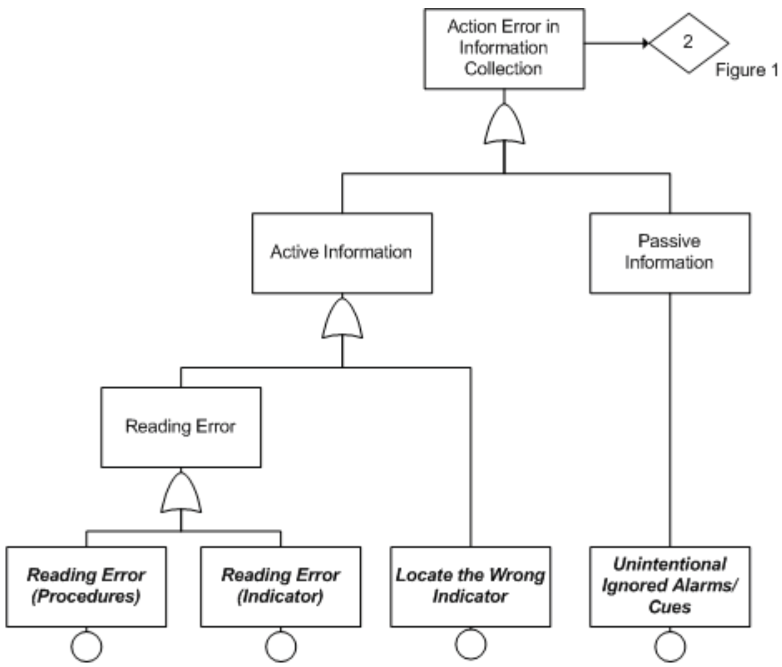

Figure 3. Fault Tree Identifying the Failure Mechanisms for the A-in-I Model Stage

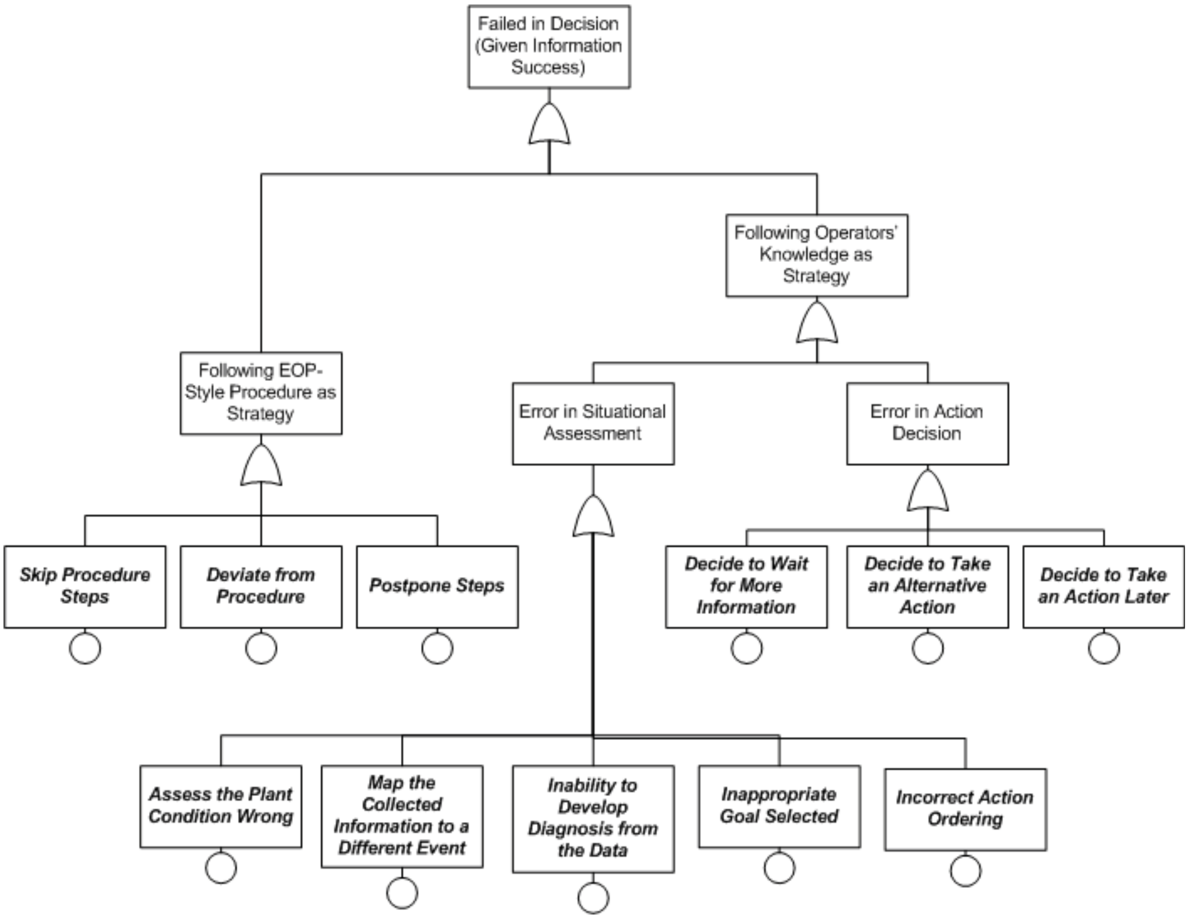

Figure 4. Fault Tree Identifying the Failure Mechanisms for the D Model Stage

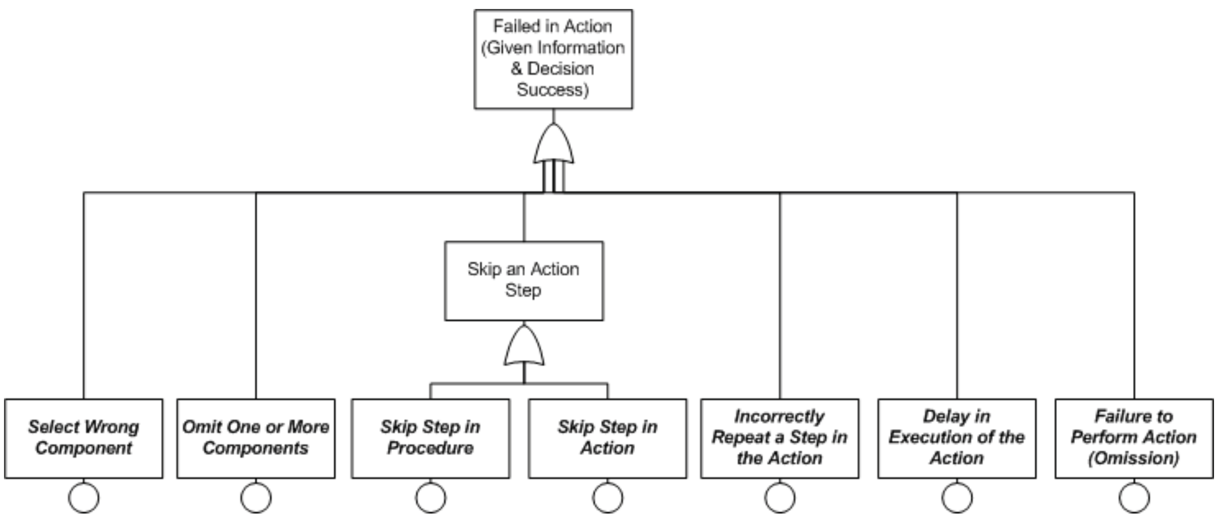

Figure 5. Fault Tree Identifying the Failure Mechanisms for the A Model Stage

2.3. Link to the Bottom Layer: PSFs

Although not shown on the fault trees presented within this paper, the failure mechanisms will be used to direct the HRA analyst to the appropriate list of PSFs relevant for the HFE in question. The failure mechanisms provide the means by which the PSFs are connected to the HFE. Where possible, this link between failure mechanism and PSF will be informed by the psychological literature, and where not possible, by expert inference. The PSFs will ultimately be used in the quantification of the human error probability (HEP) for the HFE. Within Figures 1 through 5, the PSFs should occur as the final element or basic event within the fault trees and are currently represented by small circles underneath each failure mechanism.

Groth and Mosleh [14] proposed a set of interdependent PSFs based on an analysis of all HRA methods, IDAC [4], and the Human Event Repository and Analysis system [15]. Groth and Mosleh [16] developed a hierarchical PSF structure that is grouped into six categories.[3] The PSF groups decided upon are definitionally orthogonal; therefore, relationships between the PSFs can be examined without fear of contamination by overlapping PSFs. The six PSF groupings proposed were:

1. Machine: factors associated with the physical system as it was designed by the manufacturer, including plant hardware, software, human-system interface, and system responses. Machine factors are often static.
2. Situation: factors of the situation that are likely to affect human performance, which are often dynamic. Situation factors include objective task and time load, environmental conditions, and situation and task complexity. Situation factors are often perceived as stressors.
3. Stressors: factors that can act as stressors on the person(nel) involved in the situation, including perceived task and time load, perceived severity, perceived urgency, and perceived responsibility. Stressors interact with Personal factors to produce the *stress* that the involved personnel experience.
4. Person: factors internal to the individual, including attention, psychological and physical abilities, attitude, knowledge and experience, skills, and work conduct.
5. Team: factors associated with the crew or team, including communication, coordination, cohesion, supervision, and role awareness.
6. Organization: factors that are under control of the organization, including organizational programs, safety culture, management, resources (including tools and procedures), and staffing and scheduling.

These six groups are composed of 36 PSFs. Table 4 outlines how these 36 PSFs are distributed across the six PSF groups.

[3] The authors provided multiple PSF lists but finally advocated five PSF categories, excluding Stressor as a PSF. For the present purposes, we have selected a PSF list with six PSF categories.

Table 4. Proposed Categorization of Performance Shaping Factors into Six Groups by Groth and Mosleh [14]

PSF Grouping	PSF
Machine	Human-System Interface
	System Responses
Situation	External Environment
	Hardware and Software Conditions
	Task Load
	Time Load
	Other Loads (e.g., passive information load)
	Task Complexity
Stressor	Perceived Task Load
	Perceived Time Load
	Perceived Other Loads
	Perceived Situation Severity
	Perceived Situation Urgency
	Perceived Decision Responsibility
	Perception of Alarms
Person	Attention to Task
	Attention to Surroundings
	Physical and Psychological Abilities
	Bias
	Morale / Motivation / Attitude
	Knowledge and Experience
	Skills
	Familiarity with Situation
	Work Conduct
Team	Communication
	Direct Supervision
	Team Coordination
	Team Cohesion
	Role Awareness
Organization	Programs (e.g., training or corrective action programs)
	Safety Culture
	Management
	Staffing
	Scheduling
	Work Space Adequacy
	Resources

The next phase of this effort is to connect the failure mechanisms to the PSFs, and this work is in progress. For example, the situation awareness literature [8] explicitly identifies training and experience as factors that influence whether a person will misinterpret information as he or she attempts to come to an understanding of the situation. This indicates that for the failure mechanism *Assess the plant condition incorrectly*, the PSFs of *Organization: Programs (Training)* and *Person: Knowledge and Experience* are highly important. The remaining failure mechanisms will be connected to relevant PSFs in a similar manner based on the relevant psychological and HF literature.

3. SUMMARY

This paper has presented the construction of the mid-layer component of a qualitative analysis portion of a newly formed HRA method. This HRA method is being proposed in response to a SRM posed to the ACRS and directing an effort to establish a single HRA method or guidance for the use of multiple methods in support of a full-power internal events PRA or evaluation of LPSD events.

The mid-layer model presented in this paper includes a series of failure mechanisms developed through a review of psychological and HF literature as well as input from NPP operations experts. This mid-layer links the HFEs identified within the top layer model (including the CRTs) with the PSFs of the bottom layer. The failure mechanisms offer a cognitive framework linking the performance and behavior of the NPP operators to psychological processes.

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